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VERTICAL STRUCTURE ASSESSMENT OF SPRUCE ALPINE FORESTS IN THE RHODOPE MOUNTAINS

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Abstract

Forest vertical structure is a characteristic which is of interest for many disciplines and is often discussed in the context of forest ecosystems management. The vertical stratification of tree crowns influences the growth of the single tree and also it determinates the communities thriving beneath the canopy. Close to nature forest management demands the application of silvicultural activities that will maintain the natural structure of the forest. With regard to this, the quantitative assessment of the vertical structure is a particularly important feature. Forest vertical structure is biologically important also because of its relationship with biodiversity. However, the present methods for quantitative analysis are either randomly determined and do not characterize the natural stratification of canopy stand, or they are too time consuming and are developed for analysis on landscape level. The TSTRAT program has been developed in order to define tree stratification in vertical space at stand level. Another approach used for evaluation of structural heterogeneity of stands is the use of different types of indexes. The most commonly applied indexes for vertical structure assessment are *FHD* index, Gini index, Shanon-Winen index, Pielou index and *STVI*. The connection between them and the canopy layer determined by TSTRAT, has not yet been clarified. The correlation between different indexes and canopy stratification determined by TSTRAT is being analyzed in this article. Through the execution of multiple simulations on Monte-Carlo method were determined the bootstrap intervals for each index.

Key words: bootstrap, Foliage Height Diversity **(***FHD***)**, Gini, Pielou, Shannon-Wiener, Structure index based on variance **(***STVI***)**, vertical structure TSTRAT.

Introduction

A vast variety of forest structure is observed in nature, which is a result of forest vegetation adaptation to the complex impact of environment factors. The results from a series of scientific studies confirm the hypothesis that the forest structure is the main factor determining the processes in a forest ecosystem (Jeffrey 1961, Franklin et al. 1981, Oliver and Larson 1996, Kimmins 1997, O'Hara et al. 1996, Spies 1998). According to O'Hara et al. (1996) the conditions which are desirable in a stand, and also satisfy the multifunctional needs, can be expressed the best by its structure. The importance of forest structure and its possible variations in time has always been useful information, which lays in the basis of planning a silvicultural strategy. The term 'stand structure' includes the idea of the location of stand elements (not only trees) in space. Forest can be described by its composition, the vertical and horizontal model of distribution of trees, the age and size of trees (Whittaker 1975, Franklin et al. 1981, Kimmins 1997cvbb). The stand structure can be looked at as a product of forest dynamics and biophysical factors, and at the same time as an engine of the processes in the ecosystem and the biodiversity (Spies 1998). According to contemporary understanding it is a result of autogenic development processes (regeneration, competition, etc.) and disturbances caused by nature's forces nowadays and in the past (Kuuluvainen et al. 1996, Spies 1998).

Although stand structure is most often described through the distribution of trees in width class (O'Hara 1998), vertical structure is also an important feature of forest ecosystems, since it shows key factors such as habitat conditions and ecological processes like competition or natural disturbance regime (Montes et al. 2008). Svensson and Jeglum (2001) use the distribution of trees in height class as a proper criterion of forest structure and the current processes within an ecosystem.

Canopy state, determined through the level of closing and the presence or absence of 'gap' disturbances, is often used to characterize forest vertical structure. The level of canopy closing determines the light regime in the stand and thus influences the understory dynamics, as well as the process of natural regeneration. Canopy disturbances are an important structural element and along with level of canopy closing are used for the differentiation between different phases of forest stands dynamics (Franklin et al. 2002, Oliver and Larson 1996). While the level and condition of canopy closing are important elements of forest structure, they are rather seldom used in literature. Characteristics connected to the size of tree stems such as diameter, height and volume are used in most studies. This, to some extent, shows the connection between stem size and other structural features, such as the LAI index, crown size and the presence of heartwood of different size (Spies 1998) and also is due to the fact that the data about stem size are rather easy to gather.

The vertical location of trees' crowns is one of the most often used features in stands' vertical structure characterization (Brokaw and Lent 1999). A straight subjection has been determined between the foliage height diversity (*FHD*) index, which characterizes the arrangements of leaves within the range of different vertical layers and the variety of bird species (McElhinny et al. 2005). This stimulates the use of *FHD* as a vertical structure measure and its acceptance by some authors for a reliable indicator of biodiversity (Gove 1996, Buongiorno et al. 1994), although there is not much evidence to confirm that *FHD* can explain the differences in the variety of faunistic groups other than birds. Despite the usage of that index there is no standard method for its definition. Different authors use random height classes (McElhinny et al. 2005). An alternative of randomly determined height classes is the use of separate canopy layers (Bebi et al. 2001, McElhinny et al. 2005). Each and every one of these approaches suggests that the separate layers in the canopy can be clearly and consecutively defined.

