Stand structure indices as tools to support forest management: an application in Trentino forests (Italy)

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ABSTRACT: Stand structure and species diversity are two useful parameters to provide a synthetic measure of forest biodiversity. The stand structure is spatial distribution, mutual position, diameter and height differentiation of trees in a forest ecosystem and it highly influences habitat and species diversity. The forest stand and species diversity can be measured through indices that provide important information to better address silvicultural practices and forest management strategies in the short and long-term period. These indices can be combined in a composite index in order to evaluate the complex diversity at the stand level. The aim of the paper is to identify and to test a complex index (*S*-index) allowing to take into account both the tree species composition and the stand structure. *S*-index was applied in a case study in the north-east of Italy (Trentino province). The results show that the Norway spruce forests in Trentino province are characterized by a medium-low level of complexity (*S*-index is in a range between 0.14 and 0.46) due to a low tree species composition rather than to the stand structure (diametric differentiation and spatial distribution of trees).

Keywords: stand complexity; species diversity; diametric differentiation index; mingling index; contagion index; composite stand index

Stand structure and species diversity are two important and interrelated ecological and functional features of forest ecosystem (Pretzsch 1997). Natural regeneration and the growth of trees influence the spatial forest structure and, conversely, these ecological processes are a reaction to the spatial context (Pommerening 2006). The stand structure has an effect on both aesthetic and recreational values as well as on the abundance of flora and fauna species (Pitkänen 1997; Su et al. 2012) and it has become an important factor in the analysis of forest ecosystems (Zenner, Hibbs 2000). Consequently, it can be used as an indicator of overall biodiversity and habitat suitability (Staudhammer, LeMay 2001). High natural diversity is associated with forest stands where there are multiple trees species and sizes (height and diameter), and a clumped spatial distribution (Buongiorno et al. 1994).

From the political point of view, the maintenance of diversity of forest ecosystems is stressed in the Rio Declaration on Environment and Development (1992) and renewed by the first and third Ministerial Conference on the Protection of Forests in Europe – MCPFE (Rad et al. 2009). The MCPFE Resolution S2 Conservation of Forest Genetic Resources (Strasburg, 1990) addresses the need for conserving genetic diversity because it has a great importance for afforestation and restocking. Annex 2 of MCPFE Resolution L2 (Lisbon, 1998), instead, identifies one specific criterion for Sustainable Forest Management (SFM) entitled Maintenance, conservation and appropriate enhancement of biological diversity in forest ecosystems. According to this criterion of SFM the key variables to maintain the diversity of forest ecosystem are: natural regeneration, tree species composition with special regard to the relationship between native species and introduced species, horizontal and vertical structures, quantitative and qualitative presence of deadwood and special key biotopes. In

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particular, a high variety of forest layers (vertical structure) and tree species provide a large amount of habitats for different animal species (Motz et al. 2010). Consequently, the species diversity and the stand structure can be considered two relevant indicators of the biodiversity level and a correct estimation of these variables is a valuable tool to better target management practices.

The stand structure can be defined as the spatial distribution, mutual position, diametric and height differentiation of the trees in a forest ecosystem (von Gadow, Hui 1999). According to this definition, the forest structure includes three main aspects (Pommerening 2002; Aguirre et al. 2003): diversity of positions of trees (spatial distribution), species diversity, and variations in tree dimension. Regarding the latter, the structure can be characterized horizontally (horizontal structure), by diametric distribution of the trees, and vertically (vertical structure) by height differentiation. Stand structure heterogeneity (horizontal and vertical) leads to a higher number of species (Wang et al. 2006) and contributes to higher stability (Latham et al. 1998) and forest integrity. The stand structure can be assessed by index methods (indices) that are a mathematical construct which summarizes the effects of two or more structural attributes in a single index value (McElhinny 2002). The structural indices can be calculated in two ways: considering the total number of trees in the plot (n) or referring only to the k nearest subjects to another tree randomly identified in the plot (Corona et al. 2005). The first group of indices requires a longer time for the collection of data in the field, while the second group of indices needs shorter times of data collection, but with uncertainty of the reliability of the final values. Nowadays, some researchers recognize the need for the development of a biodiversity index that uses a scoring system, based on a combination of key structural indicators of biodiversity. The indicators have weighted scores, and they are summed to give a comparative measure (Ferris 1999).

