RESEARCH

Quantifying forest structural diversity based on large-scale inventory data: a new approach to support biodiversity monitoring

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Abstract

Background: The importance of structurally diverse forests for the conservation of biodiversity and provision of a wide range of ecosystem services has been widely recognised. However, tools to quantify structural diversity of forests in an objective and quantitative way across many forest types and sites are still needed, for example to support biodiversity monitoring. The existing approaches to quantify forest structural diversity are based on small geographical regions or single forest types, typically using only small data sets.

Results: Here we developed an index of structural diversity based on National Forest Inventory (NFI) data of Baden-Württemberg, Germany, a state with 1.3 million ha of diverse forest types in different ownerships. Based on a literature review, 11 aspects of structural diversity were identified a priori as crucially important to describe structural diversity. An initial comprehensive list of 52 variables derived from National Forest Inventory (NFI) data related to structural diversity was reduced by applying five selection criteria to arrive at one variable for each aspect of structural diversity. These variables comprise 1) quadratic mean diameter at breast height (DBH), 2) standard deviation of DBH, 3) standard deviation of stand height, 4) number of decay classes, 5) bark-diversity index, 6) trees with DBH ≥ 40 cm, 7) diversity of flowering and fructification, 8) average mean diameter of downed deadwood, 9) mean DBH of standing deadwood, 10) tree species richness and 11) tree species richness in the regeneration layer. These variables were combined into a simple, additive index to quantify the level of structural diversity, which assumes values between 0 and 1. We applied this index in an exemplary way to broad forest categories and ownerships to assess its feasibility to analyse structural diversity in large-scale forest inventories.

Conclusions: The forest structure index presented here can be derived in a similar way from standard inventory variables for most other large-scale forest inventories to provide important information about biodiversity relevant forest conditions and thus provide an evidence-base for forest management and planning as well as reporting.

Keywords: Stand structure, Structural diversity, Structural diversity index, Large-scale forest inventory, Angle count sampling

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Background

The importance of forest structural elements for biodiversity monitoring

Structurally diverse forests are important to maintain species-rich communities (Simpson 1949; Brunialti et al. 2010; Taboada et al. 2010). MacArthur and MacArthur (1961) showed for example, that diversity of birds can be stronger influenced by vertical heterogeneity of forest stands than by composition of tree species. A higher diversity of bark characteristics (shapes and expressions) can lead to higher species diversity by provision of different microhabitats (Recher 1991; Woinarski et al. 1997; Michel et al. 2011). Lassauce et al. (2011) found that diversity of saproxylic organisms in boreal forests is strongly correlated with volume and decay classes of deadwood and Bouget et al. (2013) recommended the diversification of deadwood (types of deadwood, diameter and length, decay classes, etc.) as a management tool for saproxylic beetles in deciduous forests.

Over the last decades, forest management approaches such as 'close-to-nature forestry' or 'retention forestry' have been recommended to improve habitat provision through an increase in quantities of structural elements such as deadwood and large old trees (Gustafsson et al. 2012; Bauhus et al. 2013). For practical implementation, this means extending rotation periods, retaining trees with microhabitat features, increasing deadwood volume and even creating standing dead trees and high stumps artificially (e.g. Ranius et al. 2005; Abrahamsson and Lindbladh 2006; Bauhus et al. 2009). While there is a reasonably good research foundation for these measures, there is only scant documentation about their effectiveness in routine forestry.

Yet in many jurisdictions, forest owners, in particular public forest authorities, are requested to monitor biodiversity and report on their management efforts to maintain or improve biodiversity. There is, as yet, no established or accepted monitoring approach for different types of ecosystems (Pielou 1975; Noss 1990). In addition, biodiversity is extremely difficult and very expensive to monitor (Lindenmayer and Franklin 2002; Gardner 2010). This is caused by a range of factors including species-specific characteristics like large home-ranges or seasonal appearances, even when the focus is 'only' on species richness or even only on endangered species. The approach of using indicator (key) species as a surrogate for biodiversity of forests has not been widely successful because of a lack of consistent correlations between the indicator species and the occurrence or abundance of other species (Van Den Meersschaut and Vandekerkhove 2000; Margules et al. 2002; Duelli and Obrist 2003). For those reasons, comprehensive approaches to monitor forest biodiversity comprising many different taxa have so far not been implemented in regular forest inventories.

In the context of forests, the main influence of management on biodiversity is through changes in forest structure and composition (Lindenmayer et al. 2000; Raison et al. 2001; Kuuluvainen 2009), where structure and composition are commonly deliberately manipulated to achieve certain ecosystem functions and services (Plieninger et al. 2010; Bauhus and Pyttel 2015). Thus it appears logical to monitor changes in these important determinants of biodiversity in the absence of direct data on forest species and their populations and genetic variation (Taboada et al. 2010). The monitoring of biodiversity relevant aspects of forest structure and composition may be integrated into standard forest inventories at little additional cost when compared to separate approaches for biodiversity monitoring (Corona 2016).

Existing indices of forest structural diversity

Several indices estimating structural diversity of forests have been described in the literature. Some focus on specific structural elements such as deadwood (Larsson 2001) or have been developed to assess specific habitat attributes of different species or species groups (e.g. 'Structural Complexity Index' for small mammals (Barnett et al. 1978) or 'Habitat Complexity Score' for assessment of bird habitats (Watson et al. 2001)). Others have been developed for particular geographical regions and focus mainly on one tree species or stand type ('Structural Heterogeneity Index' (Sabatini et al. 2015)). Indices such as the 'Old-Growth Index' (Acker et al. 1998) are related to structural diversity of old-growth stands, assuming the highest level of diversity to be found there. The 'Austrian Forest Biodiversity Index' is based on a relatively subjective set of variables derived from Austrian National Forest Inventory (NFI)-data (Geburek et al. 2010).

