

## Do natural processes at the juvenile stage of stand development differentiate the spatial structure of trees in artificially established forest stands?

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**Abstract.** Structural diversity is one of the most interesting phenomena that have been studied by forest ecologists and practitioners. Amongst the different characteristics of forest structure, spatial diversity of trees and their attributes seem to be very important. The more spatially structured a population is, the higher its diversity in terms of size and species richness. Because most forests in Europe are managed and were artificially established, they are subjected to conversion processes turning them into more complex systems. The approach presented here aims at elucidating whether natural processes, such as self-thinning, can cause the self-differentiation of spatial structure in artificially planted stands.

Our analyses focused on untended Scots pine and pedunculate oak stands in the juvenile phase of development and were based on spatially explicit structural indices for positioning and size differentiation (diameter, total height and crown length). The obtained results indicate that live trees were dispersed more or less regularly. Unlike the angle based index, which mostly indicated randomness in tree location, a distance-based index showed clear regularity. We also found that the distribution of tree attributes auto-correlates to tree location as indicated by significantly lower index values compared to values resulting from random reassignment of the examined attributes. This low degree of spatial differentiation is further confirmed by the distribution of indices in differentiation classes. Our results allow us to conclude that, in the case of light demanding species (pine and oak.), natural processes do not increase spatial diversity of the stand, although, both species showed a certain degree of deviation in this respect.

**Key words:** spatial indices, forest diversity, self-thinning, managed forests

### 1. Introduction

One of the most interesting issues in forest ecology is its structural diversity in different development phases. Tree studies covering the entire stand cycle are scarce (Kenkel et al. 1997; Sekretenko, Gavrikov 1998; Wolf 2005; Grey, He 2009). More often, the results of research on forest structure dynamics apply to selected phases of forest development (Szymański 1964; Daniels 1978; Kenkel 1988; Kenkel et al. 1997; Kuuluvainen et al. 1998; Montes et al. 2004, 2005; Szmyt, Korzeniewicz 2007; Szmyt, Ceitel 2011).

The population structure, which is one of the most important of its characteristics, can be considered as a repeating pattern resulting from mutual interactions between individuals (Gadow et al. 2012). The structure of diameter at breast height of trees, their height or the social structure of trees give foresters a picture of the stand, a hint of the direction of its development, to provide treatments, etc. However, this picture is not complete, as these structures do not take into account the spatial relationships between individuals that determine different ecological processes (competition, cooperation, mortali-

ty, etc.). The use of indices embodying the spatial aspect allows for a better understanding of the mechanisms responsible for the formation of the observed spatial variability of the forest (including the stand). The importance of such analyses is due to the fact that structure diversity affects the dynamics of the whole forest ecosystem, including both fauna and flora. High diversity of a stand is often defined as the occurrence of many different species, which is a simplification, because the spatial variation of tree size, occurrence of dead trees, dead trees, etc. are of the same importance (Lähde et al. 1999; McElhiny et al. 2005). The stand diversity affects the formation of specific habitats of many organisms (Buongiorno et al. 1994; Lähde et al. 1999; Pretzsch 1999).

The forest ecosystem structure depends on a number of factors of biotic and abiotic, as well as of anthropogenic nature, and foremost among them are the processes of forest growth and development, regeneration, survival and mortality of individuals, competition and cooperation between individuals (Lähde et al. 1999). Most of the ecological processes are both spatial and temporal and their intensity varies with stand age, conditioning its dynamics (Gadow et al. 2012). Currently, it is obvious that stands characterised by a great diversity of age, species composition and size of trees have a higher biological stability (Lähde et al. 1999; Pretzsch 2010; Brzeziecki et al. 2013). The significance of the biological stability in the management of forest resources is included, inter alia, in the definition of sustainable forest management (Pommerening, Murphy 2004), and the benefits of forming a structurally diverse forest stands are well known. In natural stands, where human activity is limited to the minimum, this diversity is usually much greater than in commercial forests, which are often even-aged and a single species. In the latter, diversity can be shaped indirectly by using proper treatments (Pretzsch 1996, 1999; Hanewinkel 2004; Saunders, Wagner 2008; Jaworski 2013). There is, of course, no option to abandon precommercial treatments in these forests, but one can discuss methods applied depending on the species and commercial purposes. Given that the stand resistance can be shaped by silvicultural treatments affecting its structure to a greater or lesser extent, it is interesting to examine in more detail the impact of the lack of such treatments on structural diversity of untended stands.