Parker and Brown (2000) reexamined the idea of 'canopy stratification' in ecological literature and found out that the term had different meaning and methods of definition, which depend on the aims of the specific study. The authors suggested that separate canopy layers should be determined on the basis of ecological gradients, determined by tree crowns (for example, changes in light regime). Vertical stratification of tree crowns is a structural characteristic of stands and determines the distribution of light and precipitation underneath the forest canopy (Latham et al. 1998). It is also used to explain the spatial heterogeneity and time dynamics of understory, to characterize the microclimate differences in the formed gaps and as a factor determining the process of natural regeneration. Vertical structure has also been used for determination of the ecologic niches of different animal and bird species (Ulyshen 2011).

The arrangement and vertical distribution of tree crowns foliage changes during the development of stands, due to different competition and self-thinning rate, release of oppressed trees or the appearance of natural regeneration. Distinct differences in vertical structure in different development phases according to Oliver and Larson (1996) have also been observed by O'Hara et al. (1996). Despite this fact, the differences in vertical structure are often very hard to see, especially in stands dominated by shade tolerant species, which form unbroken vertical stratification (Latham et al. 1998). In this case it is very different to distinguish the differences between the models of vertical stratification, because stands are in a lap between structural phases.

An overview of the literature connected with a description of alpine spruce forests structure in Europe, presented by Kucbel et al. (2008), showed that vertical structure is a key element for the differentiation of phases of forest natural development (Korpel 1995, Hladik et al. 1993). In broad outlines, natural forests are considered structurally heterogenic, compared to managed ones (Svensson and Jeglum 2001). Structural analysis of alpine spruce forests in Babia Hora reserve in Slovakia found out that the self-thinning phase is characterized with the most differentiated vertical structure. As the altitude increases the differences between the vertical structures of stands in regeneration phase and Old growth forests decrease, while the differences between self thinning phase and the other phases become more and more distinguishable (Merganič et al. 2011).

Thorough studies on the vertical structure of alpine forests in our country are missing. Most often canopy stratification is illustrated by profile diagrams (Rafailov 2003). This approach can be used for the clarification of some common models of stand development, such as vertical differentiation of tree crowns in layers or classes but it is impossible to use for quantitative analyses of the structural heterogeneity of different stands. For this purpose the distribution of the basal areain height classes or canopy layers and the number of formed horizons are used, as well as the calculation of height variation coefficient, *FHD* index, Gini index, Shanon-Winen index, *STVI* (Zenner and Hibbs 2000).

Study Area

The aim of the present study is characterization of natural alpine spruce stands vertical structure in the Rhodope Mountains. The research was conducted in relatively undisturbed natural spruce stands.

The main criteria for the selection of studied stands were:

- Stands should be located in subalpine spruce forests;

● Stands should be representative for the variety of forest structures in spruce forests;

● They should be more than 80–100 years old;

● Stands should be a result of natural regeneration.

On the basis of the criteria pointed out, three sites located in the highest parts of the Rhodope Mountains were chosen – the foot of Goliam Perelik peak (2190.2 m), Goliama Siutka peak (2185.8 m) and Goliam Persenk peak (2094.5 m). The first site is located at the foot of Goliam Perelik peak. Since forest massifs in this part of the Rhodope Mountains are highly influenced by human activity in the past, two Permanent Sample Plots (PSP) were founded established. One of them is in the territory of ’Sokucheto‘ reserve, declared as a reserve with order No 508/28.03.1968 and total area of 177.5 ha and altitude between 1400 and 1700 m. The spruce forests in that region were identified as Acidophilic *Picea abies* forests in the mountainous and alpine belts (*Vaccinio-Piceetea*) according to NATURA 2000 classification of natural habitats. The second site is located at the foot of Goliam Persenk peak. There are three PSPs in this site. The spruce stands belong to ‘Roman road’ protected territory. The third site includes spruce stands in the territory of ‘Beglika’ reserve (Order No 751/11.05.1960), located in Western Dospat-Batak region of Western Rhodope subarea. General characteristics of SP are presented in Table 1.

Table 1. Sites and trial areas.

Sample plot	Geographic coordinates		Altitude, m	Exposure	Slope, °	Soil type	Site type*
	X	Y					
‘Beglika’ reserve							
BG1	41522381	24024066	1850	SE	7	Umbric Cambisols	B_2(85)
BG2	41521988	24030089	1750	W	12	Distric Eutric Cambisols transitional	C_2(82)
BG3	41530885	24014684	2100	SW	2	Plan – Umbric Cambisols	C_3(86)
DGS ‘Hvoina’							
HV1	41495954	24330482	1850	S	5	Distric Eutric dark	B_2(83)
HV2	41495191	24332406	2050		5	Plan – Umbric cambisols	B_2(87)
HV3	41495535	24331522	1950	NE	3	Plan – Umbric cambisols	$CD_{2,3}$(84)
‘Soskucheto’ reserve							
PR1	41363444	24374496	1700	SW	4	Distric Eutric transitional	C_2(82)
PR2	41363375	24355159	2000	NE	6	Plan – Umbric cambisols	C_3(86)

Note: *A–D – richness of the soil in ascending order; 0–4 – soil moisture in ascending order; (82–87) – number of site indexes.