Starting from these considerations, the paper compares different indices and proposes a Complex stand index (S-index) useful for describing the forest stand from the structural and functional point of view. The S-index is derived by the other three indices: Diametric differentiation index (TM), Mingling index (M) and Contagion index (W). The main objective of S-index is to evaluate the level of biodiversity of a forest ecosystem in a synthetic way. The S-index was tested in a case study in the north-east of Italy (Trentino province, Trentino-Alto Adige region) and the results were used to analyse the forest complexity from different perspectives.

MATERIAL AND METHODS

Trentino province has 345,180 ha of forests – approximately 56% of the total area – with predominantly 59% *Picea abies* (L.) H. Karst (Norway spruce), 17% *Larix decidua* Mill. (European larch), 16.7% *Fagus sylvatica* L. (beech), 10.8% *Abies alba* Mill. (silver fir), and 7.4% of *Pinus sylvestris* L. and *Pinus nigra* Arnold (Scots and black pines) forests. The climate of the province is cool, temperate and mild continental. The mean annual temperature is 11.5°C, while the annual rainfall average is 883 mm with two main peak periods, in spring (May rainfall averages 94 mm) and autumn (October rainfall averages 110 mm).

The data were collected in the field during the maximum leaf-on growing season (June-September 2012) in 54 sample plots. The sample plots were selected through a stratified sampling based on forest type considering the main four forest types in Trentino: 24 plots in Norway spruce forests pure and mixed with silver fir, 12 plots in beech forests, 12 plots in Scots pine forests, and 6 plots in European larch forests. The forest type is defined according to the Province of Trento classification (Odasso 2002). The randomly located sample plots were circular with a radius of 13 m (surface of 531 m^2). In each plot, some quantitative and qualitative site and stand features such as GPS coordinates, angle and distance of each tree from the centre of the plot, number of trees and diameter at breast height (DBH) were taken. According to the standard of the second Italian National Forest Inventory (NFI), the minimum DBH threshold used for the measurement was 4.5 cm, below this threshold the subjects are considered as saplings (Gasparini, Tabacchi 2011). Besides, four hemispherical photographs of the canopy were taken in each sample plot using a Nikon Coolpix 900 camera (Nikon Corporation, Tokyo, Japan) and a fish-eye converter Nikon FC-E8 (Nikon Corporation, Tokyo, Japan) at 1 m from the ground. The camera was run in the programme mode where exposure time and focal aperture are set automatically using the parameters fixed in FISHEYE1 lens mode (focus set to infinity, widest zoom, metering centre-weighted), while the shutter speed was varied automatically by the camera. The hemispherical images were processed by Spot Light Intercept Model (SLIM) 3.02 (Comeau, MacDonald 2012) to estimate the amount of foliage area in a canopy per unit ground surface area (Leaf Area Index – LAI). LAI is an important ecological parameter linked to the stand structure because it is strongly affected by the physical structure of the forest both in horizontal and vertical dimension, in particular the number of trees and the spatial distribution of trees play an important role in the canopy cover and LAI values (Tan et al. 2011).

The forest stand diversity was calculated only for the forest type characterized by the highest number of sample plots (24 plots in Norway spruce forests) in order to analyse the influence of forest structure on biodiversity. The forest stand diversity was evaluated using three indices, the first index is based on diametric differentiation (horizontal structure), the second index takes into account the species diversity and the last index focuses on the mutual position of trees (Table 1). The indices were calculated considering all trees in the plot (*n*) and – in a synthetic way – considering only the *k* nearest trees to a tree randomly identified in the plot (k = 3). In this case, a tree was randomly selected starting from the complete list of trees in the plot and, subsequently, the three nearest trees to it were identified to calculate the indices (Fig. 1) In each plot, the same group of trees (p_i, p_1, p_2 and p_3) was used to calculate the three indices.

