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Technical note

How to improve forest biodiversity management by comparing broad-scale stands' structural spatial heterogeneity between two forests

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ABSTRACT This article aims to propose a methodological approach to the determination of differences in structural spatial heterogeneity between two different forests, exhibiting differences in some characteristics. By comparing the variances of the Gini-Simpson index values calculated from diameter at breast height (DBH) or tree height distributions in randomly sampled plots, structural differences can be effectively quantified. An F-test is employed to compare these variances, and while we use the Gini-Simpson index as an example, our method is flexible and can be applied using any chosen diversity index appropriate for the user's specific research context. A case study was conducted in *Fagus sylvatica* L. stands in the central Rhodope mountains, Greece, using plots from high productivity and medium productivity sites. The results showed significantly greater variance in Gini-Simpson index values in medium productivity sites compared to high productivity sites, indicating higher spatial diversity heterogeneity. This straightforward method requires only basic DBH or tree height data, making it practical for integration into forest stand structure studies and aiding in informed forest management decisions. The approach provides a statistically sound and flexible tool for comparing structural spatial heterogeneity across different forests, potentially guiding practices aimed at enhancing stand complexity and ecological resilience.

KEYWORDS: Spatial heterogeneity, biodiversity indices, biodiversity management, variance, DBH distributions.

Introduction

Stand structure profoundly influences forest biodiversity by affecting forest abiotic conditions, such as climatic conditions under the tree canopy, and the presence of living and dead biomass (Dafis 1986, Oliver and Larson 1996, Barnes et al. 1998, Lindenmayer and Franklin 2002, O'Hara 2014). Recognizing this, researchers have leveraged stand structure parameters to develop tools for biodiversity assessment in forests (Gao et al. 2014, Bourma et al. 2023, Milios and Kitikidou 2025). These stand structure characteristics can thus reliably serve as biodiversity indicators, providing additional insights into species diversity and enabling a more comprehensive understanding of forest biodiversity (Gao et al. 2014, Ćosović et al. 2020).

However, simpler stand structures fall short in supporting the ecosystem values and processes found in more complex structures (O'Hara 2014). The complexity and heterogeneity of stand structures are strongly linked to a forest's capacity to support biodiversity (Lindenmayer and Franklin 2002). One key aspect of this structural complexity is stand structure diversity, which can be assessed using biodiversity indices that analyze distributions of structural characteristics such as diameter at breast height (DBH) (Kitikidou et al. 2022, Petrou et al. 2023). Such indices determine structural diversity based on the number and evenness of the structural attribute classes distribution (Berger and Parker 1970, Jost 2006, Kitikidou et al. 2022, Kitikidou et al. 2024).

A crucial stand structural attribute related to forest biodiversity is structural spatial heterogeneity, which refers to the variation in the physical structure of a forest ecosystem across different spatial scales. This includes differences in tree species, tree sizes (e.g., DBH and height), canopy layers, and the distribution of these elements within the forest, extensively discussed throughout the book by Lindenmayer and Franklin (2002), and does not pertain to geographic coordinates. Such heterogeneity is a key component of forest complexity and has several important implications:

(i) Habitat Diversity: Structural spatial heterogeneity provides a variety of microhabitats that support different species, thus contributing to greater overall biodiversity (Lindenmayer and Franklin 2002).
(ii) Ecological Resilience: Forests with greater structural spatial heterogeneity tend to be more resilient to disturbances, ensuring the stability and continuity of ecosystem functions (Franklin et al. 2002).
(iii) Resource Utilization: Diverse structural traits facilitate more efficient resource utilization within the ecosystem, supporting both shade-tolerant and light-demanding species (MacArthur and MacArthur 1961).
(iv) Ecosystem Services: Forests with high structural heterogeneity enhance ecosystem services such as carbon sequestration, water regulation, and soil fertility (Mori et al. 2012).

Understanding and quantifying structural spatial heterogeneity is critical for effective forest biodiversity management and conservation. However, traditional biodiversity indices do not account for the spatial variability of stand structure. As Gadow et al. (2012) note, complex spatial structures are more challenging to describe using simple frequency distributions. This gap necessitates novel approaches that incorporate spatial variability to accurately assess and manage forest biodiversity.

