Ecological Indicators 181 (2025) 114434

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Evaluation of the performance of forest structural indices under different National forest inventory plot designs

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ARTICLE INFO

Keywords:
Biodiversity
Common reporting
Harmonization
Monitoring

ABSTRACT

Forest structure encompasses a variety of attributes related to the arrangement of the forest components (e.g., trees, shrubs, deadwood) in both horizontal and vertical dimensions. Several indices quantify the structure of the tree layer; however, the performance of these indices under a nested plot design, which is prevalent in National Forest Inventories, is poorly understood. Furthermore, the differences in plot design complicate the comparison among indices. The primary objective of this study is to evaluate the performance of distance-independent indices in the National Forest Inventory plots of two European countries where the nested plot designs differ the most: Spain and Finland. To achieve this, we simulated 39,600 one-hectare plots with different stand characteristics, and embedded the nested plots from both countries as well as the fixed-area plots corresponding to the areas of the largest plot without the tree-size restrictions applicable to the inner plots. We calculated four species composition indices, six indices that describe forest structural complexity, and two indices assessing forest complexity with composition. In our study, tree species richness, Shannon's and Simpson's Diversity Index suitably described the tree composition component. However, the performance of tree richness as an indicator can be heavily affected by the settings applied to simulate the plots. The sum of square roots of diameter differences and Shannon's Diversity Index applied to the diameter classes along with the second L-moment were found to be the most effective indices for consistently quantifying forest structural complexity across different sample plot designs. The agreement among indices calculated for the different plot designs was positively related to tree density, i.e., nested designs and fixed-area provided a better representation of forest structure in stands with high tree densities.

1. Introduction

Forest structure is a multifaceted term that has been described using various forest characteristics, including stand variables such as basal area, tree density, mean plot diameter or age (del Río et al., 2016; Schall et al., 2018). Other authors (Hui et al., 2019; Lin et al., 2020; Pommerening, 2002) have defined the following three major characteristics related to the tree stratum: spatial distribution of trees, species composition and tree size diversity, which are considered in this paper. While the computation of stand variables is typically straightforward, there are several different alternatives on how to describe the forest structure. A common approach is to summarize the information into indices, which then act as surrogates of forest structure (del Río et al., 2003; Hui et al., 2019; Pommerening, 2002). While laser scanning may also directly be used for assessing forest structure (e.g., Seidel, 2018), we focus here only on indices derived from tree-level data.

Apart from the characteristics of the forest structure evaluated, the structure indices for the tree stratum can be classified into two main groups: distance-dependent and distance-independent indices (Hui et al., 2019; Pommerening, 2002). The first group of indices, distance-dependent indices, takes into account the position of the tree to define, among other features, the spatial pattern of the stems, i.e., random, regular or clustered patterns, the degree of species intermingling, i.e., the spatial arrangement of individuals of different species, or the spatial tree-size differentiation, i.e., the evaluation of the spatial arrangement of different size trees (Moreno-Fernández et al., 2021;

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https://doi.org/10.1016/j.ecolind.2025.114434
Received 23 June 2025; Received in revised form 20 October 2025; Accepted 11 November 2025
Available online 17 November 2025
1470-160X/

Pommerening and Stoyan, 2006). The second group, distance-independent indices, does not require tree position within the plot and is easier to compute (Pommerening, 2002). These indices rely on the tree size diversity, i.e., the assessment of forest complexity, and the species diversity, which includes both the number of species of a given life form (or several life forms as the case may be) as well as the abundance of each species (Barbeito et al., 2009; Shannon, 1948; Simpson, 1949).

Forest structure has been related to the provision of different functions, services and forest features such as forest naturalness (Myllymäki et al., 2024), forest management alternatives (Stiers et al., 2018) or the diversity of plants (Ehbrecht et al., 2021) and other life forms (Hanle et al., 2020). Furthermore, forest complexity has been related to forest productivity (Fischer et al., 2019; Schall et al., 2018) although whether this relationship is positive or negative depends on the stand development stage (Zeller and Pretzsch, 2019). Silvicultural practises can modify forest structure by promoting homogeneous or heterogeneous stands in terms of tree size and composition (Montes et al., 2005, 2004; Zavala et al., 2024). In this regard, new management guidelines aim to produce stands composed of mixtures, e.g., continuous cover systems and other close-to-nature alternatives, to enhance resilience, biodiversity and complexity (Kuuluvainen et al., 2021; Mason et al., 2022).

An adequate description of forest structure requires sampling strategies capable of covering wide spatial areas with a high temporal resolution as well as unbiased estimation of structural features. In this regard, large-scale surveys, such as National Forest Inventories (NFIs), can provide unbiased estimations for a wide range of forest attributes across large areas (Moreno-Fernández et al., 2020), and this may embrace forest structural indices (Myllymäki et al., 2024). The plot design in the NFIs, however, varies among countries, with the fixed area sampling and the nested design being the most common (Vidal et al., 2016) (see Table 1). In fixed-area sampling, information is collected on all trees within the plot that exceed a minimum size threshold (typically evaluated by diameter at breast height, dbh). The nested design, meanwhile, consists of concentric nested subplots (concentric subplots, hereafter) where the minimum dbh measured increases as the radius of the concentric subplot increases, thus reducing the sampling effort required for smaller trees (Fischer et al., 2016; Gschwantner et al., 2016).

In this regard, Lin et al. (2020) evaluated the performance of diversity and spatially-explicit complexity indices in nested designs, concluding that the traditional mathematical formulation of these indices was not suitable for an accurate description of forest structure in these nested designs. Several methodological approaches have been proposed to address this issue. For instance, Moreno-Fernández et al. (2021) proposed and evaluated an approach to estimate distance-dependent indices for the nested design. In the case of distance-independent indices, correction for nested designs usually considers the tree-sampling probability within each concentric subplot (Myllymäki et al., 2024).