Method

According to O'Hara et al. (1996) vertical structure assessment requires the appliance of different methods and approaches. According to them, agreement and consistency on stand characterization for different purposes still have not been reached. The authors pointed out the need of new approaches for structure description that will include development of models of crown dynamics, foliage distribution in space and classification, based on growth and competition. In this study were used complex methods including the use of vertical tree stratification program, TSTRAT (Latham et al. 1998, Lazarov 2002) and the definition of a group of indexes used for evaluation of stands' structural heterogeneity (Valbuena et al. 2012, Staudhammer and LeMay 2001, Pommerening 2002, Neumann and Starlinger 2001). The diameters, heights and lengths of the crowns in each width class measured in the sample plots were used as initial data.

TSTRAT has been developed for the quantitative determination of vertical structure of stands. The program simulates natural vertical arrangement of tree crowns and is used for the identification of stands' vertical layers, which are biologically connected to the process of natural stratification. TSTRAT algorithm determines multiple points of interruption based on tree height and crown length and thus arranges separate trees in vertical layers depending on the relative position of their crowns and these interruption points. The interruption points are based on the competition zones of the crowns, where most of the photosynthesis runs. For competition zone between trees has been determined a part of the crown, including 60 % of its length. Each canopy layers horizon is characterized by basic statistic indexes – average diameter, height, crown length and circular surface.

In the last decade there has been a trend towards wider appliance of the use of a number of indexes for forest structure variety (Buongiorno et al. 1994, Kuuluvainen et al. 1996, Latham et al. 1998, Pretzsch 1999, Neumann ahd Starlinger 2001, Lazarov 2002, Barbeito et al. 2009). These indexes usually, used in population ecology, are appropriate for quantitative evaluation of stand structure complicity. The use of indexes allows making direct comparisons and at the same time provides a relatively easy way for structure control with different management strategies.

For the assessment of vertical structure of observed stands the following indexes were calculated:

Shannon-Wiener index (1) widely used in ecology studies and proved to be a good index of structural complicity of forests (Kuuluvainen et al. 1996).

$$H' = -\sum p_i \ln p_i \quad (1),$$

where p_i– relative basal area in i height class.

Pielou index (2) (Pielou 1969) is derived from Shannon-Wiener's index but is easier to interpret since it varies in the interval 0÷1 and its maximal value corresponds to the maximal heterogeneity (variety).

$$J = \frac{-\sum p_i \ln p_i}{\ln S} = \frac{H'}{\ln S} \quad (2),$$

where S – number of height classes.

Gini index (3) is used as a measure of structural heterogeneity (Latham et al. 1998, Dixon et al. 1987). The values of the index belong to the interval 0÷1 and 1 shows the maximal possible theoretical variety.

$$GC = \frac{\sum_{1}^{n}(2j-n-1)H_i}{\sum H_i(n-1)} \quad (3),$$

where:

i – separate tree height class determined in ascending order;

H_i– height of the *i* tree;

n – number of trees.

FHD index (4) (foliage height diversity) (McElhinny et al. 2005). When this index is calculated, the separate height classes are adopted to be identical with phytocenotic horizons shared with TSTRAT program, as instead the foliage surface, for each horizon has been used the basal area of trees included. This substitution has been made possible since the proportional coherence between foliage surface and stem diameter is well-known (Whitehead 1978).

$$FHD = -\sum W_S \ln W_S \quad (4),$$

where W_s – relative basal area (foliage area) in corresponding horizon *s*.

STVI index (5) (Staudhammer and LeMay 2001, Barbeito et al. 2009) – it does not use height classes and therefore is considered more objective index for structural heterogeneity.

$$STVI_h = \begin{cases} 1-\left(\dfrac{S_{hu}^2 - S_h^2}{S_{hu}^2}\right)^{p_1}, when\ S_h^2 \le S_{hu}^2 \\ 1-\left(\dfrac{S_h^2 - S_{hu}^2}{m \cdot S_{h\max} - S_{hu}^2}\right)^{p_2}, when\ S_h^2 > S_{hu}^2 \end{cases} \quad (5),$$

where: $S_{hu}^2 = \frac{(b-a)^2}{12}$ is the theoretical variation of tree distribution in height in uniform distribution;

$S_{h\max}^2 = \frac{(b-a)^2}{4}$ is theoretical variation of distribution of tree number in height in bimodal distribution;

$S_h^2 = \frac{\sum_{j=1}^{n} w_j \cdot (H_j - \overline{H})^2}{\sum_{j=1}^{n} w_j}$ is actual variation in height, expressed by w_j – correlation between the circular surface of the *j* tree and the total circular surface in the trial area;

H_j is height of *j* tree from the trial area;

$\overline{H}$ is average height;

a is smallest height measured;

b is greatest height measured;

p_1= 2.40094 is a constant;

p_2 = 1.1281 is a constant.