TM-index elaborated for the first time by Füldner (1995) considers the diameter dimensions of all trees in the sample plot or the *k* nearest trees to a tree randomly identified in the plot. This index has a range from 0 to 1. Forest stands with small diameter differentiation have the index values near 0 (TM < 0.3), while forest stands with high diameter differentiation have the index values greater than 0.5.

$$TM_i = \frac{1}{n}\sum_{j=1}^{n}(1-d_{ij}) \qquad (1)$$

$$TM'_i = \frac{1}{k}\sum_{j=1}^{k}(1-d_{ij}) \qquad (2)$$

where:

d_{ij} – ratio between thinner and thicker DBH in the analysed neighbour tree pair,

n – total number of trees in the plot,

k – the three nearest trees to a tree randomly identified in the plot.

M-index is an ecological standard measure for species diversity and it describes the degree of mixing of trees species in a stand (von Gadow 1993).

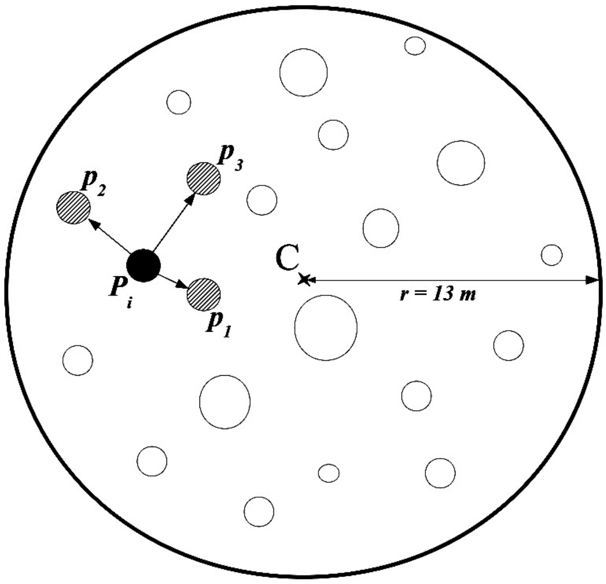

Fig. 1. Sample plot

P_i – randomly selected tree, p_1, p_2 and p_3 – the three nearest trees to a tree randomly identified in the plot, C – plot centre, n – total number of trees in the plot

Table 1. Stand structure and species diversity indices with the respective classes

Structure index	Variable	Classes
TM-index ∈ [0, 1]	diameter (cm)	small diameter differentiation: TM_i < 0.3 average diameter differentiation: 0.3 ≤ TM_i < 0.5 large diameter differentiation: TM_i ≥ 0.5
M-index ∈ [0, 1]	species	low species diversity: M_i < 0.3 medium species diversity: 0.3 ≤ M_i < 0.5 high species diversity: M_i ≥ 0.5
W-index ∈ [0, 1]	angle (°)	regular distribution of trees: W_i < 0.3 random distribution of trees: 0.3 ≤ W_i < 0.4 clumped distribution of trees: W_i ≥ 0.4
S-index ∈ [0, 1]	diameter (cm), species and angle (°)	low level of biodiversity: S < 0.3 medium level of biodiversity 0.3 ≤ S < 0.4 high level of biodiversity S ≥ 0.4

This index has a range from 0 to 1; values close to 0 indicate low diversity of species, while high values document high species diversity. In consideration of the characteristics of Alpine forests we considered three classes to take into account three levels of species diversity (low, medium and high species diversity).

$$M_i = \frac{1}{n}\sum_{j=1}^{n} v_{ij} \quad (3)$$

$$M'_i = \frac{1}{k}\sum_{j=1}^{k} v_{ij} \quad (4)$$

where:

v_{ij} – 1 if reference tree i and neighbour j are of different tree species; 0 otherwise,

n – total number of trees in the plot,

k – the three nearest trees to a tree randomly identified in the plot.