The aim of this article is to analyse the impact of natural ecological processes, in particular the process of self-thinning, on the spatial variation of oak and pine stands planted with a specific initial spacing, with the

absence of any silvicultural treatments. The diversity of these forests was determined in terms of: 1) the horizontal distribution of living trees and 2) the spatial diversity of the size of trees, i.e. their DBH, height and crown length.

## 2. Study area and methods

### 2.1. The study area

The permanent experimental plot of the Department of Silviculture of University of Life Sciences in Poznań, established by Professor Szymański (Szymański 1975, 1982), was chosen as an object of study. It is located in the southern part of Wielkopolska region, in the Siemianice Forest Experimental Station, in compartment 25. In terms of natural forest regionalisation, it is located in the Land of Silesia, the Wrocław District, and the mesoregion of Oleśnicka Plain (Zielony, Kliczkowska 2012). The average annual precipitation ranges from 550 to 600 mm (Ceitel, Wawro 1999).

We analysed the results of measurements and observations conducted in the stands of Scots pine (*Pinus sylvestris* L.) and oak (*Quercus rubra* L.) growing in the same forest site type (fresh mixed coniferous forest) on rust-podzol soil formed from loose glacial sands.

Each species is represented by three replications of an area of 0.04 hectares (19×21 m) each (designated as I, II and III). All stands were established by planting, with the square spacing of 1×1 m (initial density of 10.000 seedlings/ha). Up to now, no treatments have been performed. At the time of measurement, the trees had reached the age of 30.

### 2.2. Methods

The following tree characteristics were measured in the field: the total height of living trees ( $H$ , m), the height of the crown base, i.e. the height of the first living branch ( $h_k$ , m), and the diameter at breast height ( $d_{1.3}$ , cm). Height was measured using a Vertex III altimeter with an accuracy of 0.10 m. DBH was measured to the nearest 0.1 cm using a tree calliper. On the basis of the initial spacing, coordinates (x, y) of all living trees were determined with relation to the coordinates of one corner of the plot assumed as (0, 0). Crown length was calculated according to the formula:  $L_k = H - h_k$  (where:  $H$  – total height of tree,  $h_k$  – the height of the crown base).

In order to determine the structural diversity of analysed stands, many spatial explicit indices were calculated relating to various aspects of the structure: horizontal arrangement of living trees and spatial variation of dif-

ferent biometric characteristics of living trees (height, diameter and crown length).

### 2.3. The horizontal distribution of trees within the stands

The Clark-Evans index ( $CE$ )

This index allows specifying the type of horizontal distribution of individuals on the basis of the distance between the reference tree and its nearest neighbour by comparing it with the average distance for the theoretical random distribution of individuals. Thus, it expresses the extent to which the distribution of individuals of the studied population differs from one where individuals are distributed randomly (Clark, Evans 1954; Donnelly 1978; Pommerening 2002; Corral-Rivas et al. 2010). Details of mathematical form of the index can be found in the works of Brzeziecki (2002) and Szmyt and Korzeniewicz (2012). In this study, due to the edge effect, the modified version of the index was used (Donnelly 1978; Kint 2004):

$$CE = \frac{\frac{1}{N} \sum_{i=1}^N r_i}{0.5 \left( \frac{A}{N} \right)^{0.5} + 0.0514 \frac{P}{N} + 0.041 \frac{P}{N^{3/2}}}$$

The value of  $CE=1$  indicates a random distribution of trees,  $CE>1$  – regular and  $CE<1$  – clustering of individuals in the population. The significance of the deviation of the empirical index from the value typical for a random population is determined by the standard normal distribution  $Z$  (Clark, Evans 1954; Kint 2004; Szmyt, Korzeniewicz 2012).