The statistical analysis includes calculation of a correlation matrix for structural variety indexes. The analysis of variation is used for calculation of the correspondence between canopy stratification with TSTRAT program and calculated indexes. Due to the relatively small volume of the extracts the confidential intervals for indexes with identified practical importance are calculated through the bootstrap procedure (Leisch 2013). Bootstrap procedure is implemented by the method Monte-Carlo. The term Monte-Carlo depicts computational techniques based on simulation procedures. These techniques have become an essential part of the statistician's toolbox. Bootstrap in particular is a highly useful procedure, as it mimics sampling techniques that utilize repeated randomization of a real sample. The biological concept is critical when applying the bootstrap procedure, as it provides solutions to particular problems through statistical means. The illustration of index variation is presented by the box-plot diagrams of Tukey.

Results

TSTRAT graphics show a general picture of tree arrangement is DBH classes in the air space. The number of horizons, obtained as a result of competition analysis, gives the evaluation of stand structure complicity. The graphic image of tree width and the length of its crown provides visualization about the position of trees in the stand hierarchy according to their width class and also opportunity to foresee the ways of development (e.g. small height and small crown suggests higher possibility for the tree to drop off). Indicators for competition activation are: increase of stem self-pruning parts percentage; smaller crown length of trees of lower DBH classes and complication of vertical structure, expressed through increase in the number of horizons.

TSTRAT diagrams for two types of structure: stands with two or three formed horizons are presented in Fig. 1. The application of TSTRAT is delimited. The specific cases, which represent respectively the initial and final phase of stand development, show some resemblance in the heterogeneity classes in the vertical structure (Lazarov 2002).

The combination between the lowest level of heterogeneity of vertical structure (one canopy horizon) and the lowest level of diameter variations can be accepted as typical feature of the stand initiation phase. In the present article the type of diameter distribution is not examined and therefore the stands have not been classified according to the dynamics of their natural regeneration. The certain canopy horizons are basis for the evaluation of how adequate are the calculated different types of vertical structure assessment indexes.

The calculated indexes give assessment of structural heterogeneity of the stand according to its height. The data are presented in Table 2 along with the determined by TSTRAT canopy horizons, as well as the variation coefficient (*Wh*) for every sample plot.

The range of variation intervals of the separate indexes is different, as well as their medians (Fig. 2). It is clear that the sensibility of the indexes is represented in a different range.

With minimal variation scope is Gini index, and Shannon and *FHD* indexes vary considerably. For some of the indexes that variation is symmetrical, while for others the symmetry is broken. This raises the question about synchrony in variation, which has been studied through correlation analysis.

After the conducted correlation analysis a statistically important positive correlation has been determined between Shannon and Pielou indexes. It ensues from the way both indexes have been formulated, not from their different biological sense. Between Shannon and Gini indexes, a statistically important positive correlation has been determined, while despite the wide use of *FHD* and *STVI*, none such correlation has been established between them. Table 3 visualizes that in spite of how close Shannon and Pielou indexes are the correlation between Pielou and Gini indexes has turned out to be statistically insignificant. This fact should be looked at as an indication of the necessity of calculation of number of indexes instead of single ones.