W-index considers the degree of regularity of the spatial distribution of tree positions in a forest (von Gadow 1998). Complete regularity of the position of the n nearest neighbours around a tree i is assumed when the expected standard angle α_0 between two neighbours is equal to 360°/n. *W*-index assumes values between 0 and 1 and we consider clumped distribution when the contagion value is greater than 0.4, regular distribution when it is less than 0.3, and random distribution when it is between 0.3 and 0.4.

$$W_i = \frac{1}{n}\sum_{j=1}^{n} w_{ij} \quad (5)$$

$$W'_i = \frac{1}{k}\sum_{j=1}^{k} w_{ij} \quad (6)$$

where:

w_{ij} – 1, if α_j < 120°; 0 otherwise,

n – total number of trees in the plot,

k – the three nearest trees to a tree randomly identified.

These three indices are used to elaborate a *S*-index useful to concisely describe the level of biodiversity of a forest stand. This index is comparable with other complex indices elaborated in order to describe and evaluate the diversity at the forest stand level such as the *B*-index elaborated by Jaehne and Dohrenbusch (1997). *B*-index takes into account four variables of stand structural diversity (Vorčák et al. 2006): index of tree species composition, index of vertical structure, index of spatial distribution and index of crown differentiation. Instead, *S*-index is the weighted sum of three indices and from the theoretical point of view it can vary in a continuum from 0 (minimum level of biodiversity) to 1 (maximum level of biodiversity). The literature provides little guidance how to weight variables of stand structural diversity. Anyway, it is stressed that the weighting of variables should be carefully considered as a part of the composite index design (McElhinny 2005). The weight adopted for each index was estimated considering the relative importance of the three variables in the evaluation of forest stand biodiversity. Spies and Franklin (1991) identified the diameter differentiation as one of the most important features for characterizing wildlife habitat, ecosystem function and successional development in coniferous forests. Moreover, the variability in tree size is considered as an indicator of the diversity of micro-habitats for the wildlife (Acker et al. 1998). According to Zenner (2000) the vertical structure is a good indicator of biodiversity because it depends on the horizontal arrangement of trees as well as on the height of trees, while the spatial distribution of trees is an important explanatory structural variable for the conversional status of forest stands. Consequently, the tree spacing is a wider structural indicator in comparison with the diameter differentiation because it is indicative of both tree size and distribution of gaps (Svensson, Jeglum 2001). Tree species composition is the most common indicator used to assess biodiversity and to characterize the stand structure (Graz 2004). Nevertheless, this indicator is more useful for tropical forests rather than for temperate forests. For temperate and boreal forests the relative abundance of key groups of species is a key indicator rather than the species richness. In order to take into account these considerations the weights used for each index were as follows:

$$S = (TM_i \times w_1) + (M_i \times w_2) + (W_i \times w_3) \quad (7)$$

$$S' = (TM'_i \times w_1) + (M'_i \times w_2) + (W'_i \times w_3) \quad (8)$$

where:

w_1 = 0.2; w_2 = 0.5; w_3 = 0.3.

The variability of *S*'-index values based on random sampling was assessed with bootstrapping in order to estimate the confidence intervals that describe the uncertainty inherent in the estimated indices. Bootstrapping was implemented by constructing a number of resamples of the observed dataset (20 resamples/trees in each plot), each of which is obtained by random sampling with replacement from the original dataset. This method allowed to estimate the shape of the distribution of the means (histogram of bootstrap means) and the confidence interval of 99%.

The results of each index were compared in pairs (*TM-TM'*; *M-M'*; *W-W'*; *S-S'*) from the statistical point of view using the non-parametric Wilcoxon's Signed-Rank Test. We have chosen the Wilcoxon's Signed-Rank Test because the data do not follow a normal distribution and we have paired values. This statistical test is used in order to highlight differences between the indices that use the data on all trees in the plot and the indices that use only the *k* nearest trees to a tree randomly identified in the plot.

RESULTS AND DISCUSSION

Table 2 shows the main stand and site characteristics for each plot (number of plot, forest type, number of stems and basal area per hectare, altitude, slope, leaf area index, and GPS coordinates). The selected plots are situated at an altitude range from 1,327 m to 1,963 m and they are characterized by a slope between 10° and 45° (average slope 33.7°). The Norway spruce forests are heterogeneous (875 stems·ha^{-1}, basal area 53.7 m^2·ha^{-1}) because it includes two forest subtypes: pure Norway spruce forests and Norway spruce forests mixed with silver fir and beech. The mean value of Leaf Area Index (LAI) is 2.60 (SD = 0.65). This LAI value for the Norway spruce forests is comparable with the average value reported in the international literature for the same forest type estimated by LAI-2000 and hemispherical images (Morisette et al. 2006): $LAI_{Norway\ spruce}$= 3.49.