A comprehensive, quantitative index of structural diversity was developed by McElhinny et al. (2006) using a reproducible approach underlined by statistical analysis. In their approach, a comprehensive list of candidate variables was reduced to those that capture the variability of the different structural aspects best through Principal Component Analysis. This approach was modified and applied in our analysis to develop an index of structural diversity.

In general terms, structural diversity may be described by many different variables, or these may be combined into a single index value (e.g. McElhinny et al. 2006) as is also the case for other environmental indicators and indices (Niemeijer and de Groot 2008). One advantage of using a set of variables is the more detailed information about individual structural elements and their changes over inventory periods. This more detailed information may be required for the monitoring of certain aspects of structural diversity that are related to ecosystem functioning or habitat quality of particular taxonomic groups. This

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monitoring-oriented focus on individual aspects of structural diversity is particularly relevant for multipurpose forest management and planning (e.g. Corona 2016). The disadvantage of this approach is that it is less suitable for reporting purposes, especially for non-expert audiences. An aggregation of structural variables into a single index value facilitates reporting levels of structural diversity and their development over time in broad terms to a general audience including non-governmental organisations and decision makers. In that sense, such an aggregated index of forest structural diversity is similar to a 'state indicator' of the "pressure, state, response" concept of environmental indicators proposed by the OECD (2003). Here we combined these two approaches. On the one side, we identified individual structural variables that may be related to specific aspects of forest biodiversity and that may respond differently to forest management. On the other side, we combined these individual variables into a single number for an index of structural diversity to facilitate communication of changes in forest structure at a high level of information aggregation, for example to facilitate policy processes and decision making.

Large-scale inventories to support biodiversity monitoring

So far, large-scale inventories have been rarely used to determine the level of structural diversity (Kändler 2006; Polley 2010). However, valuable information about diversity of forests can be obtained as a 'byproduct' of existing inventory data and therefore at low costs (Corona et al. 2003; Corona et al. 2011). One advantage of such an inventory is the wide range of sampled forest attributes. Yet these types of NFI were originally not developed to capture forest structure but the main reason for the development and implementation was to analyse the development of forest growing stock and the available amounts of different types of forest products. However, the information demand gradually increased and hence additional variables with high relevance for the quantification of forest structure were included. For example, in the NFI_{2002}, variables related to biodiversity and carbon storage such as deadwood (dimensions, decay classes, types of deadwood) or regeneration were added. 'Hollow trees', as well as other habitat-tree characteristics (very old trees or crown deadwood) were added in the NFI_{2012}.

The large area covered as well as the number of sample plots used in the inventories allows quantification of structural diversity for different forest types. An overview of strengths and weaknesses of the applied large-scale inventory for the assessment of structural diversity is provided in Table 1.

Based on NFI data, indices of forests structural diversity may be developed. This could permit the quantification of levels of structural diversity in different forest types, as well as its changes over inventory periods (e.g. 10 years). Subsequently these changes may be related to other inventory information such as harvesting intensity. Indices that are based on standard inventory variables may be transferred to other large-scale forest inventories and thus facilitate assessments of structural diversity over large areas within or across jurisdictions (Chirici et al. 2011; Corona et al. 2011).

Table 1 Strengths and weaknesses of large-scale forest inventories such as the German NFI to assess surrogates for biodiversity based on forest structural diversity

Strengths	Weaknesses
Large number of inventory plots for different strata such as jurisdictions or biogeographical regions and broad forest types	Sampling based on angle count method; only a selection of trees are sampled, which leads to a loss of information at the plot-level (probability proportional to size)
Approach applicable to NFIs of other countries	The large-scale design (2 km × 2 km grid) does not capture effectively small areas like forest reserves
Adequate number of sampling plots per forest type available (for main forest types, see Additional file 5)	Biodiversity-relevant variables were originally not included in inventory-samplings; increasing integration of biodiversity-relevant variables only in recent inventories (NFI_{2002} and NFI_{2012})
Low costs for acquisition of data that are attached to or can be derived from classical inventory variables	No precise information about harvesting and other management activities at the plot-level
Dynamic changes over inventory periods can be considered (ongoing process)	Changes in sampled variables and sampling thresholds between NFIs (e.g. threshold-value for the minimal diameter for downed deadwood or the presence of hollows)
Same plots are re-sampled → Analysis on changes of structural elements and development of individual trees (over periods of 10 years)	While broad forest types can be analysed, local (regional) aspects may not be sufficiently well represented
A large number and variety of structural variables can be derived from inventory data	Owing to the sampling method and related small radius of sampling circles, plot measures are not representative of the stand in which they were collected; therefore extrapolation to hectare values is problematic
	Some important variables of forest structure are not quantified directly. They can only be addresses through surrogates (e.g. the occurrence of large living trees as surrogate for habitat-tree characteristics)

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Study aims

The main goal of this study was to explore the potential of large-scale forest inventories to assess forest structural diversity and its development over time using an objective and quantitative way to support biodiversity monitoring (Table 1). Based on the successful development of an index of structural diversity, we present, in an exemplary form, information on the status and development of structural diversity in different forest types of Baden-Württemberg, Germany.

Methods

Data of two National Forest Inventories of Germany for the state of Baden-Württemberg (NFI_{2002} and NFI_{2012}) were used for this study. The inventory design was based on a systematic sampling grid of 2 km × 2 km for the state of Baden-Württemberg, which has a denser grid than most other states with 4 km × 4 km. In the north-east corner of each grid intersection point, up to 4 permanent sampling plots (1–4) were marked invisibly (if located in forest areas) at a distance of 150 m to each other. In Baden-Württemberg, about 12.920 forest plots were sampled at both inventories and used in this analysis (Fig. 1).

At each sampling plot, a combination of sampling methods was used to collect forest stand attributes (Additional file 1). The complete sampling design and further information about the inventory can be found at https://www.bundeswaldinventur.de.