Current biodiversity indices such as the Shannon

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index (Shannon 1948), Simpson index (Simpson 1949), Gini-Simpson index (Jost 2006), and various other indices often fail to capture the nuances of DBH distribution variability within stands. Exploring the variance of these indices offers a novel approach to examining within-stand variability. A higher variance suggests a more spatially heterogeneous forest structure, whereas a lower variance indicates a more homogeneous structure.

Spatial structure in forests can be evaluated based on the relationships among neighboring trees (Pommerening 2002, Gadow et al. 2012). However, structural spatial heterogeneity at broader scales, such as forests that spread over hectares, tens of hectares, or even more, is not solely determined by differences among adjacent trees or trees growing in neighboring groups (McElhinny et al. 2005).

Our study proposes a methodological approach to distinguish differences in structural spatial heterogeneity between forest areas. While we utilize the Gini-Simpson index as an exemplar in this work, our method is flexible and can be applied using any chosen diversity index appropriate for the specific research context. By comparing the variances of these index values from DBH or tree height distributions in randomly sampled plots, our method can effectively quantify spatial structural differences. An F-test is employed to compare these variances, offering a robust means to address the spatial variability that conventional indices overlook. This method can fill the existing gaps by integrating the concept of structural spatial heterogeneity into the analysis of forest stand structures, thus facilitating a better understanding and management of forest biodiversity.

Materials and Methods

To measure the stand complexity of forests, we used biodiversity index values calculated from distributions of a structural characteristic measured in sample plots. The variance of these biodiversity index values from the plots serves as a measure of stand structural spatial heterogeneity. By comparing the variances of biodiversity index values between different forests, we can assess the differences in their structural spatial heterogeneity.

As an exemplar application of the proposed method for investigating differences in stand structural spatial heterogeneity, we used the Gini-Simpson index as the biodiversity measure. The Gini-Simpson index has the formula

$$GS = 1 - \sum_{i=1}^{R} p_i^2 ,$$

where R is the number of DBH classes, p_i is the proportion of individuals of DBH class i. It ranges from 0 to 1, and values closer to 0 indicate lower diversity (Jost 2006, Kitikidou et al. 2022). Data were collected from ten plots established in *Fagus sylvatica* L. stands in the central Rhodope mountains, Greece (Milios 2000). Five plots of 500 m^2 were randomly set up in high productivity sites, and another five in medium productivity sites (Milios 2000). To measure the stand complexity of forests, we used biodiversity index values calculated from distributions of DBHs measured in sample plots. The variance of these biodiversity index values from the plots serves as a measure of stand structural spatial heterogeneity. By comparing the variances of biodiversity index values between different forests, we can assess the differences in their structural spatial heterogeneity. We also note that proposed method for comparing stands' structural spatial heterogeneity is independent of the specific sampling method, plot size, or extent where the forest sites within the plots were set up (McElhinny et al. 2005). The method is focusing only on the variance of biodiversity indices between the chosen forests to evaluate structural spatial heterogeneity, independently of anything else.

Following established classifications, we categorized the productivity of our study sites based on environmental conditions influencing tree growth. In this context, we defined as high productivity sites the forest areas characterized by optimal environmental conditions, including soil characteristics. These factors collectively support rapid and vigorous tree growth. On the other hand, we defined as medium productivity sites the forest areas with moderate environmental conditions. These conditions are not as optimal as in high productivity sites, resulting in moderate rates of tree growth. Productivity classifications for the plots used in this exemplar application are described in detail in Milios (2000).

The DBHs of living trees in each plot were classified into 4 cm width classes (e.g., the DBH class of 6 cm includes DBHs in the range [4, 8), the DBH class of 10 cm includes DBHs in the range [8, 12), and so on). For each plot, a DBH distribution was created (Tab. 1).

For each plot, the Gini-Simpson index was calculated using the template created by Kitikidou et al. (2022). These indices are then grouped into two variables:

(i) GS_1: Gini-Simpson indices in the plots of the high productivity sites (sample size n_1).
(ii) GS_2: Gini-Simpson indices in the plots of the medium productivity sites (sample size n_2).