Table 3 reports the description and the number of plots for each type of forest stand with the corresponding values of *S*-index. In the study area, two

Table 2. Stand and site characteristics for each sample plot (Norway spruce forests)

Plot	*n* (stems·ha^{-1})	Basal area (m^2·ha^{-1})	Altitude (m)	Slope (°)	LAI	X	Y
1	716	55.6	1,549	20	1.94	71°08'76"	51°31'310"
2	1,168	75.2	1,538	35	2.66	71°09'36"	51°31'234"
3	1,018	61.5	1,568	35	2.47	71°10'37"	51°31'192"
4	754	47.4	1,901	40	2.17	70°41'18"	51°27'537"
5	829	51.7	1,894	30	2.15	70°41'10"	51°27'493"
6	490	38.5	1,963	10	2.32	70°42'66"	51°27'486"
7	1,168	45.1	1,594	40	2.00	68°78'15"	51°14'420"
8	396	41.2	1,592	40	2.01	68°73'26"	51°14'177"
9	1,074	56.2	1,601	43	2.27	68°72'83"	51°14'197"
10	490	60.1	1,413	10	2.98	68°85'62"	51°13'713"
11	377	56.6	1,476	45	3.04	68°92'01"	51°13'346"
12	471	63.7	1,479	45	3.67	68°94'93"	51°13'175"
13	1,018	73.1	1,490	30	2.47	70°72'86"	51°12'890"
14	1,112	55.5	1,470	25	2.89	70°66'33"	51°12'698"
15	565	36.0	1,610	45	1.97	70°73'37"	51°13'086"
16	1,545	37.8	1,460	35	3.75	70°15'81"	51°06'954"
17	1,734	58.3	1,410	40	3.39	70°17'25"	51°07'102"
18	791	37.9	1,552	45	2.75	70°11'69"	51°06'544"
19	810	68.2	1,453	40	3.93	63°00'84"	50°88'760"
20	1,112	40.2	1,327	40	1.71	62°95'60"	50°89'105"
21	471	54.4	1,634	40	1.74	62°98'05"	50°88'576"
22	829	73.3	1,707	30	2.86	61°69'06"	50°99'906"
23	1,206	47.7	1,715	10	3.23	71°45'70"	51°53'588"
24	848	53.5	1,771	35	2.09	61°67'09"	51°00'411"

LAI – Leaf Area Index

Table 3. The range of *S*-index values for different types of Norway spruce forest stand

Description of forest stand	No. of plots	*S*-index	SD
Regular distribution, small diameter differentiation, low species diversity	1	0.14	–
Regular distribution, average diameter differentiation, low species diversity	3	0.17–0.28	0.06
Regular distribution, average diameter differentiation, medium species diversity	2	0.37–0.40	0.03
Regular distribution, large diameter differentiation, low species diversity	1	0.17	–
Regular distribution, large diameter differentiation, medium species diversity	2	0.36–0.37	0.01
Regular distribution, large diameter differentiation, high species diversity	1	0.46	–
Random distribution, average diameter differentiation, low species diversity	7	0.18–0.27	0.03
Random distribution, average diameter differentiation, medium species diversity	1	0.35	–
Clumped distribution, small diameter differentiation, low species diversity	1	0.18	–
Clumped distribution, average diameter differentiation, low species diversity	4	0.27–0.30	0.01
Clumped distribution, large diameter differentiation, low species diversity	1	0.23	–
Total	24	0.14–0.46	0.09

SD – standard deviation of the *S*-index

types of forest stand are the most frequently represented: forests characterized by random distribution, average diameter differentiation and low species diversity (29.2% of all plots), and forests characterized by clumped distribution of trees, average diameter differentiation and low species diversity (16.7%). The values of *S*-index are in a range between 0.14 and 0.46 with the mean value of 0.26 (SD = 0.09). Forest stands with the lowest level of biodiversity are those with regular distribution of trees, small diametric differentiation and low species diversity (*S*-index around 0.15), while forest stands with the highest values of *S*-index are characterized by regular distribution of trees, high number of species and large diametric differentiation (*S*-index equal to 0.46).