To construct an index of structural diversity of forests ('FSI' = Forest Structure Index), we adopted and improved the method developed by McElhinny et al. (2006). This approach consisted of 4 steps:

1) Defining aspects of structural diversity. Based on a literature review and the information derivable from NFI data, 11 aspects of structural diversity were identified to be represented in a comprehensive index.

2) Establishing a comprehensive list of structural variables derived from National Forest Inventory data (measured in both NFI_{2002} and NFI_{2012}) that are related to the above aspects of structural diversity. Each variable belongs to one aspect of structural diversity (Table 2, see also Sabatini et al. 2015).

3) Reducing the number of variables to a core set of structural attributes by applying the following five selection criteria: a) distribution of data for the different variables should cover as much as possible the potential range of values and be as even as possible; unlike McElhinny et al. (2006), who used kurtosis as a criterion to assess the distribution of data for each variable, here the distribution was assessed visually. Testing the distribution of variables was mandatory because variables with wide spread and/or evenly distributed data are most suitable for this analysis. Variables with highly skewed data distributions or rare observations were not appropriate, because they would likely not be able to discriminate between different levels of structure across the plots; b) the variable functions as a surrogate for other variables of the same aspect c) continuous variables are better suited than categorical variables (aggregation in classes leads to a loss of information, enhanced by subjective class limits); d) all aspects of structural diversity must be included in the index (Table 2); e) the variable shall be a non-compound measure, excluding for example Shannon-like indices which amalgamate richness and abundance.

4) Combining core variables into a simple additive index, scored relatively to observed maxima in NFI_{2002}.

The information provided by core variables had to be transferred and combined into a single index-score to express the overall level of structural diversity in forests and hence to allow the assessment of temporal changes
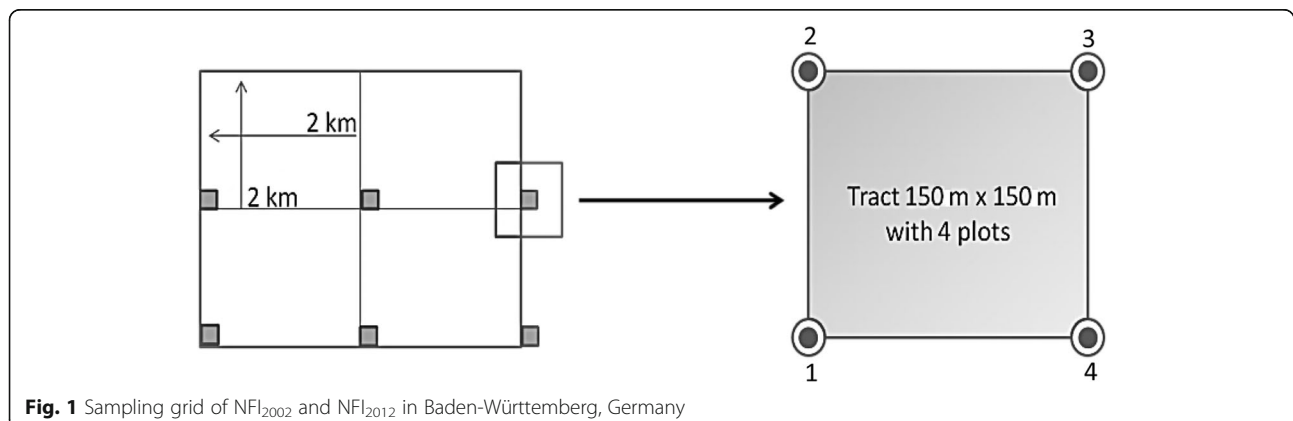

Fig. 1 Sampling grid of NFI_{2002} and NFI_{2012} in Baden-Württemberg, Germany

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Table 2 Aspects of structural diversity and references for publications, in which the ecological rationale for the relevance of the different aspects of structural diversity for forest biodiversity are provided; see also Sabatini et al. (2015). The right column refers to the number of variables that can be derived from the National Forest Inventory in relation to this aspect. The complete list of these 52 variables is provided in the Additional file 3. The aspects 'litter layer, 'microhabitats, 'tree spacing' and 'epiphytes and organisms on deadwood' could not be considered in this analysis because they were not sampled by the NFI. Some 'microhabitats' were only added to sampling during NFI_{2012}, so they could not be taken into account for this work

Aspect of structural diversity	Acronym	Authors	Number of variables
Uneven-agedness	UA	Keeton (2006); Hatanaka et al. (2011)	7
Growing stock	GS	Houghton (2005); Norris et al. (2012); Hoover et al. (2012)	7
Compositional heterogeneity	CH	Barbier et al. (2008); Barbier et al. (2009); Burrascano et al. (2011); Hatanaka et al. (2011)	5
Vertical heterogeneity	VH	Staudhammer and LeMay (2001); Hao et al. (2007); Burrascano et al. (2013)	3
Large living trees	LLT	Nilsson et al. (2002); Brunialti et al. (2010); Persiani et al. (2010)	3
Deadwood standing	DW st	Brunialti et al. (2010); Hatanaka et al. (2011)	5
Deadwood downed	DW d	Castagneri et al. (2010); Lassauce et al. (2011); Zotti et al. (2013)	8
Deadwood decay classes	DW DC	Burrascano et al. (2008); Lassauce et al. (2011); Lombardi et al. (2011)	2
Bark diversity	BD	Bhadra et al. (2008); MacFarlane and Luo (2009); Michel et al. (2011)	1
Diversity of flowering and fruiting trees	FD	Singh and Kushwaha (2005)	1
Regeneration	REG	Hello (1985); Boyden et al. (2005); Müller et al. (2008)	10
Litter layer	LL	Barnett et al. (1978); Newsome and Catling (1979); Gilmore (1985) (for habitats of birds); Watson et al. (2001)	0
Microhabitats	MH	Dueser and Shugart (1978); Winter and Möller (2008); Michel et al. (2011); Bütler et al. (2013)	0
Tree spacing	TS	Spies and Franklin (1991); Pretzsch (1997); Acker et al. (1998); Bachofen and Zingg (2001)	0
Epiphytes and organisms on deadwood (lichen, mosses, fungi)	DW G	Humphrey et al. (2002); Blaser et al. (2013); Dittrich et al. (2014); Hoppe et al. (2016)	0

over a period of time (development) or comparisons among different forest types. If NFI-values were assumed to include extreme values (caused by the sampling method) or implausible measurements, ranges of possible minimum and maximum values for the respective variables were used, based on NFI_{2002} data or literature. All variables showing higher values than the threshold-value were reduced to the maximum score of 1. Thereby, the loss of information was very small, because only few sampling plots were affected. An overview of the applied threshold-values is provided in Additional file 2.