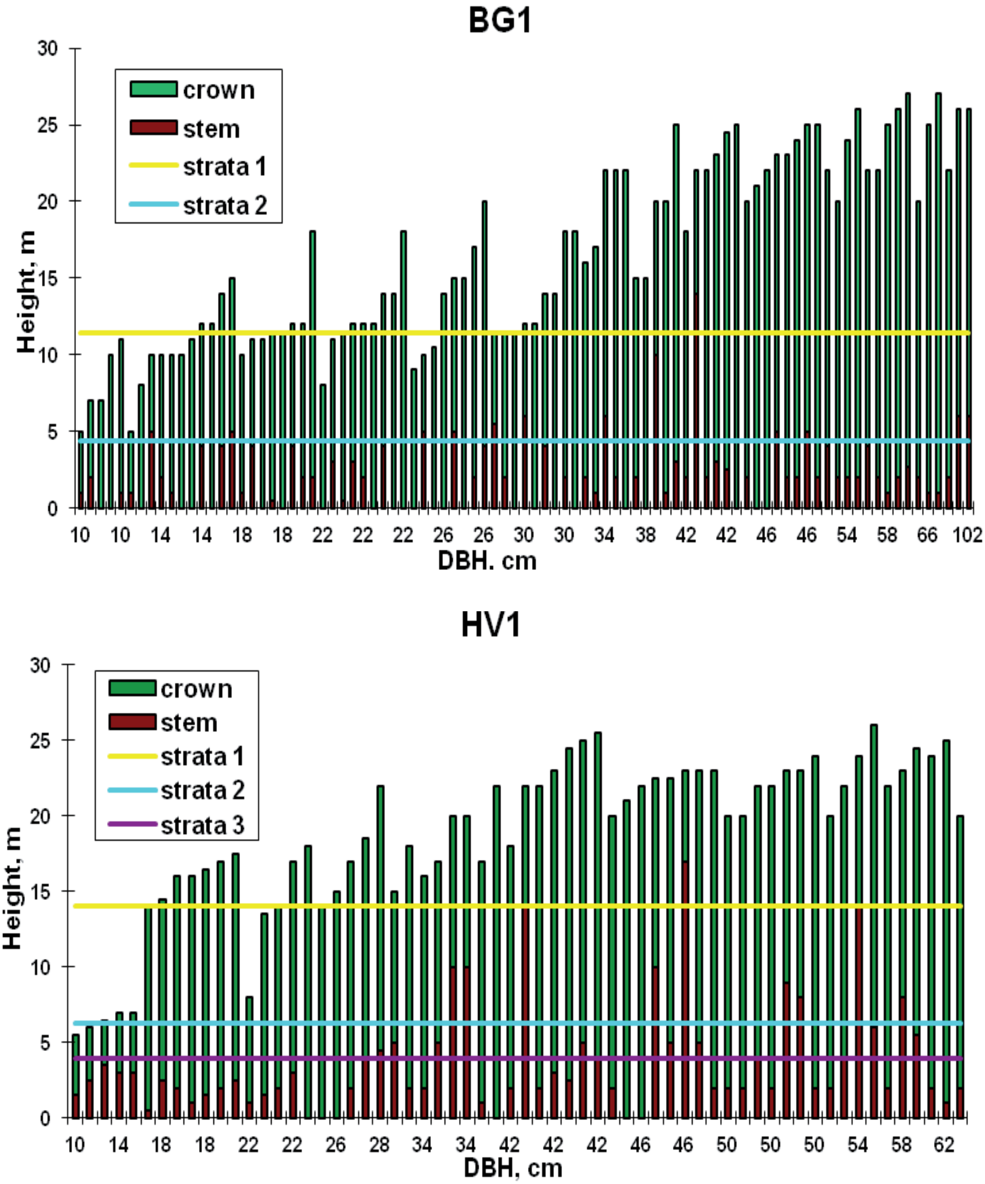

Fig. 1. TSTRAT diagrams for two types of structure.

In order to identify the correlation between indexes and determined by TSTRAT canopy horizons, an ANOVA analysis has been conducted (Table 4). It has been determined that the values of Shannon index statistically significantly (p=0.023) depend on the canopy stratification.

To determine the confidence interval

Table 2. Results from TSTRAT data analysis in trial areas (TA).

Sample plot	Shannon Index	Pielou Index	*STVI*	*GINI*	*FHD*	TSTRAT	*Wh*
BG1	1.3937	0.7779	0.6842	0.215	0.412	2	35,051
BG2	1.1968	0.7436	0.9958	0.196	0.544	2	36,642
BG3	0.8560	0.6175	0.8814	0.113	0.603	2	25,811
HV1	0.9791	0.6084	0.8175	0.145	0.640	3	28,462
HV2	0.8112	0.5041	0.6880	0.121	0.781	3	23,246
HV3	0.8701	0.5406	0.7547	0.161	0.488	3	38,526
PR1	0.7276	0.4521	0.7692	0.235	0.610	3	35,057
PR2	1.2732	0.7911	0.8806	0.223	0.566	2	40,374
Tp1	1.0980	0.6128	0.6941	0.213	0.435	2	36,666
Tp2	1.0238	0.6361	0.8036	0.205	0.460	2	35,395
Tp3	0.9359	0.6751	0.9364	0.157	0.235	2	24,891
Tp4	0.7834	0.4868	0.6887	0.142	0.518	3	27,371
Tp4.2	1.0403	0.6464	0.9224	0.201	0.442	3	31,291
Tp5	1.0090	0.6269	0.9859	0.179	0.510	3	37,434

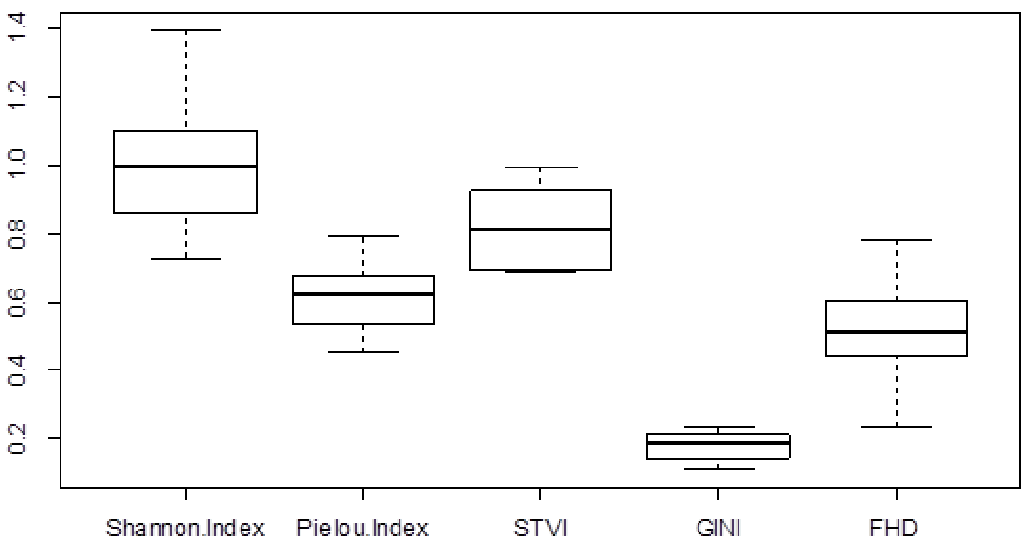

Fig. 2. Box-plot diagrams for the variation of separate indexes.