The values of *S'*-index are reported in Table 4, also for this index the most frequently represented forest stand types are the stands with random distribution of trees, average diameter differentiation, and low species diversity (29.2% of all plots), and secondly the stands with clumped distribution of trees, large diameter differentiation, and low species diversity (20.8%). The values of *S'*-index are in a range between 0.10 and 0.50 with the mean value of 0.28 (SD = 0.12). The data analysis shows that the *S'*-index in comparison with the *S*-index provides the highest difference in values between the different types of forest stands.

Fig. 2 shows the value distribution of *S*-index and *S'*-index along the increasing level of biodiversity. It suggests that certain biodiversity levels may correspond to many forest structures. Consequently, the analysis of forest stands must be based on both the value of the index and the description of the

Table 4. The range of *S'*-index values for different types of Norway spruce forest stand

Description of forest stand	No. of plots	*S'*-index	SD
Regular distribution, average diameter differentiation, low species diversity	1	0.10	–
Regular distribution, average diameter differentiation, medium species diversity	1	0.26	–
Regular distribution, large diameter differentiation, low species diversity	2	0.12–0.15	0.02
Random distribution, average diameter differentiation, low species diversity	7	0.16–0.19	0.01
Random distribution, average diameter differentiation, medium species diversity	1	0.36	–
Random distribution, average diameter differentiation, high species diversity	1	0.50	–
Clumped distribution, large diameter differentiation, low species diversity	5	0.30–0.33	0.01
Total	24	0.10–0.50	0.12

SD – standard deviation of the *S'*-index

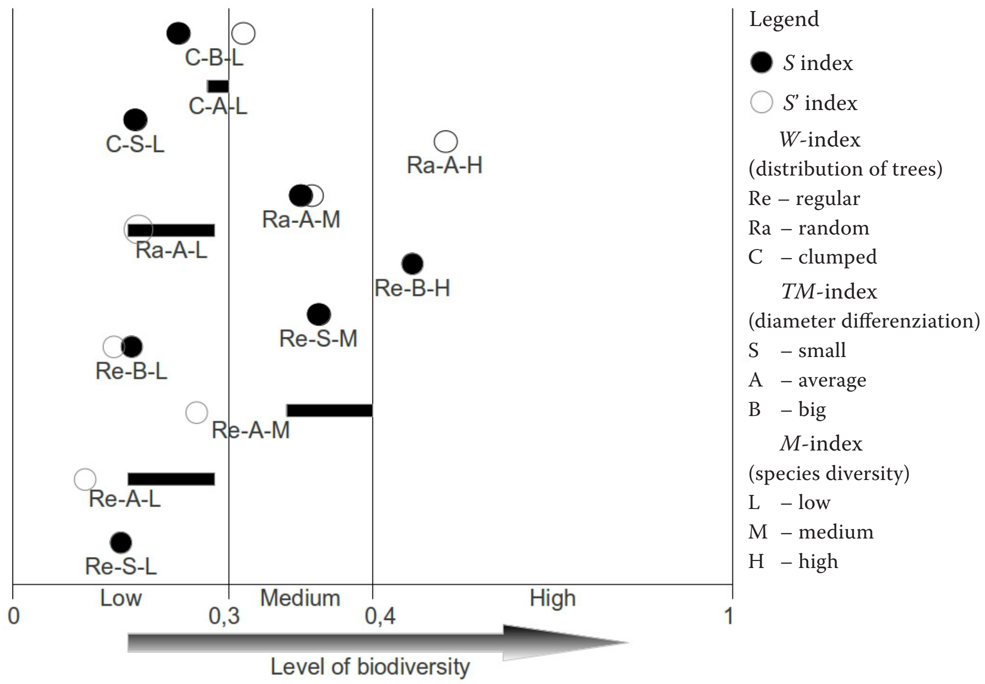

Fig. 2. Distribution of forest stand types in consideration of the level of biodiversity calculated by *S*-index and *S'*-index

forest stand. These two pieces of information can help the forest managers in making the choice of the variables (i.e. horizontal structure or tree species composition) on which to focus with the aim to increase the index and, consequently, the biodiversity of forest stand.