The equation to calculate variables-scores:

$$\text{Variable-Score} = \frac{(X-X_{\min})}{(X_{\max}-X_{\min})}$$

X was the measured variable-value at plot-level and $X_{\min}$ respectively $X_{\max}$ were the minimum and maximum values observed in NFI_{2002} data for each variable.

The sum of scores of the core variables divided by the number of variables included in this index yields a value between 0 and 1, where 0 indicates 'lowest level of structural diversity' and 1 'highest level of structural diversity'. Multiplying variables to calculate an index value, as was done for example in the index developed by Geburek et

al. (2010), was regarded as unsuitable in our case because it assumes that structural diversity is depending on the presence of all structural elements captured by the variables (Burgman et al. 2001). If a single variable had a value of zero, the complete index would be zero. Rejecting those zero-values from index calculations would solve this problem but prevent a further comparison of index-scores, if these are based on different numbers of applied variables. Therefore, we decided to follow an additive way to construct this index as described above.

In theory, the individual variables of the index could receive a different weight according to their relevance for overall richness of habitats and associated species. Here, the index was calculated with unweighted variables because we had no prior information whether individual variables of forest structure were more or less important than others, e.g. for species richness within certain taxonomic groups. To test whether the assignment of different weightings to individual variables has a significant influence on the distribution of index values across inventory plots, a sensitivity analysis was performed, using for each variable random weightings between 0 and 2, which were repeated 100,000 times.

Finally, sampling plots were aggregated to forest types by different stand attributes like dominant tree functional type

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(broadleaf or coniferous species), stand development phase, dominant tree species (beech, oak, spruce or pine), forest-ownership or number of canopy-layers. For these forest types, mean FSI-scores were calculated for both inventories and compared to each other, as well as among different types of forests. Thus, information was aggregated from the plot- to the forest-type level and a statement about the structural diversity as well as changes in structural diversity in forests representing large areas was possible.

Microsoft Access 2010 was used to calculate variables, derived from NFI_{2002} and NFI_{2012}, describing structural diversity of forests. For further analysis, the statistic software R (Version 3.1.2) and its package beanplot was used for beanplots.

The study area

Almost 39% or 1.371 million ha of the area of Baden-Württemberg (SW-Germany) is covered by forests. To develop an index for structural diversity, 13.106 inventory plots of NFI_{2002} were used. By excluding plots that a) were without merchantable timber at the time of NFI_{2002}, b) experienced a change in land use (e.g. plot covered by forest at NFI_{2002} but converted into urban or agricultural land at NFI_{2012}), and c) that were not accessible at both inventory dates, 12.918 plots or 98.6% of all sampled forest plots remained for this analysis.

Results and discussion

Aspects of structural diversity

In a first step, we identified through a broad literature review 11 aspects of structural diversity that should be included in a comprehensive index of forest structural diversity (FSI) (Table 2).

Core variables of structural attributes

After application of the above mentioned selection criteria, the following variables were identified as the most suitable to represent the corresponding aspect of structural diversity (Table 3). If reduction of variables resulted in more than one variable that was suitable to represent the aspect of structural diversity, a Principal Component Analysis (PCA) could be performed. To perform a PCA, distribution of variable-data must be approximately normal. In our study, this final step was not necessary because only one variable per aspect was considered as suitable for a further application in the index.

Even though some of these applied variables were closely correlated, we did not remove any of them for subsequent development of the index because they represented clearly different aspects of structural diversity. For example 'volume of trees ≥ 40 cm DBH' (describing the aspect of large living trees) and 'species richness of trees with DBH ≥ 7 cm' (describing compositional heterogeneity) were highly

correlated. The correlations among different variables associated with a particular aspect of structural heterogeneity as well as correlations with other variables for the whole forest of Baden-Württemberg are listed in Additional file 4.

Scaling of variables to derive index values

Extreme values of variables (outliers), leading to scores higher than 1 were reduced to a score of 1 to maintain the data distribution unchanged and use the whole spectrum of data-variety for the analysis. The low values for downed deadwood, standing deadwood and number of decay classes (Fig. 3) can be explained by the distribution of data for these variables, respectively the large number of sampling plots without deadwood or different decay classes. In addition, the small sampling plot for deadwood applied in the NFI (radius of 5 m), exacerbates this problem, because deadwood occurs often in a clumped distribution and is not equally distributed within forest stands, so the actual amounts of deadwood might not be recorded accurately.

Scaling up from plot to forest type-level

To aggregate information on structural diversity (FSI-score) from a plot- to a forest type-level, single plots were assigned to strata, here categories of forest types (related to NFI-classifications, e.g. ownership or number of canopy layers). It is important to work with larger forest types that are represented by an adequate number of sampling plots (Lappi and Bailey 1987; Sterba 2008) to obtain reliable results for the FSI (or information about the level of structural diversity). A table containing the different forest types and their corresponding number of inventory plots is provided in the Additional file 5.