However, information on the evaluation and performance of distance-independent indices in nested designs is scarce (see Motz et al. (2010) regards the capacity of structural indices in the case of angle count sampling). This information would be highly valuable given that international reporting requirements, such as State of Europe's Forests (SoEF, 2020) or other information requirements (such as the Habitat Directive, the Nature Restoration Regulation European Forests or the proposal for a Regulation on a monitoring framework for resilient European forests) either necessitate or could include accurate structural indicators that can be applied to a broad spectrum of monitoring networks. Thus, the objective of this research is to evaluate the behavioural stability of complexity and composition indicators in nested and fixed-area designs to provide insights into the performance of each approach, with a particular focus on identifying those that remain robust under contrasting NFI designs so that they could be reliably applied across different forest conditions and inventory approaches. A simulation approach was employed to create 1-hectare square plots with

Table 1
Plot designs of some National Forest Inventories in European countries and bioregions by country (Tomppo et al., 2010) (see Fridman et al. (2014) for Sweden, Jevšenak and Skudnik (2021) for Slovenia and Korhonen et al. (2024) for Finland).

Country	Plot radii (dbh size thresholds)	Bioregion
Austria	Nested plots together with angle count. Cluster (4 circular plots of 300 m^2 in the vertices of a square of 200 m), 5 cm ≤ dbh ≤ 10.4 cm: Fixed area plot r = 2.6 m, 10.5 cm ≤ dbh ≤ 39.0 cm: trees selected with relascope (basal area factor 4), dbh ≥ 39.1 cm: Fixed area plot radius = 9.77 *m*	Alpine, Continental
Belgium (Wallonia)	4.5 m (tree circumference ≥ 20.0 cm), 9.0 m (tree circumference ≥ 70.0 cm) and 18.0 m (tree circumference ≥ 120.0 cm)	Continental
Croatia	3.5 m (dbh ≥ 5.0 cm), 7.0 m (dbh ≥ 10.0 cm), 13.0 m (dbh ≥ 30.0 cm), 20.0 m (dbh ≥ 50.0 cm)	Alpine, Continental, Mediterranean
Czech Republic	3.0 m (dbh ≥ 7.0 cm) and 12.62 m (dbh ≥ 12.0 cm)	Continental, Pannonian
Denmark	3.5 m (dbh > 0.0 cm), 10 m (dbh ≥ 10.0 cm) and 15 m (dbh ≥ 40.0 cm)	Atlantic, Continental
Estonia (permanent plot case)	5.0 m (dbh < 8.0 cm) and 10.0 m (dbh ≥ 8.0 cm)	Boreal
Finland	4.0 m (dbh ≥ 4.5 cm) and 9.0 m (dbh ≥ 9.5 cm) plus a Bitterlich relascope sample plot with a basal area factor of 1.5 for trees with a dbh below 4.5 cm	Boreal
France	6.0 m (dbh ≥ 7.5 cm), 9.0 m (dbh ≥ 22.5 cm) and 15.0 m (dbh ≥ 37.5 cm)	Alpine, Atlantic, Continental, Mediterranean
Germany	Relascopic sampling. permanent, cluster (25 m, 10 m, 5 m, 2 m, 1 m radii circular plots in the vertices of a 150 m square), relascopic (Angle Count Sampling with basal area factor 4, dbh minimum = 7 cm for living volume, biomass, stem damage and stem characteristics,	Atlantic, Alpine, Continental
Iceland (natural birch forests case)	3.99 m (h ≥ 2.0 cm) and 7.98 m (d0.5 ≥ 10.0 cm)	Arctic
Ireland	3.0 m (dbh ≥ 7.0 cm), 7.0 m (dbh ≥ 12.0 cm) and 12.62 m (dbh ≥ 20 cm)	Atlantic
Italy	3.99 m (dbh ≥ 4.5 cm) and 12.99 m (dbh ≥ 10.0 cm)	Alpine, Continental, Mediterranean
Latvia	5.64 m (dbh ≥ 6.1 cm) and 12.62 m (dbh ≥ 14.1 cm)	Boreal
Lithuania	5.64 m (dbh ≥ 6.0 cm) and 12.62 m (dbh ≥ 14.0 cm)	Boreal
Luxemburg	4.5 m (dbh ≥ 7.0 cm), 9.0 m (dbh ≥ 20.0 cm) and 18.0 m (dbh ≥ 40.0 cm)	Continental
Norway (temporary plots case)	5.64 m (dbh ≥ 5.0 cm) and 8.92 m (dbh ≥ 20.0 cm)	Alpine, Atlantic, Artic, Boreal
Poland	Larger: 7.98 m (dbh ≥ 7.0 cm) or 11.28 m (dbh ≥ 7.0 cm) or 12.62 m (dbh ≥ 7.0 cm) depending on stand features and Smaller: 2.52 m (dbh < 7.0 cm)	Atlantic, Alpine, Continental
Portugal	8.92 m (dbh ≥ 7.5 cm), 12.62 m (dbh ≥ 17.5 cm) and 17.84 m (dbh ≥ 27.5 cm)	Atlantic, Mediterranean
Romania	7.98 m (dbh ≥ 5.6 cm) and 12.62 (dbh > 28.5 cm)	Alpine, Black Sea, Continental, Pannonian, Steppic

(*continued on next page*)

Table 1 (*continued*)

Country	Plot radii (dbh size thresholds)	Bioregion
Slovakia	3.0 m (dbh ≥ 7.0 cm) and 12.62 m (dbh ≥ 12 0.0 cm)	Alpine, Pannonian
Slovenia	7.98 m (dbh ≥ 10 cm) and 12.62 m (dbh ≥ 30 cm)	Alpine, Continental
Spain	5.0 m (dbh ≥ 7.5 cm), 10.0 m (dbh ≥ 12.5 cm), 15.0 m (dbh ≥ 22.5 cm) and 25.0 m (dbh ≥ 42.5 cm)	Atlantic, Alpine, Mediterranean, Macaronesian
Sweden	1.0 m (dbh > 0 cm), 3.5 m (dbh ≥ 40 cm), 7.0 m (dbh ≥ 100 cm) and 20.0 m (dbh threshold depending on the species and region)	Alpine, Boreal, Continental
Switzerland	7.98 m (dbh ≥ 12.0 cm) and 12.62 m (dbh ≥ 36.0 cm)	Alpine, Continental
The Netherlands	Variable radii. Plot minimum radius: 5 m, maximum radius: 20 m, at least 20 trees with dbh ≥ 5 cm	Atlantic

dbh: diameter at breast height; h: tree height; d0.5: tree diameter at 0.5 m.

varying characteristics of stand, into which we embedded concentric plot designs from two European NFIs which present the most notable differences in terms of plot configuration.