We assessed the equality of variances between GS_1 and GS_2 with the following procedures:

- If GS_1 and GS_2 are normally distributed: We would perform an F-test, where F is distributed with (n_1-1), (n_2-1)) degrees of freedom (Snedecor and Cochran1989).
- If GS_1 or GS_2 are not normally distributed: We would transform the data as follows:

$$ZGS_1 = \left| GS_1 - \overline{GS_1} \right|$$

$$ZGS_2 = \left| GS_2 - \overline{GS_2} \right|$$

where $\overline{GS_1}$ and $\overline{GS_2}$ are the average of GS1 and GS2, respectively; then, we would use the F-test on these transformed variables (Levene 1960).

In any case, the p-value is computed for the F-distribution $F = var_2 / var_1$, where var_2 and var_1 are the variances of GS_2 and GS_1, respectively.

Table 1 - Data of DBH distributions of the plots established in high productivity and in medium productivity sites.

DBH class (cm)	Number of trees in the plots of high productivity sites					Number of trees in the plots of medium productivity sites				
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5
6	0	0	0	0	0	0	5	14	6	0
10	0	0	0	0	0	0	2	2	3	0
14	2	0	0	0	0	0	4	1	7	0
18	2	2	0	0	1	0	2	6	3	0
22	1	2	0	0	0	0	2	0	4	2
26	6	3	3	0	1	0	2	3	4	3
30	5	5	0	1	0	1	6	0	5	4
34	1	4	1	3	2	1	2	0	2	3
38	1	2	2	2	0	9	1	1	2	3
42	4	2	2	2	3	0	1	0	0	2
46	2	0	1	1	4	1	2	1	0	0
50	0	0	1	2	0	1	1	1	0	0
54	1	2	1	0	1	0	0	1	0	0
58	0	0	0	0	0	1	0	1	0	0
62	0	0	0	0	0					
66	0	0	0	0	1					

Results

The trees in the plots of the high productivity site have a mean DBH of 34.77 cm, a standard deviation of DBH of 10.42 cm, a minimum DBH of 13 cm, a maximum DBH of 65 cm, and a basal area of 33.90 m^2/ha. The trees in the plots of the medium productivity site have a mean DBH of 23.42 cm, a standard deviation of DBH of 13.78 cm, a minimum DBH of 4 cm, a maximum DBH of 58 cm, and a basal area of 29.64 m^2/ha. In our case study of the proposed method, the variables GS_1 and GS_2 (Tab. 2) were found to be normally distributed (p-values for the Jarque-Bera normality test were 0.4317 and 0.3694, respectively, both greater than 0.05). Thus, we applied the F-test for GS_1 and GS_2, resulting in a p-value of 0.0026. This indicates a statistically significant difference in the variance of Gini-Simpson index values between the stands of the two site productivity types (Tab. 2).

Table 2 - Gini-Simpson index values in the high productivity and medium productivity sites.

	GS_1	GS_2
Plot 1	0.8512	0.5612
Plot 2	0.8554	0.8844
Plot 3	0.8264	0.7388
Plot 4	0.8099	0.8704
Plot 5	0.8047	0.8235

The stands of the medium productivity sites exhibit a greater variance compared to those of the high productivity sites (var_1=0.0005, var_2=0.0176). Although there was no statistical difference in DBH distribution diversity between the stands of the two site productivity types ($\overline{GS_1}$=0.8295, $\overline{GS_2}$=0.7757, p-value for t-test=0.4191>0.05), there is greater spatial diversity heterogeneity in the stands of the medium productivity sites.

Discussion

Our findings indicate that stands in medium productivity sites exhibit greater structural spatial heterogeneity compared to those in high productivity sites, suggesting a more complex and diverse stand structure in medium productivity sites. Forest practice through appropriate silvicultural treatments can potentially increase the spatial variability of stand structure in productive sites. *Fagus sylvatica*, being a shade-tolerant species (Korakis 2019) with a strong capability to fill growing spaces of varying types (Assmann 1970), responds well to treatments aimed at creating structural spatial heterogeneity. O'Hara (2014) details treatments designed to foster within-stand structural spatial heterogeneity.