The angle index ( $W$ )

In contrast to the  $CE$ , the angle index ( $W$ ) allows specifying the type of horizontal arrangement based on the classification of angles between the straight lines connecting the reference point  $i$  (tree) and  $n$  of the closest neighbours (Pommerening 2002; Corral-Rivas et al. 2010). The method is based on a comparison of angles  $\alpha_{ij}$  with the reference angle  $\alpha_0$  ( $\alpha_0=72^\circ$  for four neighbours), for which  $W_i = 0.5$ . The  $W_i$  index is defined as following:

$$W_i = \frac{1}{n} \sum_{j=1}^n v_j$$

where  $v_{ij}=1$  for  $\alpha_{ij}<\alpha_0$  and  $v_{ij}=0$  otherwise.

The  $W$  index can take values from 0 to 1. Small values indicate a regular distribution of trees, while values close to 1 indicate group nature of their occurrence. The  $W$  index is determined for each tree in the stand and then averaged for the stand. For  $n=4$  index may take five values: 0, 0.25, 0.50, 0.75 and 1.0 (Pommerening 2002). As boundaries separating distribution types of random, regular and cluster, the ranges  $0<W_i<0.5$  – regular distribution,  $0.5<W_i<0.6$  – random distribution and  $W_i>0.6$  – clusters (Pommerening 2002) can be assumed.

### 2.4. The difference in size of trees within the stands

The indices of spatial differentiation of diameter, tree height and crown length ( $T_d$ ,  $T_H$ ,  $T_{Lk}$ , respectively) were applied to describe their spatial variation in the stands. To assess the diversity of the closest neighbourhood in terms the tree characteristics mentioned above, the following formula was used (Gadow 1993):

$$T_i = \frac{1}{n} \sum 1 - \frac{\min(X_i, X_j)}{\max(X_i, X_j)}$$

where:  $n$  – the number of nearest neighbours;  $X_i$  – the feature of reference tree  $i$ ; and  $X_j$  – the feature of nearest neighbour  $j$  ( $j=1 \dots n$ ).

In the study,  $T_i$  index was determined for  $n=4$ , i.e. for the four nearest neighbours of the reference tree. Taking into account all the trees in the population, the average  $T_i$  index of the stand can be calculated. Calculating the  $T_i$  index for each tree in the stand, the frequency distribution of five diversity classes was obtained (Szmyt, Korzeniewicz 2012). In order to determine the significance of deviations between the empirical index and the expected (theoretical) value, the procedure of 1000 permutations was applied (Kint 2004). Expected value refers to the random assignment of attributes ( $d_{1,3}$ ,  $H$ ,  $L_k$ ) to a tree.

All indices of the structural diversity of stands were calculated using Crancod V.1.4 software (Pommerening 2012) and SIAFOR V.1.0 (Kint 2004).

## 3. Results and discussion

### 3.1. Statistical characteristics of biometric features of trees in analysed pine and oak stands

The basic statistical characteristics of the analysed features in the stands of both species are presented in Table 1. It shows that pine stands were less diverse than oak

stands in terms of all the analysed features. For both species, the least variation was observed for the total height of trees, then the thickness, while the crown length varied the most. Diameter distribution of both species was typical for even-aged stands with right-sided asymmetry more pronounced in oak stands. The tree height distribution differed between the two species. In pine stands, it was clearly left-skewed, due to the small number of low trees, while in oak stands it was right-skewed. Crown length distribution in both stands was right-skewed.

### 3.2. The horizontal distribution of trees within the stand

Determination of the type of horizontal arrangement of trees was different depending on the applied index (Table 2).

The *CE* index clearly indicated significant regular spacing of trees ( $\alpha=0.05$ ) in all stands of both species. Its value in oak stands ranged from 1.13 to 1.28, and in Scots pine was significantly higher and amounted to 1.35, 1.34 and 1.28.