2. Material and methods

2.1. Plot simulations

We simulated the spatial distribution of trees within 1-hectare square plots (see Fig. 1A for the representation of a plot). We established three main forest attributes: species richness (S, ranging from monospecific to 10-tree species stands), basal area (BA, from 10 to 50 m^2 ha^{-1}, with 5 m^2 ha^{-1} steps) and tree density (N, from 100 to 2000 trees ha^{-1}, with 100 tree ha^{-1} steps). To simplify the simulations, the same number of trees per hectare was set for all the species. Furthermore, we considered three distinct spatial patterns: regular, random and clustered. The regular pattern was created by embedding a grid within the plot, taking into account the tree density. As regards the random pattern, we randomly simulated coordinates within the margins of the plot. In the case of the clustered spatial patterns, we simulated from three to five clusters within the plot. The cluster centers were randomly located in the inner part of the plot, at least 10 m from the border of the plot.

The alternative combinations of S, BA, N and spatial patterns resulted in an array of 1980 plot configurations (see Fig. 1B for the relationship between N, quadratic mean diameter (Dg) and BA). Furthermore, we created 20 repetitions for each of the 1980 plot configurations, giving a total of 39,600 plots. We used the Gamma and Normal distributions to simulate tree diameter distribution. Thus, we generated species-specific diameter distributions by adjusting the parameters, i.e., shape and scale for the Gamma distribution, and mean and standard deviation for the Normal distribution.

At each plot centre, we embedded the plot designs of the Spanish and Finnish NFIs. We considered these two NFI plot designs as they present the greatest differences in plot configuration in terms of dbh thresholds and plot size, hence encompassing intermediate plot designs (Table 1):

– The Spanish NFI follows a nested plot design with four concentric subplots with increasing radii of 5, 10, 15 and 25 m, where the minimum tree dbh is 7.5, 12.5, 22.5 and 42.5 cm, respectively. For each stem, information on tree variables, such as dbh and species, is collected (Alberdi et al., 2016).

– We use the nested plot design of the 13th Finnish NFI, which consists of two concentric subplots of 4 and 9 m radii, where the dbh thresholds are 4.5 and 9.5 cm, respectively (Korhonen et al., 2024). Trees smaller than 4.5 cm in dbh were not considered in this study.

2.2. Forest structural indices and corrections for nested designs

In this study, we focused on distance-independent structural indices while referring to Moreno-Fernández et al. (2021) for the evaluation of distance-dependent indices. We classified the structural indices into three categories: species composition-related indices, tree size diversity indices (Pommerening, 2002) and the combination of both categories (Staudhammer and LeMay, 2001). As species-composition indices we considered: i) tree species richness, i.e., number of tree species in a given area (S) (Chao and Chiu, 2016), ii) Shannon's Diversity Index (SDI_sp) (Shannon, 1948), iii) Simpson's Diversity Index (D) (Simpson, 1949) and iv) Margalef's Richness Index (MRI) (Margalef, 1958). We used the following indices to quantify forest tree size diversity: v) sum of square roots of dbh differences to mean dbh (SQRI) (Barbeito et al., 2009), vi) Shannon's Diversity Index applied to diameter classes of 10 cm (SDI_dbh) (Staudhammer and LeMay, 2001), vii) Gini Index (Gini), viii) coefficient of variation of the mean plot dbh (CV) (Astigarraga et al., 2020; Zeller and Pretzsch, 2019), ix) interquartile range (IQR), x) and the second L-moment or L-scale (L2), which is analogous to the standard deviation (Table 2). Finally, we considered formulations of Shannon's Diversity Index to describe species composition and structure together (Staudhammer and LeMay, 2001): xi) Shannon's Diversity Index post-hoc method defined as the arithmetic mean of the exponential transformation of SDI_sp and SDI_dbh (SDI_ph) (see Jost (2006) for further details of the transformation), and xii) Shannon's Diversity Index combination method, that is, Shannon's Diversity Index applied to the combinations of species and diameter classes of 10 cm (SDI_cm). We refer to Table 2 for the mathematical definition of the indices.

All indices were calculated for the entire 1 ha plot (Total), for the

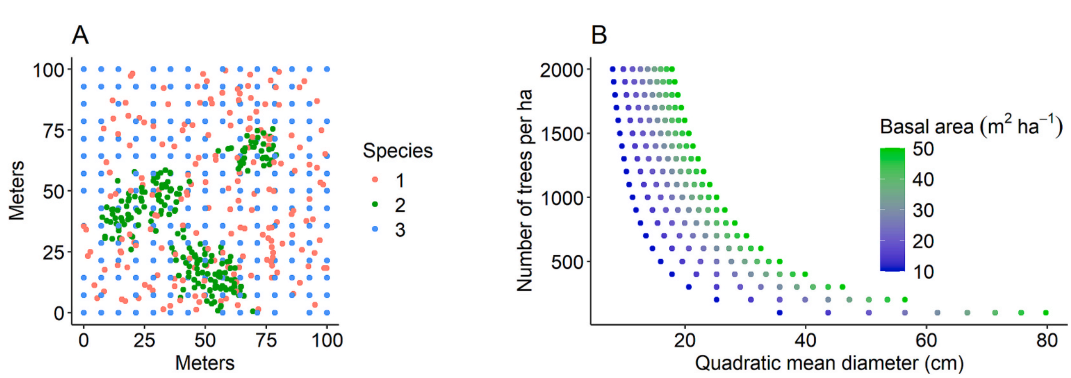

Fig. 1. A: Representation of a 1 ha plot with three species and a basal area equal to 25 m^2 ha^{-1} and a tree density of 600 trees per ha. Species 1 (red dots) follows a random spatial pattern, Species 2 (green dots) a clustered pattern and Species 3 (blue dots) a regular pattern. B: Relationship between number of trees per ha, quadratic mean diameter and basal area for the whole array of simulated plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Mathematical formulation of the indices and the range.