This example demonstrates the capability of our proposed F-test method to highlight differences in spatial heterogeneity that other metrics may overlook. Our study is primarily methodological, aiming to present and validate a novel approach for comparing structural spatial heterogeneity between forests. To our knowledge, there are no existing methods directly comparable to this F-test approach for such comparisons. Thus, the comparison of our methodological findings with other studies is not the intent, as our focus is on showcasing the utility and application of this specific statistical method.

It should be noted that other diversity indices, besides Gini-Simpson, can also be used to determine differences in stand structural spatial heterogeneity between two forest areas. For comparisons involving more than two forest areas, variance comparisons should be systematically conducted in pairs for comprehensive analysis.

While the proposed method offers a straightforward approach to evaluating structural spatial heterogeneity, it does have certain limitations. Different distributions of a stand characteristic might result in the same biodiversity index value, potentially underestimating structural spatial heterogeneity. Moreover, the variance of biodiversity index values from randomly selected plots may not capture the full extent of variability within larger forest areas. Practical experience and the specific traits of forest tree species should therefore be considered when interpreting results.

The suggested method is not limited to DBH distributions; it may also be used for tree height distributions. However, when applying this method to tree height distributions, careful consideration must be given to factors such as tree height class intervals and distribution patterns to properly understand structural spatial heterogeneity. Notably, tree height classes are typically narrower than DBH classes, and the distinction of height classes is more arbitrary than that of DBH classes (McElhinny et al. 2005).

Conclusions

The proposed method for determining differences in structural spatial heterogeneity between forest areas is based on comparing the variances of Gini-Simpson index values calculated from DBH (or tree height) distributions of randomly established sample plots. This approach, utilizing the F-test, effectively quantifies heterogeneity differences with statistical rigor. Additionally, other diversity indices can be employed for assessing variations in stand structural spatial heterogeneity, providing flexibility and robustness to the method. When comparisons need to be extended to more than two forest areas, variance comparisons can systematically be conducted in pairs, ensuring a structured and comprehensive analysis.

The simplicity and applicability of this method are its significant strengths. Requiring only basic data on DBH or tree height, it can be seamlessly integrated into forest stand structure studies. This makes it a practical tool for forest managers and researchers alike, aiding in understanding and managing forest ecosystems more effectively.

In summary, this method provides a straightforward, statistically sound, and flexible approach to compare structural spatial heterogeneity between different forest areas. It holds the potential to guide forest management practices aimed at enhancing stand complexity and ecological resilience. Future research could explore the application of this method across different forest types and in conjunction with other ecological indicators to further validate its robustness and utility.

References

Assmann E. 1970 - *The Principles of Forest Yield Study*. Gardiner S.H. Translator, Pergamon Press, Oxford. 506 p.

Barnes B.V., Zak D.R., Denton S.R., Spurr S.H. 1998 - *Forest Ecology*. 4th ed. Wiley, New York. 774 p.

Berger W.H., Parker F.L. 1970 - *Diversity of planktonic foraminifera in deep-sea sediments.* Science 168 (3937): 1345-1347. https://doi.org/10.1126/science.168.3937.1345.

Bourma K., Milios E., Radoglou K., Kitikidou K. 2023 - *Development of a Graded Biodiversity Assessment (GBA) Index for the assessment of the biodiversity of managed natural forests.* Ecologies 4 (3): 614-626. https://doi.org/10.3390/ecologies4030040.

Ćosović M., Bugalho M., Thom D., Borges J. 2020 - *Stand structural characteristics are the most practical biodiversity indicators for forest management planning in Europe.* Forests 11 (3): 343. https://doi.org/10.3390/f11030343.

Dafis S. 1986 - *Forest Ecology.* Giahoudis-Giapoulis, Thessaloniki. 443 p.

Gadow K.V., Zhang C.Y., Wehenkel C., Pommerening A., Corral-Rivas J., Korol M., Myklush S., Hui G.Y., Kiviste A., Zhao X.H. 2012 - *Forest Structure and Diversity.* In: "Managing Forest Ecosystems", Pukkala T., von Gadow K. Eds., Springer, Dordrecht 23: 29-83. https://doi.org/10.1007/978-94-007-2202-6_2.