On the basis of the average angle index ( $W_i$ ), it must be stated that in the stands of the two species the random placement of trees dominated (Table 2). Yet, the average index does not give the full picture of the situation within the stand. Analyzing its distribution, it can be concluded that, in fact, the dominant type of tree distribution for both species is the random one, but it is not the only type. In both cases of pine and oak stands, some trees are arranged regularly, and some occur in clusters (Fig. 1).

Conflict of horizontal arrangement types obtained using the two indices is due to methodological differ-

**Table 1.** Biometric features of trees in pine and oak stands

Plots	DBH $d_{1.3}$			Total height $H$			Crown length $L_k$			
	$d_{1.3\text{sr}}/\text{DBH}$ (cm)	skewness	<i>CV</i> (%)	$H_{\text{sr}}$ (m)	skewness	<i>CV</i> (%)	$L_{k\text{sr}}$ (m)	skewness	<i>CV</i> (%)	
So	I	10.52	0.7650	26	12.51	-0.8746	13	4.08	1.1978	37
	II	11.81	0.2885	25	14.69	-0.5721	12	4.26	0.7119	30
	III	11.12	0.4222	30	13.85	-1.0591	18	4.19	0.3145	32
Db	I	6.28	0.4480	28	7.95	-0.2590	35	4.07	0.5813	53
	II	7.33	-0.5979	34	7.33	1.2507	28	4.12	0.7808	52
	III	5.95	1.4646	40	6.97	0.4804	37	3.12	0.8152	53

Notes:

*CV* – coefficient of variation

So – pine stands

Db – oak stands

**Table 2.** Average values of the Clark-Evans index (*CE*), an angle index ( $W_i$ ) and the difference in thickness ( $T_d$ ), height ( $T_H$ ) and the length of the crown ( $T_{Lk}$ ) in oak and pine stands

Plots	$W_i$	<i>CE</i>	$T_d$	$T_H$	$T_{Lk}$	
Db	I	0.523	1.24*	0.22* (0.26) <sup>a</sup>	0.22* (0.31)	0.31* (0.41)
	II	0.517	1.13*	0.26 (0.27)	0.23* (0.26)	0.31 (0.33)
	III	0.468*	1.28*	0.28* (0.31)	0.27* (0.32)	0.26* (0.34)
So	I	0.456*	1.35*	0.22 (0.23)	0.12* (0.13)	0.27* (0.30)
	II	0.494	1.34*	0.23 (0.24)	0.10* (0.12)	0.27 (0.27)
	III	0.504	1.28*	0.26* (0.28)	0.14* (0.18)	0.29 (0.29)

\* significant differences at the level  $\alpha=0.05$

<sup>a</sup> in parentheses are theoretical values corresponding to the situation in which the values of features are randomly assigned to a location of a tree

ences in their calculation, wherein the distance-based indices (e.g. the CE index) seem to give more reliable results than the angle-based ones ( $W_i$ ). Also, the method for determining the significance of differences between the calculated indices and the theoretical values for random distribution may have some impact on the classification of the same set of individuals into two different types of arrangement.

The distribution of the  $W_i$  index gives the basis for the conclusion that the random distribution was not the only type in the studied stands. Similar contradictory results based on the CE and  $W_i$  indices were obtained by Pommerening (2002) in a 24-year-old stand of Douglas fir established artificially, as well as in a 53-year-old beech stand. The differences between the results derived by various methods of horizontal distribution determination were also pointed out by Bolibok (2003). In his work, however, the differences related to the results obtained by using the Ripley and the CE indices.