of Shannon index, which is needed for its comparative characteristic formed by strata with TSTRAT bootstrap procedure is implemented by the method Monte-Carlo. The results are presented graphically in Fig. 3. From the resulting intervals it is clear that Shannon index can be used as an objective evaluator of height forest

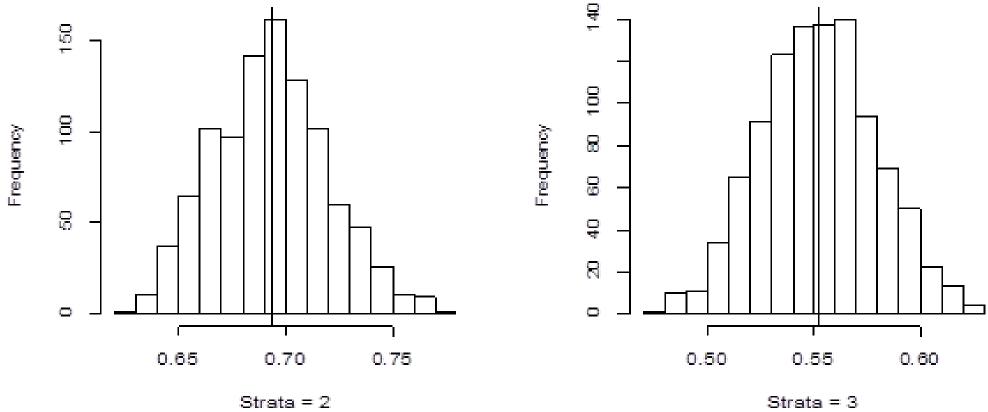

Fig. 3. Bootstrap intervals of Shannon index in canopy stratifications.

structure in terms of canopy stratification.

The figure shows that both confidence intervals do not overlap significantly, i.e. Shannon index clearly has a different range of variation for both strata's.

ANOVA analysis (Table 5) applied to Pielou index found statistically significant (p = 0.00459) variation between the levels of strata obtained by TSTRAT and the index value.

The designed bootstrap intervals for this index are presented in Fig. 4. The lack of overlapping between both intervals determines that index as a better indicator of structural heterogeneity and canopy stratification.

ANOVA analysis applied to Gini index does not show a statistically proved variation in horizons. However, the bootstrap procedure shows certain differences in the index distribution in both horizons (Fig. 5).

The solid lines show the average values of Gini index for both strata. Despite overlapping histograms, Monte-Carlo simulation shows that low values of Gini are more typical for strata 3 and outlines both index ranges.

Table 3. Correlation matrix of the used indexes.

Index	Shannon	Pielou	*STVI*	*GINI*	*FHD*
Shannon	1.0000	0.9209	0.1774	0.5305	-0.3265
Pielou		1.0000	0.4466	0.3627	-0.4002
STVI			1.0000	0.0497	-0.2205
GINI				1.0000	-0.3163
FHD					1.0000

Table 4. Shannon-index ANOVA.

Source of Variation	*Df*	Sum *Sq*	Mean *Sq*	*F* value	*Pr* (>*F*)
Strata	1	0.1731	0.1731	6.7870	0.023*
Residuals	12	0.3060	0.0255		

Table 5. Pielou-index ANOVA.

Source of Variation	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Strata	1	0.0699	0.0699	12.0700	0.00459 **
Residuals	12	0.0694	0.0058		

Note: `Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

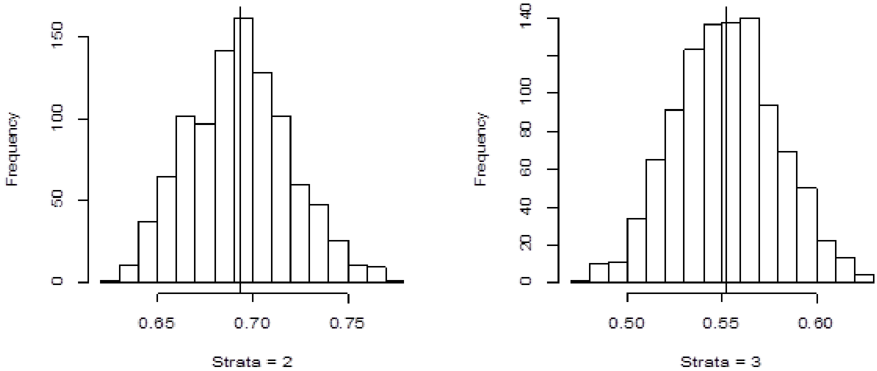

Fig. 4. Bootstrap intervals of Pielou index in the canopy stratifications.