The Norway spruce forests in Trentino province are characterized by a medium-low level of biodiversity; this fact is mainly due to the low presence of other tree species. In the pure Norway spruce forests the maximum valorisation of biodiversity should focus on diameter differentiation and spatial distribution of trees (theoretical *S*-index equal to 0.5).

The bootstrap method used to estimate the confidence interval for each synthetic index highlights that the reference values are internal to the confidence intervals in three of the four cases (Table 5). The reference value of *S'*-index weighted on the basis of other three indices was in the confidence interval, consequently, this value can be used as estimator of *S*-index. The histogram of bootstrap means for each index is shown in Fig. 3.

The results of the non-parametric Wilcoxon's test using the data on *n* trees in the plot and the *k* nearest trees to a tree randomly identified show no significant statistical differences for all pairs of indices: *W-W'* [V = 128.0, V-expected = 150.0, level of probability (*P*-value) = 0.539, statistical significance $\alpha = 0.01$], *M-M'* [V = 147.0, V-expected = 111.0, level of probability (*P*-value) = 0.270, statistical significance $\alpha = 0.01$], *TM-TM'* [V = 76, V-expected = 150.0,

Table 5. Mean, standard deviation and confidence interval for each synthetic index estimated by the bootstrap method

	TM'-index	*W'*-index	*M'*-index	*S'*-index
Reference value	0.522	0.347	0.153	0.285
Bootstrap mean	0.508	0.313	0.145	0.268
Bootstrap SD	0.031	0.044	0.048	0.031
Bootstrap min.	0.456	0.250	0.083	0.209
Bootstrap max.	0.554	0.417	0.236	0.328
Confidence interval	[0.487; 0.528]	[0.285; 0.340]	[0.115; 0.176]	[0.248; 0.288]
Level of probability (*P*-value)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Statistical significance α	0.01	0.01	0.01	0.01
m	20	20	20	20