Kenkel et al. (1997) found that clustering of natural regeneration of trees in natural stands of Jack pine, due to competition and the resulting process of self-thinning, changed over time towards a more regular arrangement

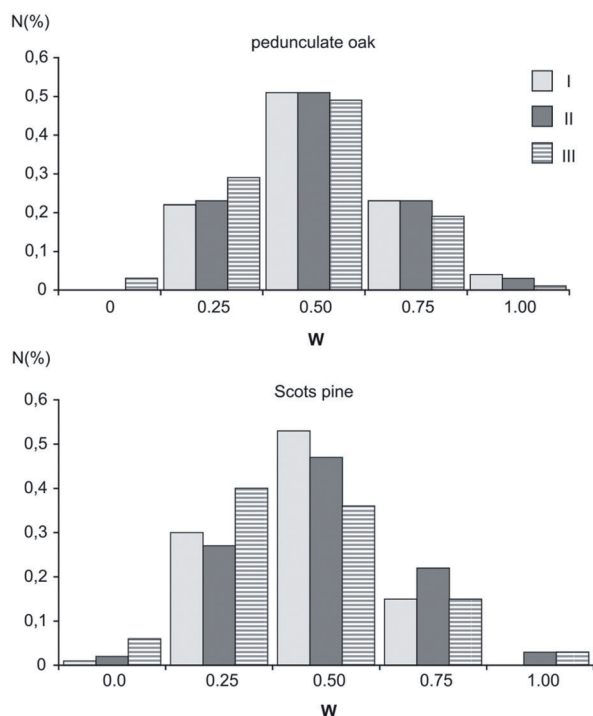
of trees. In another study on this species, Kenkel (1988) showed a marked regularity of distribution of trees. In both works, the distance-based CE index was used. Regular or random distribution of trees in untended stands of birch has been noted by Szmyt and Korzeniewicz (2012). Szmyt and Ceitel (2011) observed regular distribution of trees in pine stands planted with dense, medium and loose initial spacing. Crecente-Campo et al. (2009) also recorded regular spacing of trees in pine stands in northern Spain. However, this regularity of tree arrangement decreased with stand age as a result of treatments. In both the works mentioned above, the authors used the CE index as well. Research by Brzeziecki (2005) in a 35-year-old pine monoculture – using  $W_i$  index – showed a similar frequency of all three major types of tree distribution, with a predominance of regular distribution. Different thinning did not affect the characteristics of these stands. A similar arrangement of trees, determined using the angle-based index as well, was also observed in a pine stand with natural regeneration (Bilski, Brzeziecki 2005).

### 3.3. Spatial variation in diameter, height and crown length of trees

The average index value of spatial diversity of diameter ( $T_d$ ) and height ( $T_H$ ) was low in the stands of both species, while the value for crown length diversity ( $T_{Lk}$ ) was slightly higher (Table 2). In almost all oak and pine stands, the average empirical indices were significantly smaller than the theoretical ones, corresponding to random assignment of index values (DBH, height, crown length) to the tree position.

The distribution of  $T_d$  values (Fig. 2) in oak stands indicates that in the nearest neighbourhood, diameter does not vary usually more than 40%. Such diversity affected neighbourhood from about 64% to almost 92% of trees. In the pine stands, the  $T_d$  distribution was similar, with even clearer domination of trees, whose neighbourhood demonstrated the diameter variation of less than 40% (Fig. 2). The share of trees with neighbours exhibiting higher diversity of DBH is similar to that of oaks, and the stands vary considerably in the share of trees in these classes.

The variation of height of oaks is markedly smaller than diversity of its diameter at breast height. In all oak stands, the tree height differentiation of neighbours was no higher than 40% (in about 86%–92% of cases, depending on the stand) (Fig. 3). Less than 15% of oaks differed in height by more than 40%. In pine stands, the