Index	Equation	Range	Equation
Species composition			
S	Number of tree species per plot	[1, S]	(1)
SDI_sp	$SDI\_sp = -\sum_{s=1}^{S} g_s \ln g_s$	[0, ln(S))	(2)
D	$D = 1- \sum_{s=1}^{S} g_s^2$	[0, 1]	(3)
MRI	$MRI = \frac{(S\text{-}1)}{\ln n}$	[0, ∞)	(4)
Forest structural complexity			
SQRI	$SQRI = \sum_{i=1}^{n} g_i \sqrt{\lvert dbh_i - \overline{dbh} \rvert}$	[0, ∞)	(5)
SDI_dbh	$SDI\_dbh = -\sum_{p=1}^{P} g_p \ln g_p$	[0, ln(P))	(6)
Gini	$Gini = \frac{\sum_{i=1}^{n}(2i\text{-}n\text{-}1) \bullet \overline{dbh}}{n \bullet \overline{dbh}}$	[0, 1]	(7)
CV	$CV = \frac{\sigma}{\overline{dbh}}$	[0, ∞)	(8)
IQR	$IQR = Q_3\text{-}Q_1$	[0, Q3]	(9)
L2	$L2 = \frac{1}{2} E[X_{(2)}\text{-}X_{(1)}]$	[0, ∞)	(10)
Forest complexity in conjunction with composition			
SDI_ph	$SDI\_ph = \frac{\exp(SDI\_sp) + \exp(SDI\_dbh)}{2}$		(11)
SDI_cm	$SDI\_cm = -\sum_{z=1}^{Z} g_z \ln g_z$	[0, ln(Z))	(12)

SDI_sp = Shannon's Diversity Index; D = Simpson's Diversity Index; MRI = Margalef's Index; SQRI = sum of square roots of dbh differences; SDI_dbh = Shannon's Diversity Index applied to the 10 cm diameter classes, IQR = interquartile range, L2 = second L-moment or L-scale. SDI_ph = mean value of the exponential of SDI_sp and SDI_dbh; SDI_cm = Shannon's Diversity Index applied to the combinations of species and 10 cm diameter classes. g = relative basal area (tree basal area/plot basal), S = number of tree species per plot. *dbh* and $\overline{dbh}$ are the tree dbh and the mean plot dbh, respectively; σ = standard deviation of the mean dbh. Q_3 is the third quartile and Q_1 is the first quartile. n = number of trees per ha. $X_{(1)}$ and $X_{(2)}$ are the first and second order statistics (values ordered from smallest to largest) in a sample of size 2, while $\boldsymbol{E}$ denotes the expected value or the mean. P is the number of 10 cm diameter classes. Z is the number of combinations of species and 10 cm diameter classes.

nested plot design specific to each NFI (Nested), and for a fixed-radius plot using the largest radius of each design (Fixed), always applying the minimum dbh threshold defined for each case. Thus, in the case of the Spanish NFI, we calculated the indices for the entire 1 ha plot (Total) with a minimum dbh of 7.5 cm as well as for a 25-m radius plot (Fixed) with a minimum dbh of 7.5 cm and for the Nested plot with the corresponding dbh thresholds by concentric subplot radii. In the case of Finland, the Total plot (1 ha plot) includes trees with dbh larger or equal to 4.5 cm in 1 ha, Fixed plot includes trees with dbh larger or equal to 4.5 cm in a 9 m radius plot and Nested plot includes trees meeting the criteria defined above for Finland. As a result, for each simulated 1 ha plot, we obtained the index values for the entire 1 ha (Total), as well as two additional values per country (one for the nested design (Nested), and another for the largest plot (Fixed) (Fig. 2).

The nested design modifies the probability of sampling trees based on their size and location within the plot. As a result, it is necessary to weight the trees in the nested design to account for these shifts in probability (Moreno-Fernández et al., 2021; Myllymäki et al., 2024). In the case of D, SQRI and the four Shannon Index–related structural indices, we calculated g, relative basal area, converting tree basal area values to values per hectare, considering the differing sizes of the concentric subplots. For Gini and IQR, we weighted the trees according to their size and the radius of the subplot where they occur as follows: $weight = 1/(radius)^2$. For instance, a tree with a dbh of 15 cm measured in a nested Spanish NFI plot was assigned a weight of $1/10^2$ since they are only sampled in the 10 m radius subplot. The coefficient of variation of the diameter was estimated by calculating the standard weighted deviation and the weighted mean. Weighted L2 was calculated according to the approach proposed by Myllymäki et al. (2024). Tree richness cannot be weighted and consequently, MRI was computed without weighting.

2.3. Metrics to evaluate the performance of the structural indices under different plot designs

We used the following three statistical metrics to evaluate the performance of the structural indices both in Nested and Fixed designs:

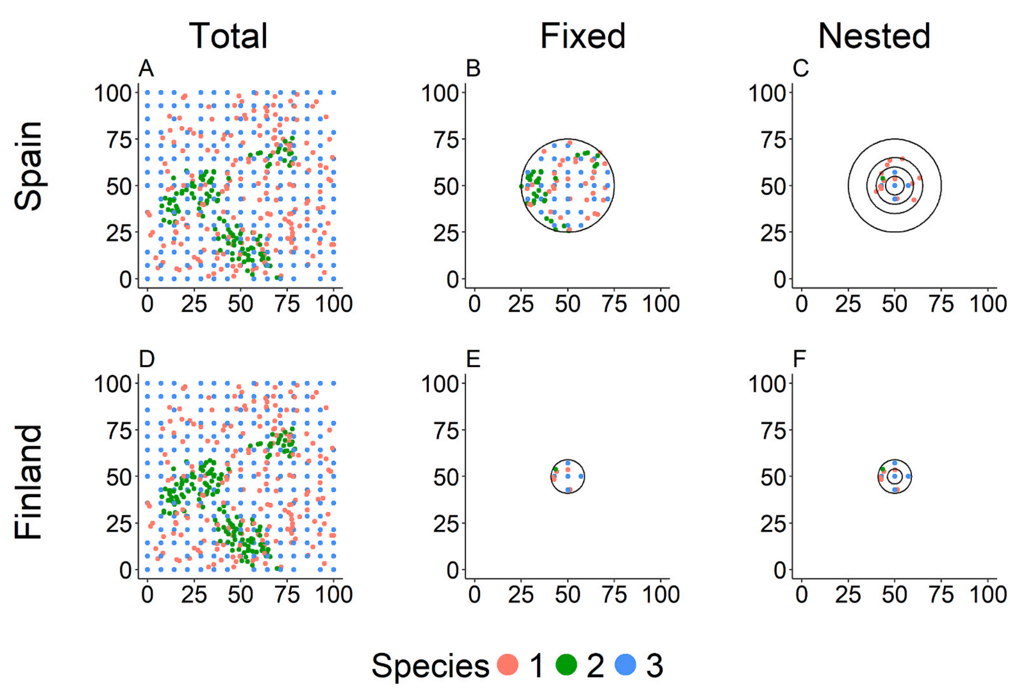

Fig. 2. Representation of a Total (basal area equal to 25 m^2 ha^{-1} and a tree density of 600 trees per ha), Fixed and Nested plot for Spain and Finland in a three-species plot. Units on the axes refer to meters. Species 1 (red dots) follows a random spatial pattern, Species 2 (green dots) a clustered pattern and Species 3 (blue dots) a regular pattern. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Coefficient of determination R^2, calculated as:

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (1)$$

Percentage of bias:

$$Perc\_bias = \frac{1}{n}\sum\left(\frac{y_i - \hat{y}_i}{|y_i|}\right) \quad (2)$$

Mean absolute percent error:

$$MAPE = \frac{1}{n}\sum\left(\frac{|y_i - \hat{y}_i|}{|y_i|}\right) \quad (3)$$

y_i, $\hat{y}_i$, $\bar{y}$ are the actual, predicted and mean values, respectively, while n is the number of observations (n = 39,600 observations or plots). We chose these metrics because they are independent of the order of magnitude and units of the indices and therefore allow indices to be compared. In this study, we compared the values of the indices for Total and Nested, where Total represents the actual values and Nested the predicted values. Values of R^2 close to 1 indicate strong agreement between Total and Nested. Ideally, the error metrics (*Perc_bias* and *MAPE*) should be close to 0. Positive *Perc_bias* values indicate an underestimation by the Nested model, while negative values suggest overestimation. The *MAPE* provides measures of the absolute error magnitude and, therefore, cannot take negative values. Furthermore, we analysed Fixed (predicted) against Total (actual). Finally, we also analysed Nested (predicted) against Fixed (actual) but to facilitate the interpretation of the results, we present these results in the Supplementary Material 1.

2.4. Assessing the influence of stand variables on the performance of nested and fixed designs

To identify the forest stand variables which influence the deviations between Nested and Total, we calculated the absolute difference (*diff*) of the actual value (Total) and predicted (Nested) as $|y_i - \hat{y}_i|$ for each index. We then modelled *diff* as a function of the standardized and centred values of the number of trees per ha (*N*) and *Dg* in Total, combining the data for both countries. Since *diff* always takes non-negative values, we assumed that it follows a Tweedie distribution for all the indices except for S (species richness). For S, the differences *diff* were modelled using a Poisson distribution since the response variable here was count data. Additionally, we included a two-level *Country* factor to investigate the impact of the different nested designs on the index performance. For the diagnosis of the Tweedie and Poisson model residuals, we created scaled residuals using a simulation-based approach. These analyses were repeated for the comparison of Total (actual value) and Fixed (predicted). The minimum dbh thresholds of the sampled trees considered were those established in each NFI.

2.5. Software used

All the simulations and statistical analyses were carried out in R 4.4.1 (R Core Team, 2024). SDI_sp and D were calculated using the "vegan" package (Oksanen et al., 2024). The "dineq" (Schulenberg, 2018) and "modi" (Hulliger, 2023) packages were used to compute the Gini coefficient and IRQ, since both packages support the weighting of observations. Unweighted L-moments were calculated using the "lmom" package (Hosking, 2024), while we refer to Myllymäki et al. (2024) for further details on weighted L-moments. The "Metrics" package (Hamner and Frasco, 2018) was employed to derive *Perc_bias* and *MAPE*, while R^2 was calculated with the "caret" package (Kuhn, 2008). Finally, "glmmTMB" (Brooks et al., 2017) was used to fit the Tweedie and Poisson models, while the diagnosis of model residuals was conducted in "DHARMa" (Hartig, 2022).

3. Results

3.1. Discrepancies in National forest inventory nested designs

For the Spanish NFI, R^2 was higher for Fixed (i.e., Total against Fixed) than for Nested (i.e., Total against Nested) across all indices, while both *Perc_bias* in absolute value and *MAPE* were lower for Fixed than for Nested (Fig. 3). In the case of Finland, the largest values of R^2 and those closest to zero for the other two error metrics were similarly observed for Fixed (Fig. 4). This means that the discrepancies between Total against Fixed were lower than those between Total against Nested.

The R^2 ranged from 0.42 to 0.88 in Spain and from 0.13 to 0.72 in Finland for Nested (Figs. 3A and 4A). When benchmarking Total against