m – number of resamples

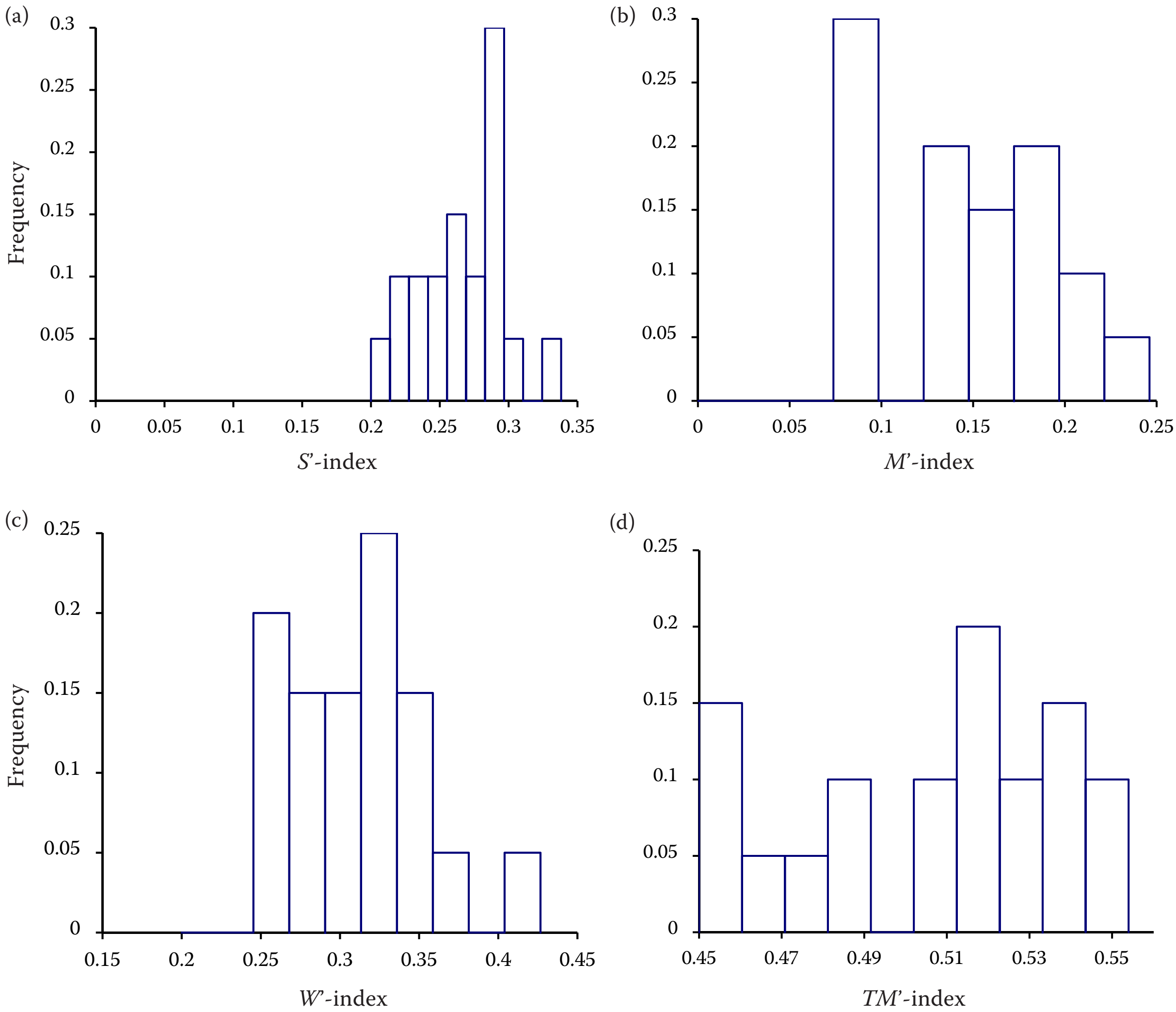

Fig. 3. Histogram of bootstrap means: (a) *S'*-index, (b) *M'*-index, (c) *W'*-index and (d) *TM'*-index

level of probability (*P*-value) = 0.034, statistical significance α = 0.01], and *S*-*S'* [V = 117, V-expected = 150.0, level of probability (*P*-value) = 0.360, statistical significance α = 0.01]. These results demonstrate that the *S'*-index can be used as an alternative to the *S*-index because the differences between the two indices are not statistically significant. The graphic representation of *S*-index and *S'*-index values in Fig. 2 confirms that there are limited differences between the two indices.

CONCLUSIONS

The *S*-index is an interesting tool to evaluate the level of biodiversity of a forest ecosystem in a synthetic way. However, in order to evaluate a forest stand from the ecological – and at the same time – silvicultural point of view it is necessary to associate the values of *S*-index with the brief description of forest stand derived by the individual indices. This information helps to identify the key aspects (i.e. species composition, horizontal structure or spatial distribution of trees) for management in order to maintain the level of biodiversity and to improve the stability of the stands. The use of *S*-index or *S'*-index is related to the time and cost of field surveys and the reliability of the data required. In the analysed plots, the time needed to collect the data for processing the *S'*-index are on average a twelfth (10 min vs. 2 h) of that to collect the data on the entire plot for processing the *S*-index. Furthermore, the time in the field varies depending on the forest density: minimum for open forests and maximum for closed forests.

As expected, the *S*-index is highly important in terms of the horizontal structure, while the most important part of future work on this subject is to integrate the *S*-index with a suitable index of vertical structure such as the tree height diversity (THD) calculated by the Shannon-Weaver's formula (Kuuluvainen et al. 1996) or other similar indices. The inclusion of vertical structure index in the *S*-index would provide an index enabling to consider all the main structural components of a forest stand.

In conclusion, we can state that the proposed index is an interesting and easy tool to monitor the level of biodiversity of a forest affected by management strategies, pests or other natural hazard impacts.

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