Some previously developed indices of structural diversity used individual weightings for variables (Parkes et al. 2003; Geburek et al. 2010). This can only be justified, if there is a clear rationale for valuing some variables more or less than others, i.e. if it was known that a certain aspect of structural diversity had a proportionally higher or lower influence on species richness or diversity. In our study, there were no obvious variables that should receive more or less weight than others in order to represent the overall forests biodiversity. Weighting of variables could be performed when the FSI is linked to individual taxonomic groups, because some elements of structural diversity that are crucial for one taxonomic group could lead to an absence of other taxonomic groups (Økland 1996). In addition, we tested the performance of the FSI using random weightings applied to the selected variables. The results of the sensitivity analysis, which used random weightings between 0 and 2 for each variable, show that the performance of the FSI was insensitive to weightings of variables ($R^2 = 0.97$, CV = 0.01), which were therefore not applied in routine calculations (Fig. 2).

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Table 3 Core variables used in the Forest Structure Index and their recognized importance for biodiversity of forests

Variable	Aspect	Author	Explanation
DBHq (quadratic mean diameter of trees ≥ 7 cm at breast height)	GS growing stock	Spies and Franklin (1991); Uuttera et al. (1997); Acker et al. (1998); Ferreira and Prance (1999); Ziegler (2000); Tanabe et al. (2001)	Common variable to describe stand structure; higher DBHq implies older and taller stands with high biomass, typical forest microclimate, and more presence of habitat attributes of mature forests
DBH sd (standard deviation of diameter at breast height of trees ≥ 7 cm)	UA uneven-agedness	Acker et al. (1998); Neumann and Starlinger (2001); McElhinny et al. (2006)	High standard deviation of DBH implies a diverse stand structure with patches of different densities and tree dimensions; many niches are provided for different taxa; relates to canopy layering
Height sd (standard deviation of mean height of trees ≥ 7 cm DBH)	VH vertical-heterogeneity	MacArthur and MacArthur (1961); Sabatini et al. (2015); McElhinny et al. (2006)	Standard deviation of stand height describes the vertical heterogeneity of stands directly; relates to canopy layering
Bark (index to describe diversity of bark types)	BD bark diversity	Gilmore (1985); Dickman (1991); Pearce (1996); Eyre and Smith (1997); McElhinny et al. (2006); Bhadra et al. (2008)	Diversity of bark types (smooth, fissured, peeling, scaly, cracked, etc.) in forest stands implies a variety of habitats for many species to be found there (insects, fungi, yeasts, spiders, epiphytes). Tree diameter and bark-development phases are considered
Flower-diversity (diversity of fruiting and flowering trees)	FD Flower diversity	Kavanagh (1987); Andrews et al. (1994); Smith et al. (1994); Soderquist and MacNally (2000); Herrera et al. (2001); Singh and Kushwaha (2005)	Food source for nectarivorous and frugivorous species (mainly insects, bats and birds)
VolTrees40 (volume per hectare of trees with a DBH ≥ 40 cm)	LLT Large living trees	Spies and Franklin (1991); Tyrrell and Crow (1994); Koop et al. (1995); Acker et al. (1998); Van Den Meersschaut and Vandekerkhove (2000); Ziegler (2000); Larrieu and Cabanettes (2012)	Large trees have a special function as habitat or source of food for many taxa; they have a greater probability to provide microhabitat structures such as hollows, crown dead wood, etc.
N DC (number of decay classes)	DW DC deadwood decay classes	Lassauce et al. (2011); Blaser et al. (2013); Lachat et al. (2013); Dittrich et al. (2014)	Important for many taxonomic groups; many decay classes indicate a continuous recruitment of deadwood; indicator for natural forest conditions
Deadwood st mean DBH (mean DBH of standing deadwood)	DW s standing deadwood	Drapeau et al. (2009); Rondeux and Sanchez (2010); Lassauce et al. (2011); Verkerk et al. (2011); Lachat et al. (2013)	Important structural element for many taxa of xylobiotic species (habitat and food source); more suitable than volume/ha because of strong extrapolation effects when sampled on small plots; stumps are excluded from the calculation
Deadwood d average mean diameter (average mean diameter of downed deadwood)	DW d downed deadwood	Drapeau et al. (2009); Rondeux and Sanchez (2010); Brin et al. (2011); Lassauce et al. (2011); Verkerk et al. (2011); Lachat et al. (2013); Kappes and Topp (2004)	Important structural element for many taxa of xylobiotic species (habitat, food source, regeneration niche); surrogate for deadwood types and N/ha of dead wood pieces, justified by level of correlation and better distribution
SR (richness of tree species with DBH ≥ 7 cm)	CH compositional heterogeneity	Lähde et al. (1994); Maltamo (1997); Uuttera et al. (1997); Tilman (1999); Van Den Meersschaut and Vandekerkhove (2000); Uuttera et al. (2000); Sullivan et al. (2001); Pretzsch (2003); Pretzsch (2005)	Species richness of trees with DBH ≥ 7 cm is important for diversity of dependent species, in particular host-specific herbivores, detritivores, symbionts and pathogens
SR Reg (species richness of regeneration (DBH < 7 cm))	REG regeneration	Mosimann et al. (1987); Du Bus de Warnaffe and Deconchat (2008); Müller et al. (2008)	Important for many taxa like insects, mammals and birds; high SR Reg leads to more diverse future stand conditions