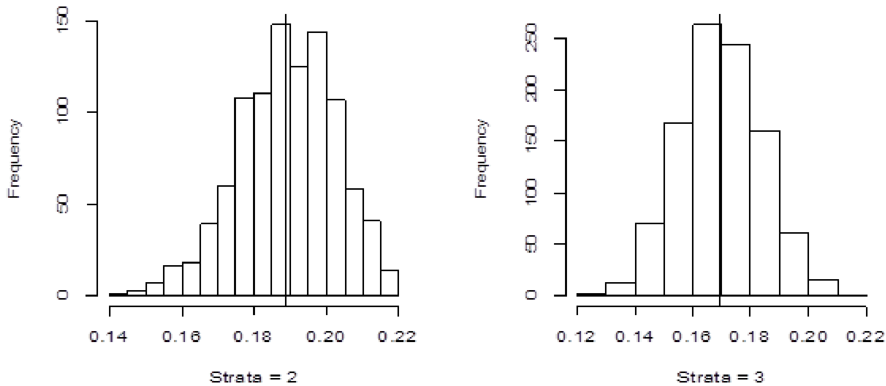

Fig. 5. Bootstrap intervals of Gini index in canopy stratifications.

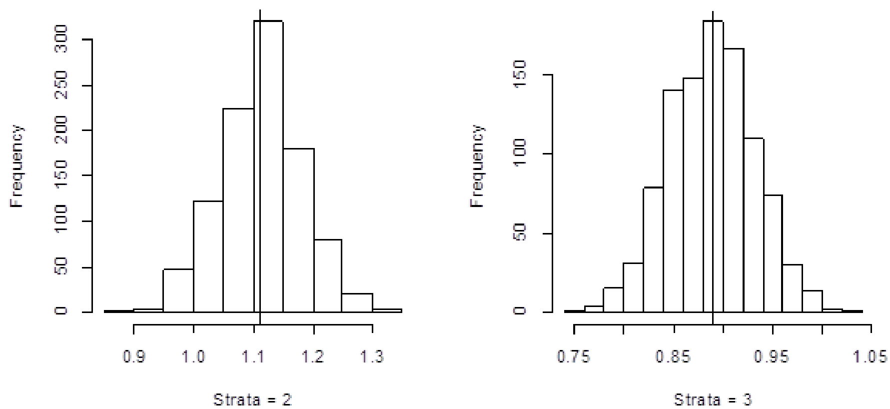

Fig. 6. Bootstrap intervals of Gini index in strata based on Shannon index.

The determined statistically significant correlation between Shannon and Gini indexes, allows the following approach towards the confidential interval of Gini index: We are trying to create a model for the correlation between both indexes – Shannon and Gini, using data for both strata numbers 2 and 3. The model was statistically significant with *F*-statistic: 4.7 on 1 and 12 *Df*, and *p*-value: 0.05099 – very close to 95 % level of significance.

This means that it can be build a bootstrap interval for Gini index indirectly using two bootstrap simulations for Shannon index to the respective strata and calculating Gini-bootstrap values under the received straight line model (Fig. 6.).

This means that we can build a bootstrap interval for Gini index indirectly using two bootstrap simulations for Shannon index to the respective strata and calculating Gini-bootstrap values under the received straight line model.

Conclusion

The correlation analysis of the most commonly used indexes for assessment of structural variation in height and the obtained results through TSTRAT program confirmed a strong correlation between Shannon-Wiener index, Pielou and Gini indexes. These may be used successfully for evaluation of stands' vertical structure. On the basis of the data calculated by TSTRAT program application for alpine spruce forests in the Rhodope Mountains and the calculated indexes for the same sample plots, and through the application of a bootstrap procedure and multiple simulations through Monte-Carlo method, the intervals of variation of indexes were determined. Pielou index turned out to be the best indicator of canopy stratification in the observed stands. The use of this index, along with Gini one, as an assessment of the structural irregularity of stand height, as well as the graphic visualization through TSTRAT diagrams, enables the making of a complex evaluation of forest vertical structure. Thus, the changes in forest structure after different forestry impacts or natural disturbance can be evaluated and also the natural development phase of the forest may be determined.

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References

Barbeito I., Canellas I., Montes F. 2009. Evaluating the behavior of vertical structure indices in Scots pine forests. Annals of Forest Science 66, 710 p.

Bebi P., Kienast F., Schönenberger W. 2001. Assessing structures in mountain forests as a basis for investigating the forest's dynamics and protective function. Forest Ecology and Management 145(1–2): 3–14.

Brokaw N.V.L., Lent R.A. 1999. Vertical structure. In: Hunter I., Malcom L. (Eds.), Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge: 373–399.

Buongiorno J., Dahir S., Lu H., Lin C. 1994. Tree size diversity and economic returns in uneven-aged forest stands. Forest Science 40: 83–103.

Dixon P.M., Weiner J., Mitchell-Olds T., Woodley R. 1987. Bootstrapping the Gini coefficient of inequality. Ecology 68: 1548–1551.

Franklin J.F., Cromack K.J., Denison W., McKee A., Maser C., Sedell J., Swanson F., Juday G. 1981. Ecological Characteristics of Old-Growth Douglas-Fir Forests. USDA Forest Service General Technical Report 118, 48 p.

Franklin J.F., Spies T.A., Van Pelt R., Carey A.B., Thornburgh D.A., Berg D.R., Lindenmayer D.B., Harmon M.E., Keeton W.S., Shaw D.C., Bible K., Chen J. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-Fir forests as an example. Forest Ecology and Management 155: 399–423.