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(1–3): 399–423. https://doi.org/10.1016/s0378-1127(01)00575-8

Gao T., Hedblom M., Emilsson T., Nielsen A.B. 2014 - *The role of forest stand structure as biodiversity indicator.* Forest Ecology and Management 330: 82-93. https://doi.org/10.1016/j.foreco.2014.07.007.

Jost L. 2006 - *Entropy and diversity.* Oikos 113 (2): 363-365. https://doi.org/10.1111/j.2006.0030-1299.14714.x.

Kitikidou K., Milios E., Stampoulidis A., Pipinis E., Radoglou K. 2022 - *Within-forest stand or formation or plot and between-forest stand or formation or plot biodiversity indices.* MethodsX 9: 101919. https://doi.org/10.1016/j.mex.2022.101919.

Kitikidou K., Milios E., Stampoulidis A., Pipinis E., Radoglou K. 2024 - *Using biodiversity indices effectively: Considerations for forest management.* Ecologies 5 (1): 42-51. https://doi.org/10.3390/ecologies5010003.

Korakis G. 2019 - *Forest Botany. Trees and Shrubs Native in Greece.* Athanasiou Altintzi Editions, Thessaloniki. 520 p. ISBN 978-960-9465-36-6.

Levene H. 1960 - *Robust Tests for Equality of Variances.* In: "Contributions to Probability and Statistics", Olkin I. Ed., Stanford University Press, Palo Alto: 278-292.

Lindenmayer D.B., Franklin J.F. 2002 - *Conserving Forest Biodiversity: A Comprehensive Multiscaled Approach.* Island Press, Washington DC. 352 p.

MacArthur R. H., MacArthur J. W. 1961. *On bird species diversity.* Ecology 42(3): 594–598. https://doi.org/10.2307/1932254

McElhinny C., Gibbons P., Brack C., Bauhus J. 2005 -

Forest and Woodland Stand Structural Complexity: Its Definition and Measurement. Forest Ecology and Management 218: 1-24. https://doi.org/10.1016/j.foreco.2005.08.034.

Milios E. 2000 - *Dynamics and Evaluation of the Rhodope Mixed Stands in the Region of Xanthi*. PhD thesis, Faculty of Forestry and Natural Environment, Aristotle University of Thessaloniki, Thessaloniki, Greece.

Milios E., Kitikidou K. 2025 - *Enhancing Biodiversity Assessment in Forests: Integrating Instrumented Measurements for a Robust Graded Biodiversity Assessment (GBA) Index*. Environment and Ecology Research 13(1): 131-139. http://doi.org/10.13189/eer.2025.130112

Mori A. S., Furukawa T., Sasaki T. 2012 - *Response diversity determines the resilience of ecosystems to environmental change*. Biological Reviews/Biological Reviews of the Cambridge Philosophical Society 88(2): 349–364. https://doi.org/10.1111/brv.12004

O'Hara K. 2014 - *Multiaged Silviculture: Managing for Complex Forest Stand Structures*. Oxford University Press, Oxford. 472 p.

Oliver C.D., Larson B.C. 1996 - *Forest Stand Dynamics*. McGraw Hill, New York. 520 p.

Petrou P., Stampoulidis A., Kitikidou K., Milios E. 2023 - *Comparison of the stand structure diversity of open* Pinus brutia *Ten. forests in areas of different productivity in central Cyprus*. Forests 14 (11): 2200. https://doi.org/10.3390/f14112200.

Pommerening A. 2002 - *Approaches to Quantifying Forest Structures*. Forestry 75 (3): 305-324. https://doi.org/10.1093/forestry/75.3.305.

Shannon C.E. 1948 - *A Mathematical Theory of Communication*. Bell Labs Tech. J. 27 (379–423): 623-656.

Simpson E.H. 1949 - Measurement of diversity. Nature 163(4148): 688. https://doi.org/10.1038/163688a0

Snedecor G.W., Cochran W.G. 1989 - *Statistical Methods*. 8th ed. Iowa State University Press, Ames. 503 p.