The small number of plots with very high and very low FSI-values indicate that the developed index is potentially sensitive to the existing level of diversity of structural elements in forests of SW-Germany, which include a broad range of structural diversities (from intensively managed forests to strict reserves). In contrast, one-sided
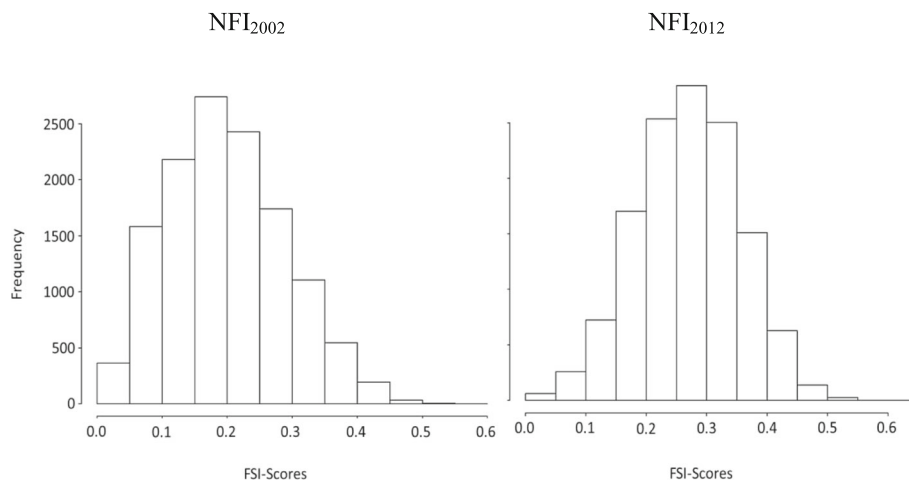
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Fig. 2 Frequency distribution of scores of the forest structural diversity index (FSI) for the second (NFI_{2002}) (left, mean = 0.18) and third (NFI_{2012}) national forest inventory (right, mean = 0.21). Scores were calculated for 12.918 inventory plots within Baden-Württemberg. Differences between NFI_{2002} and NFI_{2012} are significant for an applied confidence level of 0.95

distributions for this diverse data-set would indicate that the FSI produces similar values for many sampling plots and was not sensitive enough to describe the diverse spectrum of structural diversity in forests. The histograms show a close to normal distribution and a broad range of FSI-scores, which represent different structural 'qualities' (from structurally poor to comparatively high levels of structural diversity (Fig. 2). A maximum FSI-score of 1 is theoretically possible but very unrealistic in reality, because all applied variables must be present at their maximum expression. In addition, high scores for some variables might exclude high scores for other variables (e.g. high species richness (mixture of shade-tolerant and shade-intolerant species) might exclude high species richness in the regeneration layer, caused by missing shade-intolerant species). The highest FSI-score calculated on the basis of NFI_{2002}-data was 0.52, which represents the highest level of structural diversity in forest-plots of Baden-Württemberg. The lowest FSI-scores were found in young stand development phases and the highest FSI-scores are found in old broadleaf-dominated stands which are conform to general assumptions on the level of structural diversity in different stand development phases of managed forests (e.g. Bazzaz 1975; Spies and Franklin 1991; Scherzinger 1996). Distributions of the FSI scores for other categories of forests (e.g. broadleaf/coniferous--dominated, beech-, oak-, pine-, spruce-dominated, three stand development phases, ownerships or number of canopy layers) are provided in the Additional file 6.

A comparison of FSI scores for the NFI_{2002} and NFI_{2012} showed that the index is sensitive to temporal changes in forest structure and composition and that the scores increased for all individual variables contributing to the index, except standing deadwood decreased slightly (Fig. 3).

The changes in the FSI for NFI data from Baden-Württemberg corresponded to results of the analysis of NFI-data for single variables (Fig. 3). These showed a small general increase in all structural elements apart from standing deadwood for the period between NFI_{2002} and NFI_{2012}. In general, young stands had a lower structural diversity than middle-aged stands (Stand development phase 1 - FSI NFI_{2012} = 0.14; Stand development phase 2 - FSI NFI_{2012} = 0.21). Not surprisingly, the FSI score for NFI_{2012} indicated that one-layered stands (0.14) were less diverse than two- (0.21) or multi-layered stands (0.24). The highest level of structural diversity was observed in old stands (0.28), followed by multi-layered stands (0.24). For all analysed forest types, except for young and young-coniferous dominated stands, an increase of structural diversity took place for the period $NFI_{2002} - NFI_{2012}$. The highest
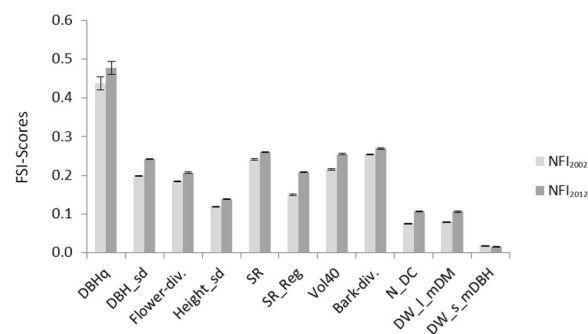

Fig. 3 Change in scores of individual variables of the structural diversity index of Baden-Württemberg from the second to the third national forest inventory (NFI_{2002}, NFI_{2012}). Error bars represent standard error of means. Differences between NFI_{2002} and NFI_{2012} are significant for an applied confidence level of 0.95 for all applied variables

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increase in structural diversity was found for stand development phase 2 and pine-dominated stands (0.04) (Additional file 7 and Fig. 4).

Assessment of absolute FSI-scores

Expressing the level of structural diversity in a single number may yield questionable results, especially if several, quite different aspects of structure are combined in one index (Whitman and Hagan 2007). For example, a deadwood-rich but species-poor stand can receive the same index-score as a stand without deadwood but a more diverse diameter distribution or species richness. However, this 'hidden information' of the FSI score can be made visible by depicting the changes in single FSI-variables (Fig. 3). This variation in structural attributes behind similar FSI-values is an inevitable

Fig. 4 Beanplots of FSI distributions in different forest types – left half of beans represents NFI_{2002} and the right half of beans represents NFI_{2012}; direct comparison of FSI for NFI_{2002} and NFI_{2012} per stand type as well as a comparison between different forest types; black lines indicate mean values of forest types; except of young conifer-dominated stands, all types of forests show an increase between the FSI-score for NFI_{2002} and NFI_{2012}. All types of forests show significant differences between the two NFIs (t-test, confidence level of 0.95)

consequence of aggregation, but it is not per se unrealistic, because biodiversity is depending on many different structural aspects. If we assume that the different types and combinations of structural variables represent habitats for different taxa, then we can also expect quite different forest communities for similar FSI-scores.