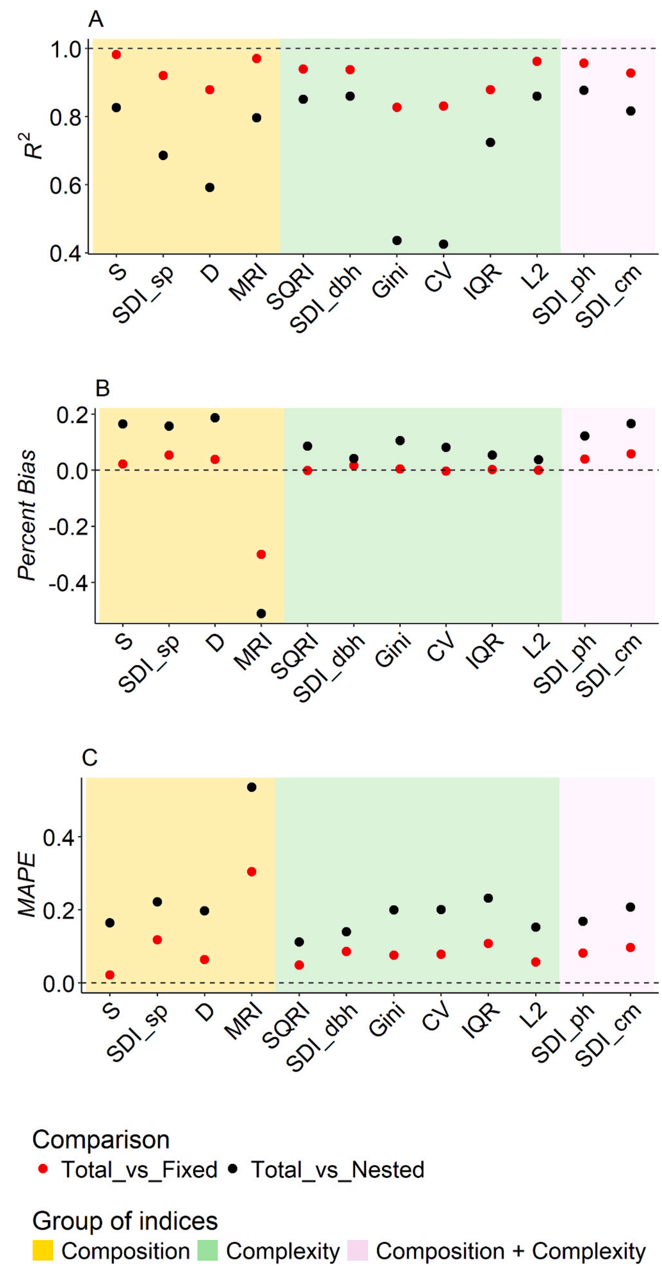

Fig. 3. Metrics evaluating the performance of the structural indices benchmarking the Total against Fixed and Nested plot designs for Spain. Refer to Table 2 for a detailed description of the indices. *Perc_bias* = Percentage of bias, *MAPE* = Mean absolute percentage error. In the R^2 panel (A), the horizontal dashed line at 1 denotes the maximum achievable R^2 score while the zero line in the *Perc_bias* and *MAPE* plots (B and C) acts as a reference point.

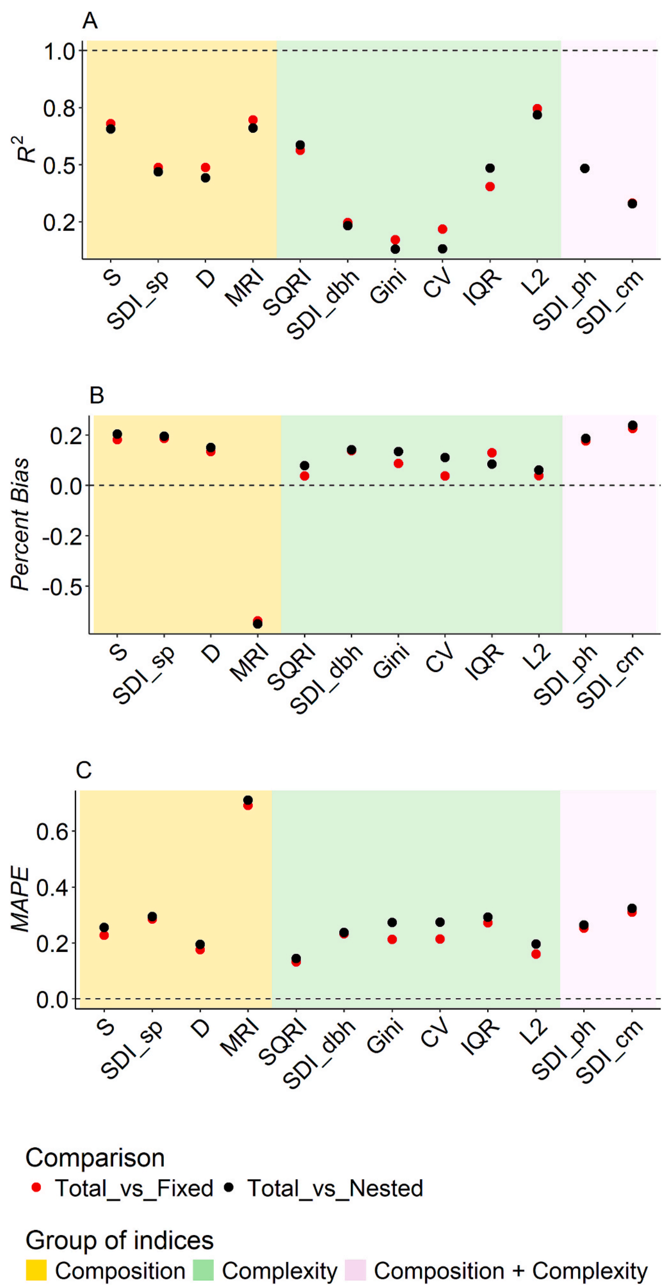

Fig. 4. Metrics evaluating the performance of the structural indices benchmarking the Total against Fixed and Nested plot designs for Finland. Refer to Table 2 for a detailed description of the indices. *Perc_bias* = Percentage of bias, *MAPE* = Mean absolute percent error. In the R^2 panel (A), the horizontal dashed line at 1 denotes the maximum achievable R^2 score while the zero line in the *Perc_bias* and *MAPE* plots (B and C) acts as a reference point.

Fixed, the R^2 ranged between 0.83 and 0.98 for Spain and between 0.17–0.75 for Finland.

3.2. Species composition indices

For the Spanish NFI, R^2 and the two error metrics (*Perc_bias*, and *MAPE*; Fig. 3) suggest that MRI is the species composition index exhibiting the largest differences between Total against Nested and Fixed, whereas S, SDI_sp and D were those found to be the most stable indicators of species composition.

For the Finnish design, S, D and SDI_sp were also the indices which best described the species composition since they provided large values of R^2 together with around zero values for *Perc_bias* and *MAPE* (Fig. 4) while MRI was highly biased.

3.3. Forest structural complexity indices

According to R^2, *Perc_bias* and *MAPE* calculated for Nested and Fixed (Fig. 3), L2, SDI_dbh and SQRI exhibited the best performance in describing forest complexity when considering the Spanish design. In this NFI, the lowest values of R^2 (lower than 0.6) were observed for CV and Gini while *Perc_bias* and *MAPE* suggest a poor performance of IQR when comparing Total against the two other designs.

As regards the Finnish NFI, L2 and SQRI displayed the best values for the three metrics considered. On the other hand, IQR had the largest values of *MAPE*; and SDI_dbh, Gini and CV had the lowest values of R^2.

3.4. Indices assessing forest complexity in conjunction with composition

In the case of the Spanish NFI, the two indices describing forest complexity in conjunction with species diversity (SDI_cm and SDI_ph) displayed a similar performance in the case of the Spanish design.

Finally, when considering the Finnish design, SDI_ph exhibited higher R^2 values and lower *Perc_bias* and *MAPE* values than SDI_cm, indicating its superior performance in describing the relationship between forest complexity and species composition.