**Figure 1.** Distribution of angle index  $W_i$  in oak and pine stands.

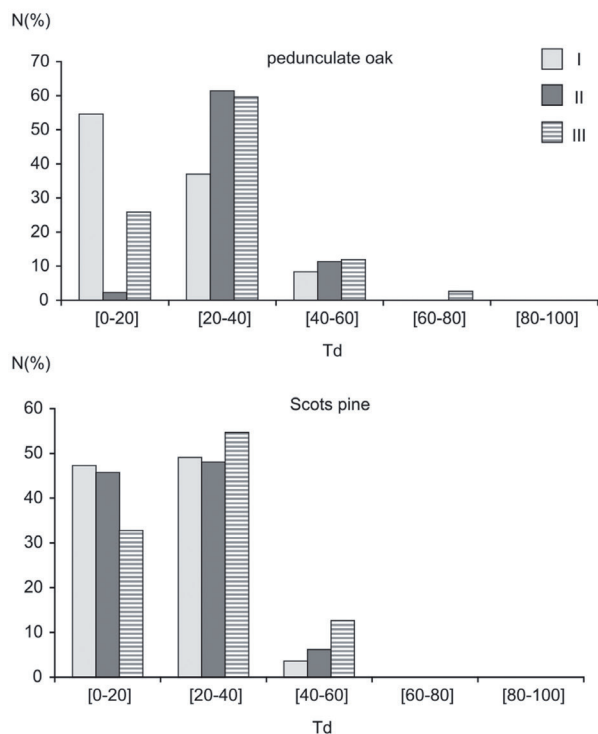
situation was similar, except that low variation in height was even more pronounced here due to a very large share of trees with height differences between neighbours below 20% (Fig. 3). In pine stands, the difference in height of trees was not greater than 40%.

Both in oak and pine stands, the greatest difference between nearest neighbours was in terms of crown length (Table 2, Fig. 4). In the case of oak trees, the most common was crown length variation of 20%–40%, and then the lowest variation of this feature (<20%). There was quite a proportion of trees characterised by the crown length difference of more than 40% (Fig. 4), including those that differ by as much as 80%–100%. In pine stands the arrangement was similar, but more pronounced was the participation of trees that differ from the nearest neighbours in crown length at the level of 20%–40%. The share of trees was clearly smaller than in oak stands with the diversity of crown length higher than 40%. It is worth noting that in the given pine stands, the differences were significantly smaller than in the case of oak stands (Fig. 4).

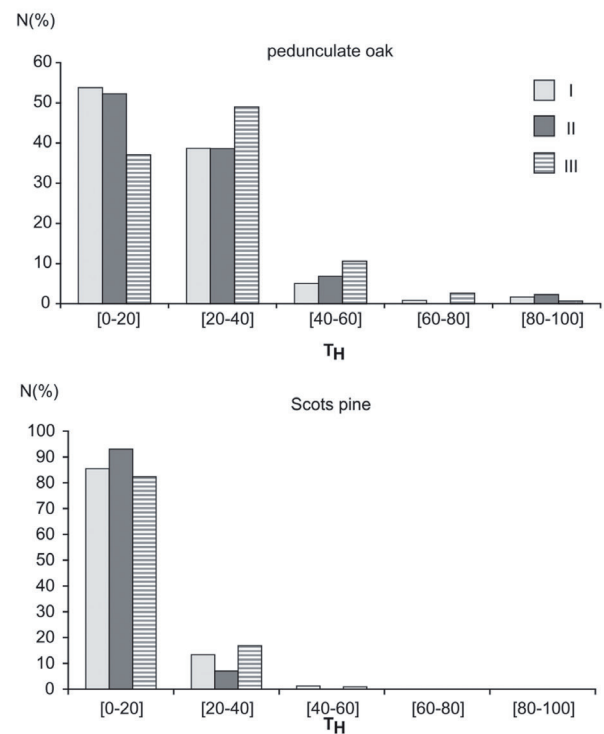
Slight variation in the studied features of trees reflects their spatial positive autocorrelation. Kenkel et al. (1997) obtained similar results with respect to the diameter at breast height in natural and single-species stands of Jack pine, both before the period of intensive self-thinning and after its culmination.

Reed and Burkhart (1985) examining young *Pinus teada* plantations recorded a positive autocorrelation of pine sectional area. The authors related this with weak competition in the stand. In stands where competition was moderately intensive, they observed negative autocorrelation, reflecting greater diversity of features among neighbours, while along with the extremely strong competition they again found a positive correlation of sectional area between pairs of trees.