In general, the FSI-score provides a standardised and transparent assessment of the overall diversity of large forest types. The highest FSI-score was found in old stands. In this type of forest, all variables included in the FSI, except for 'quadratic mean diameter at breast height', 'standard deviation of diameter at breast height', 'occurrence of large living trees' and 'Bark-diversity' assume approximately average values for forests in Baden-Württemberg. However, old stands scored significantly higher than the average for the above mentioned four variables, providing the underlying causes for the high overall FSI values in this forest type.

The adaption of NFIs to support biodiversity monitoring has developed over the last decades and is now more widely used. Additional variables for further information on deadwood or habitat trees, which are important to gain a comprehensive view on biodiversity in forests, have been included in the list of inventoried variables (Corona et al. 2011). Adaptations of threshold-values (for example changes in minimum sampled diameter of deadwood or threshold-diameter for large trees, which is used as a surrogate for habitat-trees) are easily possible in the FSI. This makes the FSI a flexible tool which can be adapted easily to inventory data from other types of forest ecosystems or other regions. In addition, variables that have not been sampled in past NFIs (of Germany) but provide information about further aspects of structural diversity can be included in the index, when data become available (e.g. information about the litter layer or microhabitats, Table 2). This important information could be obtained in upcoming NFIs to further support biodiversity monitoring in a more comprehensive way and thereby improve the information value of the FSI.

A comparison between the performance of FSI and other indices describing structural diversity of forests based on inventory data (e.g. Newsome and Catling 1979; Denslow and Guzman 2000; Parkes et al. 2003) was not possible in this study, because some variables required by these indices were not sampled in the NFI (e.g. 'canopy cover' or information about 'litter'). These other indices of stand structural diversity use variables that are not measured in most conventional forest inventories (e.g. litter decomposition, litter dry weight and thickness, number of hollow trees, amount of crown deadwood, swelling of trunk bases, species richness of small plants (shrubs or ground vegetation)), which would need to be collected in separate inventories that can be typically carried out only in specific forest types or regions. In contrast, the FSI presented here can be readily adapted to
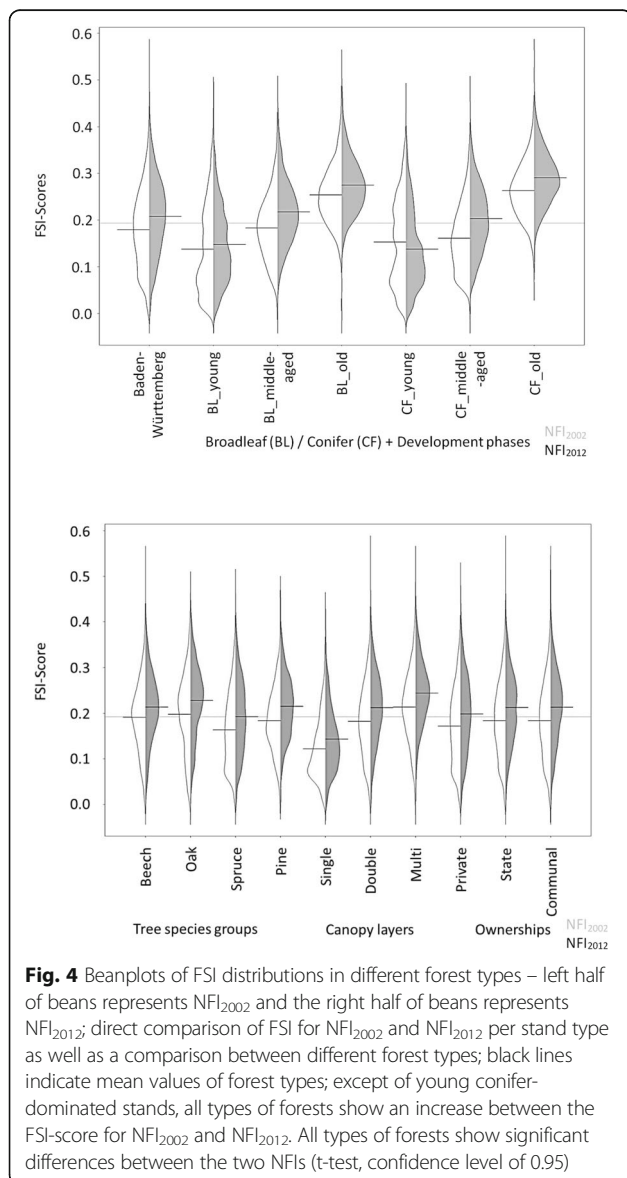
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most other European large-scale National Forest Inventories, easily (e.g. Austria, Switzerland, Italy or Spain) because it uses variables that are measured in most European NFIs (Tomppo et al. 2010). In addition, it is possible to reduce the number of applied variables in the FSI (if some information is missing) because the aggregated score is calculated in a simple additive way and results are expressed in a relative instead of absolute numbers. However, the comparability of the FSI and its constituent variables with other inventories depends also on the sampling methods employed in the inventories.

Angle count sampling and transfer of our approach to different inventory methods

When using inventory data for a structural diversity index like the NFI of Germany, which is partly based on sampling via the angle count method, it is important to aggregate index-scores at a stratum level (e.g. forest-type) (Bitterlich 1952; Lappi and Bailey 1987; Sterba 2008). Observations or changes of structural diversity for single inventory plots should not be considered because dramatic changes recorded at individual plots may be caused by the sampling design rather than by actual changes in forest structure. Observed differences in variables between two inventories at a single plot may be attributable to the method of PPS (probability proportional to size) sampling, that angle count sampling is based on. Whether a tree is included in the sample or not depends on its diameter at breast height and its distance to the centre of the inventory plot. The associated low number of trees leads, in most cases, to a loss of information at the plot-level (justified by the need to optimize the sampling effort). For larger study areas and inventory strata, the accuracy of observations from angle count sampling is as high as that from inventories employing fixed radius circles (Lappi and Bailey 1987; Sterba 2008). On this basis, accurate calculations of harvested timber volume or biomass, growing stock, availability of certain products, etc. have been successfully performed in the past (Polley 2005; Kändler and Cullmann 2014; Polley and Kroiher 2017).