3.5. Assessing the influence of stand variables on the performance of nested and fixed designs

The models for the absolute difference (*diff*) of the Total (actual value) and Nested (predicted value) revealed that the indices performed better for the Spanish nested design than for the Finnish design for all the indices in the simulations performed, since the coefficient for the Spanish level was significantly lower (Table 3). Furthermore, we found that Nested designs described forest structure more accurately in denser stands (negative estimation coefficient of *N*; Table 3) for all the evaluated indices, except for MRI. We also found a statistically significant relationship between *Dg* and *diff*. However, the direction of this

Table 3
Estimation coefficient of the stand variables included in the models on the mean absolute error (*diff*) of the actual value (Total) and predicted (Nested) for the 12 structural indices. *N* refers to the standardized number of trees per ha and *Dg* is the standardized mean quadratic diameter of the trees within the Total design (1 ha plot).

Index	Intercept	Country_Spain	*N*	*Dg*
Species composition				
S	0.51389***	−0.35400***	−0.29790***	−0.20640***
SDI_sp	−0.88798***	−0.35189***	−0.17760***	−0.11623***
D	−1.941466***	−0.03293***	−0.16297***	−0.14806***
MRI	−0.69319***	−0.22261***	-0.00414^{ns}	−0.01257**
Forest complexity				
SQRI	−1.04883***	−0.25842***	−0.18812***	0.25495***
SDI_dbh	−1.03907***	−0.76306***	−0.25707***	0.21905***
Gini	−2.78523***	−0.47699***	−0.19299***	0.13709***
CV	−2.20786***	−0.47157***	−0.19019***	0.14143***
IQR	1.24458***	−0.40039***	−0.25274***	0.38934***
L2	−0.09834***	−0.46402***	−0.27966***	0.39309***
Forest complexity in conjunction with forest structure				
SDI_ph	−0.19826***	−0.43644***	−0.17805***	0.14585***
SDI_cm	−0.31552***	−0.51565***	−0.21939***	0.06331***

Asterisks refer to significance levels: * indicates that p-value is lower than 0.05, ** p-value < 0.01 and *** p-value < 0.001. ns = non-significant. S = number of species per plot; SDI_sp = Shannon's Diversity Index; D = Simpson's Diversity Index; MRI = Margalef's Index; SQRI = sum of square roots of dbh differences, SDI_dbh = Shannon's Diversity Index applied to the diameter classes of 10 cm, IQR = interquartile range, L2 = second L-moment or L-scale. SDI_ph = mean value of the exponential of SDI_sp and SDI_dbh; SDI_cm = Shannon's Diversity Index applied to the combinations of species and 10 cm diameter classes.

relationship varied among the structural categories considered. For instance, *Dg* was positively related to the forest complexity indices as well as to the indices quantifying forest complexity along with forest structure, indicating that nested designs better describe these structural attributes in stands with low *Dg*. In contrast, this relationship became negative for all the species composition indices, indicating that nested designs better represent species composition in stands with large *Dg*.

These results align with those from the models for *diff* between the Total (actual value) and Fixed (predicted value). The indices performed better for the design with the largest plot, i.e., Spain, and N depicted a negative and statistically significant association with *diff* for all the indices (Table 4). Furthermore, we found a positive relationship between *Dg* and *diff* for every index.

4. Discussion

This study compared the ability of 12 established indices to quantify forest structure (composition and forest structural complexity) using the nested designs from two NFIs with notable differences in plot configurations (large plots with four concentric subplots vs small plots with two concentric subplots and low diameter thresholds) to evaluate the performance of the indices under alternative conditions. Therefore, because the analyses were based on two NFIs with markedly different designs, our findings are likely to be applicable to other forest inventories as well. Our results revealed that the Spanish Nested and Fixed designs quantify forest structure better than the Finnish designs when benchmarked against Total (from 1-ha plot). This can be explained by the fact that the size of the plot is larger in the Spanish design than in the Finnish one (25 vs 9 m) (Alberdi et al., 2016; Korhonen et al., 2024). Additionally, the spatial configuration of plots varies between countries. In the Spanish NFI, plots are spaced 1 km apart, whereas in the Finnish NFI, plots are arranged in clusters to achieve a cost-efficient design. Therefore, we advise against comparing the results from the two countries but instead recommend comparing the overall performance of the indices. At this point, it is worth noting that each European country, as well as other countries around the world, adjusts the NFI design to the characteristics (including the above-mentioned spatial configuration of the plots) of their forests, among other criteria. As their forests are more homogeneous and less complex, Northern European countries (e.g., Finland, Norway, Sweden) use smaller plots than temperate, Mediterranean countries (e.g., France, Italy, Spain) (Tomppo et al., 2010), which have forests with more dominant species and diverse structures ranging from open agroforestry stands to plantations of fast-growing species (Moreno-Fernández et al., 2020; Svenning and Skov, 2005). In this regard, it is possible that the plots we simulated could be more complex and diverse in terms of species richness than the boreal forest in Finland and some of the intensive and monospecific reforestation in Spain. The main limitation of this work is that our results are based on simulated plots. This implies that some plot configurations (e.g., the number of species or spatial arrangement of the trees) may not be realistic. Hence, we cannot neglect the fact that some of the simulated tree densities are relatively low and uncommon in boreal forests. In fact, the number of trees per ha was found to be a relevant factor in explaining the deviations between designs. Therefore, the structural indices in both Nested and Fixed could perform better under real data for Finnish forests.

Table 4
Estimation coefficient of the stand variables included in the models on the mean absolute error (*diff*) of the actual value (Total) and predicted (Fixed) for the 12 structural indices. *N* refers to the standardized number of trees per ha and *Dg* is the standardized mean quadratic diameter of the trees within the Total design (1 ha plot).

Index	*Intercept*	*Country_Spain*	*N*	*Dg*
Species composition				
S	0.368949***	−2.21091***	−0.26391***	0.11436***
SDI_sp	−0.92881***	−1.14040***	−0.14158***	0.07482***
D	−2.05130***	−1.36175***	−0.14574***	0.06799***
MRI	−0.69273***	−0.75861***	−0.06958*	0.03899***
Forest complexity				
SQRI	−1.14181***	−1.01832***	−0.18211***	0.32036***
SDI_dbh	−1.45444***	−1.23733***	−0.23245***	0.32750***
Gini	−3.09407***	−1.16255***	−0.14777***	0.24953***
CV	−2.51113***	−1.11046***	−0.13812***	0.23765***
IQR	1.15267***	−1.08529***	−0.22687***	0.53226***
L2	−0.32660***	−1.24507***	−0.25019***	0.53015***
Forest complexity in conjunction with forest structure				
SDI_ph	−1.21656***	−1.28399***	−0.18766***	0.22103***
SDI_cm	−0.36977***	−1.33499***	−0.19657***	0.24851***

Asterisks refer to significance levels: * indicates that p-value is lower than 0.05, ** p-value < 0.01 and *** p-value < 0.001. S = number of species per plot; SDI_sp = Shannon's Diversity Index; D = Simpson's Diversity Index; MRI = Margalef's Index; SQRI = sum of square roots of dbh differences, SDI_dbh = Shannon's Diversity Index applied to the 10 cm diameter classes, IQR = inter-quartile range, L2 = second L-moment or L-scale. SDI_ph = mean value of the SDI_sp and SDI_dbh; SDI_cm = Shannon's Diversity Index applied to the combinations of species and 10 cm diameter classes.