Gove J.H. 1996. Optimising the management of uneven-aged Spruce-Fir stands while preserving structural diversity. In: Bachmann P., Kohl M., Paivinen R. (Eds.), Assessment of Biodiversity for Improved Forest Planning. Kluwer Academic Publishers, Monte Verita, Switzerland: 123–134.

Hladik M., Korpel S., Lukac T., Tesar V. 1993. Management in mountain forests. Matice lesnicka Pisek, 123 p.

Jeffrey W. 1961. Origin and structure of some white spruce stands on the lower Peace River. In: Gap dynamics of forest trees: A review with particular attention to boreal forests. 2001. McCarthy J. Environmental Reviews 9(1): 1–59.

Kimmins J.P. 1997. Forest ecology. A foundation for sustainable management. Prentice-Hall, New Jersey, 560 p.

Korpel S. 1995. Die Urwealder der Westkarpaten. In: Selection Management of Forests. 2003. Rafailov G. Publishing house of University of forestry, 213 p. (In Bulgarian).

Kucbel S. Vencurik, J., Jaloviar P., Kuris P. 2008. Analysis of the structure of a subalpine protection forest in the Low Tatra Mts. Acta Facultatis Forestalis Zvolen L 2: 57–65.

Kuuluvainen T., Penttinen A., Leinonen K., Nygren M. 1996. Statistical opportunities for comparing stand structural heterogeneity in managed and primeval forests: An example from boreal spruce forest in southern Finland. Silva Fennica 30(2–3): 315–328.

Latham P.A., Zuuring H.R., Coble D.W. 1998. A method for quantifying vertical forest structure. Forest Ecology and Management 104(1): 157–170.

Lazarov S. 2002. Study of the prerequisites for selection management of young fir-spruce stands in the Western Rhodopes. PhD Thesis, Sofia, 135 p. (In Bulgarian).

Leisch F. 2013. S original, from StatLib and by Rob Tibshirani. (bootstrap: Functions for the Book 'An Introduction to the Bootstrap'. R package version 2012.04-1. Available: http://CRAN.R-project.org/package=bootstrap

McElhinny C., Gibbons P., Bauhus J., Brack C. 2005. Forest and woodland stand structural complexity: Its definition and measurement. Forest Ecology and Management 218: 1–24.

Merganič J., Merganičová K., Vorčák J. 2011. Height structure of spruce mountain forests of Babia hora – Oravské Beskydy. Beskydy 4(1): 27–38.

Neumann M., Starlinger F. 2001. The significance of different indices for stand structure and diversity in forests. Forest Ecology and Management. 145: 91–106.

O'Hara K.L. 1998. Silviculture for structural diversity: a new look at multiaged? systems. Journal of Forestry 96(7): 4–10.

O'Hara K.L., Latham P.A., Hessburg P., Smith B.G. 1996. A structural classification for inland northwest forest vegetation. Western Journal of Applied Forestry 11(3): 97–102.

Oliver C.D., Larson B.C. 1996. Forest Stand Dynamics. McGrawHill, New York, 520 p.

Parker G.G., Brown M.J. 2000. Forest Canopy Stratification – Is It Useful? The American Naturalist 155: 473–484.

Pommerening A. 2002. Approaches to quantifying forest structures. Forestry 75(3): 305–324.

Pretzsch H. 1999. Structural diversity as a result of silvicultural operations. In: Olsthoorn A.F.M., Bartelink H.H., Gardiner J.J., Pretzsch H., Hekhuis H. J. & Franc A. (Eds.)

Management of mixed of mixed species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN – DLO), Wageningen: 157–174.

Rafailov G. 2003. Selection Management of Forests. Publishing house of University of forestry, 213 p. (In Bulgarian).

Spies T.A. 1998. Forest structure: a key to the ecosystem. Northwest Science 72: 34–39.

Staudhammer C.L., LeMay V.M. 2001. Introduction and evaluation of possible indices of stand structural diversity. Canadian Journal of Forest Research 31(7): 1105–1115.

Svensson J.S., Jeglum J.K.. 2001. Structure and dynamics of an undisturbed old-growth Norway spruce forest on the rising Bothnian coastline. Forest Ecology and Management 151(1–3): 67–79.

Ulyshen M.D. 2011. Arthropod vertical stratification in temperate deciduous forests: Implications for conservation-oriented management. Forest Ecology and Management 261(9): 1479–1489.

Valbuena R., Packalen P., Martin-Fernandez S., Maltamo M. 2012. Diversity and equitability ordering profiles applied to study forest structure. Forest Ecology and Management 276: 185–195.

Whitehead D. 1978. The Estimation of Foliage Area from Sapwood Basal Area in Scots Pine. Forestry 51(2): 137–149.

Whittaker R.H. 1975. Communities and Ecosystems. 2nd edition, MacMillan, Ney York, 385 p.

Zenner E.K., Hibbs D.E. 2000. A new method for modeling the heterogeneity of forest structure. Forest Ecology and Management 129: 75–87.