The low scores of deadwood-related variables of the FSI for Baden-Württemberg (deadwood standing, deadwood downed and deadwood decay classes, see Fig. 3) may be explained through the sampling of this attribute, which has a rare occurrence, on relatively small plots of 5 m radius (Meyer 1999; Ritter and Saborowski 2012). However, large amounts of deadwood, when scaled up to a hectare, can be recorded at individual plots (for example the highest value of downed deadwood (1713 $m^3 \cdot ha^{-1}$) was the result of only two large trees sampled within the 5 m plot). Therefore, average mean diameter was chosen for downed deadwood, mean DBH for standing deadwood and number of decay classes for the aspect of decay classes. These variables did not have

to be scaled up to hectare values and therefore delivered more accurate values than volume·ha^{-1} or number·ha^{-1}. This problem (rare occurrence) may be exacerbated by the high threshold value for deadwood in NFI$_{2002}$ (20 cm diameter at the large end). In addition, in most forest areas deadwood occurs in a clumped distribution. Hence single 5-m-radius plots are not sufficiently large to quantify dead wood representatively for entire stands (Ritter and Saborowski 2012). While this variability can normally be dealt with through aggregation of inventory plots to the level of sufficiently large strata to derive representative mean values (e.g. Lombardi et al. 2015), it leads to very high deviation of deadwood volumes determined at the plot level from the mean of the stratum, if dead wood volumes determined in one such plot are scaled directly to the hectare level. Similarly, the occurrence of other rare elements (like hollow trees, very large trees or rare tree species) is probably underestimated when compared to other inventory methods using larger fixed sampling plots.

A transfer of the approach presented here to inventories using fixed radius circles, as they are used in other types of inventories appears to be possible, but further research has to be done on this topic, e.g. if an adaption of threshold-values for the applied variables is needed.

Conclusion

The main goal of this study was to assess the feasibility of an index of forest structural diversity based on large-scale forest inventory data to support biodiversity monitoring. Our results show that the index developed here provides an objective assessment of the status of structural diversity for different forest types and that it is sensitive to temporal changes. More detailed information about the level of structural diversity (single variables or their development over time) in different forest types can be derived. Our index of forest structural diversity can be readily adapted to other, similar types of national or regional forest inventories. The index of forest structural diversity developed here serves one of the major directions in recent developments of forest inventories towards multipurpose resources surveys, namely the incorporation of additional variables that are not directly related to traditional inventory purposes such as assessment of timber, wood volume increments or carbon stocks and sequestration (Corona 2016). However, the index has been derived from variables that are already measured in current forest inventories and hence it can be easily calculated without much extra cost. It can provide an evidence basis to support societal debates and decision making processes about biodiversity conservation in forests at large-scale. The expression of structural

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diversity in a single number allows a direct comparison among different types of forest stands and it facilitates the depiction of changes within single types of forests over time. These are considered important aspects of the reporting on sustainability of forests in a general way. A more specific assessment of individual structural elements used in the index can be easily derived, if the focus is on monitoring particular aspects of structural diversity (e.g. the presence of large living trees or the number of tree species), for example to guide forest management and planning.

Additional files

Additional file 1: Sampling design of NFI in Germany; Elements and methods of data sampling applied in NFI2002 and NFI2012 of Germany; *: sampling of deadwood pieces with a diameter of 20 cm in NFI2002 was reduced to 10 cm in NFI2012; further information can be found at https://www.bundeswaldinventur.de. (PDF 137 kb)

Additional file 2: Transformation of variables into scores (between 0 and 1) based on variable-values of NFI2002 and literature; '-': threshold values from literature not available or (needed). (PDF 61 kb)

Additional file 3: Comprehensive list of variables derived from NFI2002 and NFI2012; $N = 52$. (PDF 230 kb)

Additional file 4: Variables, aspects of structural diversity and correlations with other calculated variables of the comprehensive list of structural attributes, derived from NFI2002 data for whole Baden-Württemberg (forest type 'BW'). (PDF 230 kb)

Additional file 5: Analysed forest types and corresponding number of sampled plots, distributed over Baden-Württemberg, Germany: (PDF 145 kb)

Additional file 6: FSI-distribution for a selection of different forest types of Baden-Württemberg for NFI2002 and NFI2012 (y-axis: frequency of sampling plots; x-axis: FSI-score). (PDF 214 kb)

Additional file 7: Overview of analysed forest types and FSI-scores for NFI2002 and NFI2012. (PDF 143 kb)

Abbreviations
BW: State of Baden-WürttembergSW-Germany; Cor: Level of correlation (pearson); CV: Coefficient of variation; DBH: Diameter at breast height (130 cm); FSI: Forest structure index; $m^3 \cdot ha^{-1}$: Cubic metre per hectare; N: Number; NFI: National forest inventory; PCA: Principal component analysis; R^2: Coefficient of determination; X_{min}/X_{max}: Minimum/Maximum of variable-values applied to calculate the FSI

Availability of data and materials
The datasets that form the basis of all analyses in our study are free available at https://bwi.info/Download/de/BWI-Basisdaten/ACCESS2003/.
The datasets supporting the conclusions of this article are included in the additional files (Additional files 1, 2, 3, 4, 5, 6 and 7).

Authors' contributions
FS planned and conducted the study including data management and analysis and wrote the majority of the manuscript; CFD provided support in statistical methods and analysis and contributed to the manuscript; JB conceived and guided the study and co-wrote the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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