Brzeziecki (2005) observed little variation in diameter in pine monoculture before thinning, and treatment performed in the lower layer contributed to the further decline of this diversity. On the other hand, selective thinning, touching also the upper stand, resulted in a slight increase of DBH diversity. A similar trend in the



**Figure 2.** Distribution of spatial differentiation index for DBH ( $T_d$ ) in oak and pine stands.



**Figure 3.** Distribution of spatial differentiation index for height ( $T_h$ ) in oak and pine stands.

case of DBH and height was noted in pine stands by Crecente-Campo et al. (2009). These authors also concluded the impact of the intensity of prescribed thinning on the diversity of thickness and height of trees. Within the stand, where no treatment was performed, differentiation of both features decreased with the age of stand. A similar trend was observed in treated stands, except that with greater intensity of treatment a decrease in diversity – and even then only in relation to tree height – was smaller. Spatial diversity of diameter was also stated by Pommerening (2002) in Jack pine plantations and by Szmyt and Korzeniewicz (2012) in the aforementioned birch stands.

Diversity of tree crown length is a feature of stands rarely analysed so far. This work indicates, however, that among all analysed features it varies spatially the most. Two factors play role in this diversity – light requirements of species and habitat conditions. The more light a species demands, the smaller the differences of this feature occur between the nearest neighbours, as a result of competition for light. Shade-tolerant species

may maintain longer crown in lesser light conditions under the canopy of the main stand, and the nearest neighbourhood can have a varied crown length. Our results confirm this assumption. Pedunculate oak, as a species less demanding light than pine, shows a greater variation of this feature.

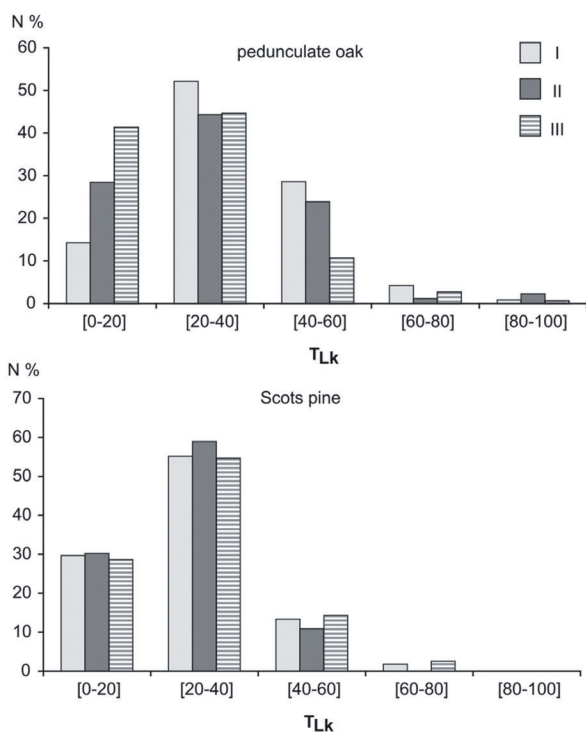
#### 4. Conclusions

On the basis of the results obtained, it can be stated that stands of light-demanding species such as pine and oak, with a simple structure and without treatments in the juvenile phase of development, do not self-differentiate significantly. Initial regularity of trees imposed by artificial spacing stays visible over a long period, and the natural process of self-thinning does not significantly affect the change. In the studies described, the two indices of spatial distribution showed the dominance of different types of spatial arrangement in the same stands, which is rather due to methodological differences in their calculation. With the knowledge of angle-based index distribution, it is possible to determine differences in the distribution of trees in the stands of both species. Random occurrence of trees prevails in both species; however, some trees are distributed regularly or in clusters. The oak stands noted a greater share of tree clusters than the pine ones in which regular distribution of individuals in the neighbourhood was more frequent than grouping.

The results confirm previous studies, providing evidence that the natural process of self-thinning does not increase the diversity in height, diameter or crown length of the two tree species. Among the analysed biometric features, the least diverse was tree height, then diameter, and crown length varied the most.

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**Figure 4.** Distribution of spatial differentiation index for crown length ( $T_{Lk}$ ) in oak and pine stands.

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### Contributions:

J. S. – manuscript writing, field data analyses and statistical analyses; R. K – data collection and analyses.