4.1. Species composition indices

Some studies have stressed that nested plot designs do not adequately capture the total number of tree species (tree species richness) (Lin et al., 2020; Moreno-Fernández et al., 2024). When comparing to our study, it is important to note that we assumed equal tree density for all species but different proportions of basal area. In this regard, Moreno-Fernández et al. (2024) found that the species most frequently missed in nested survey designs are typically subordinate and of smaller diameters. As a result, estimates of tree species richness under nested designs may be overly optimistic in this study. The bias in tree richness estimation in nested designs also affects other measures of composition, especially MRI, which is inaccurate and biased. In contrast, SDI_sp and D are less affected by the nested design since they include the abundance (evaluated through the basal area), which can be corrected in nested designs. Furthermore, several studies have evaluated the performance of SDI_sp and D in the representation of ecological diversity, reporting contradictory results (Kitikidou et al., 2024; Mulya et al., 2021). Some authors, such as Kitikidou et al. (2024), advocate the use of SDI_sp since it effectively reflects changes in species richness, while Franc (1998) states that SDI_sp does not change with the occurrence of rare species. According to Neumann and Starlinger (2001), there are no big differences between the two indices when applied to the tree stratum. The ability of SDI_sp to adequately describe species composition in nested designs, as found in this study, aligns with the results from Motz et al. (2010) for plot designs based on count angle sampling.

4.2. Forest structural complexity indices

Based on our study, SDI_dbh, i.e., Shannon's Diversity Index for dbh variability, was one of the most promising indices, being well estimated from the Spanish NFI plot. However, one of the main drawbacks of this index is that it requires continuous dbh measures to be segregated into discrete classes. This involves an arbitrary selection of the class size as well as a loss of information, which can impact the index performance (Staudhammer and LeMay, 2001; Valbuena et al., 2012). However, this index has been shown to adequately describe forest complexity (Staudhammer and LeMay, 2001). Moreover, it is correlated to other indices such as SQRI that do not require artificial class boundaries to be set (Barbeito et al., 2009). Furthermore, SDI_dbh, as well as Gini and CV, are tree size insensitive, i.e., the magnitude of the tree size does not affect the index but rather the variability. This property is required to compare stands of different ages (Staudhammer and LeMay, 2001). In this regard, Barbeito et al. (2009) state that since SQRI is based on the sum of the square roots of absolute value differences, the number of differing values contributes more to the final score than the actual magnitude of those differences. In contrast, IQR and L2 are affected by the magnitude of the tree size.

L2, as well as other L-moments, are more robust to outliers and provide more secure inferences in the case of distributions with small sample sizes than conventional moments (e.g., mean, standard deviation, CV, coefficient of Kurtosis) (Hosking, 1990). Therefore, this approach could be instrumental in the evaluation of forest structure in nested plot designs, where the sample size is not expected to be large (Myllymäki et al., 2024).

4.3. Indices assessing forest complexity in conjunction with composition

Finally, our results indicate a similar ability of SDI_ph and SDI_cm to represent structure and composition together. Both indices share the strengths and weaknesses of SDI_sp and SDI_dbh because SDI_ph and SDI_cm combine both indices. Staudhammer and LeMay (2001) stressed that SDI_ph is more informative since it also allows the diversity of each component (dbh and species) to be examined separately.

4.4. Other methodological remarks

To obtain comparable indicators, one possible approach is to harmonize the data by using the same field information. Two main strategies can be considered: (i) using a common minimum dbh—in this case, the largest threshold among datasets, 7.5 cm—to ensure all data are included; and/or (ii) using a common plot area—excluding trees in Spanish plots beyond 9 m radius to match the smallest sampling area. These two strategies have been employed in recent harmonization efforts, such as Gschwantner et al. (2024) in the case of the first approach and Portier et al. (2022) the second. While we opted not to apply these methods, future studies should explore the role of harmonization for forest structure indices. Our findings indicate that, across all the considered simulations, plot area had a relevant influence, with the indices providing more interpretable results for larger plot designs. However, future studies should aim to use plots that reflect the actual forest structure present in each country to improve the robustness of the comparisons.

5. Conclusions

Based on the comparison among plot designs, to achieve an accurate description of species composition, both in nested and fixed plot designs, we recommend using Shannon’s (SDI_sp) or Simpson’s Diversity (D) Indices rather than tree richness (S) or Margalef’s Index (MRI). Tree species richness (S) also described tree composition reasonably well in our study, but its performance can be heavily affected by the settings applied to simulate the plots. The sum of square roots of dbh differences (SQRI), Shannon’s Diversity Index applied to diameter classes (SDI_dbh) and the second L-moment (L2) were found to be the most effective indices to quantify forest complexity, and most comparable for different sample plot designs. Ultimately, both the post-hoc and combination methods using Shannon’s Diversity Index (SDI_ph and SDI_cm, respectively) proved effective in describing forest complexity and composition together.

Finally, we recommend that this study is replicated considering other simulation settings (e.g., with different tree densities across species) and/or NFI plot designs as well as extending the study to the case of field data.

CRediT authorship contribution statement

Daniel Moreno-Fernández: Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Nerea Oliveira:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mari Myllymäki:** Writing – review & editing, Validation, Supervision. **Isabel Cañellas:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Mikko Kuronen:** Writing – review & editing, Validation, Resources, Methodology, Data curation. **Iciar Alberdi:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

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.

Acknowledgement

We thank Adam Collins for revising the English grammar and two anonymous reviewers for their critical input.

Funding sources

The research leading to these results has also received funding from the European Union Horizon Europe (HORIZON) Research & Innovation programme under the Grant Agreements no. 101056907 (PathFinder project) and 101134991 (MoniFun project).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.114434.

Data availability

Data will be made available on request.

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