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Spatial structure of managed beech-dominated forest: applicability of nearest neighbors indices

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Abstract: High structural diversity is often attributed to old-growth forests, usually established naturally and unmanaged. Forest diversity should be considered not only in terms of species diversity and richness but also the variation in trees dimension and their spatial distribution have to be taken into consideration. The main goal of this paper was the answer if nearest neighbor indices are suitable for spatial forest structure description. To answer this question results obtained from 3 managed beech-dominated forests from natural regeneration are presented and discussed. The following indices were calculated: Clark-Evans aggregation index (R), DBH and height differentiation indices (TD and TH, respectively) and mingling index (DM) analyzing horizontal and vertical spatial structure of the forest. Results indicated that managed beech forests demonstrated rather homogenous spatial structure in both aspects. Living trees as well as future crop trees were mostly regularly distributed. Spatial variation in DBH and height between living nearest neighbors was rather low. The lowest variation in sizes was demonstrated by future crop trees. Mature beech forests revealed single species structure and other tree species – if present – were spatially segregated from beech. It can be supposed that high homogeneity structure of these forests results from biological characteristics of this species as well as thinning treatments conducted by foresters.

Additional key words: spatial structure, beech forests, nearest-neighbor indices, *Fagus sylvatica*, managed forests

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Introduction

In dynamic ecosystems, such as forests are, the processes and structures are mutually related, what means that processes affect the structures and structures influence processes operating in such system. Therefore, processes and structures are not independent. Such feedback mechanism can be observed obviously in the forests (Pretzsch 2009).

Ecological forestry (forestry on ecological backgrounds) is based on the understanding of the natural processes operating in different kinds of forests. The easy way to understand them is the recognition of the structural patterns they follow. It is possible because forest structure can be easier measured than processes. Structure recognition is then helpful in the interpretation of processes (Leps 1990, Pretzsch 2009, Comas and Mateu 2007). Stand structure refers to the way in which trees and their attributes (e.g. species, size etc.) are distributed in the forest. It can be characterized in different aspects and they are usually referred to species mixing in space, spatial distributions of individuals and spatial variation of their sizes (Pommerening 2002, Aguirre et al. 2003, Kint et al. 2003, Boyden et al. 2005, Gadow and Hui 2007). Coexistence of different species, their mutual interactions and certain spatial distribution of trees may lead to a different structures of the forest influencing its dynamics. The recognition of spatial pattern is not so easy task because the same spatial pattern can be result of different processes and the certain process can create different spatial structure (Lepš 1990, Kenkel 1997, Stoyan and Penttinen 2000, Boyden et al. 2005, Stoll and Bergius 2005, Wolf 2005, Pommerening 2006, Comas and Mateu 2007, Comita et al. 2007, Jagodzinski and Oleksyn 2009a, Eichhorn 2010, Ruprecht et al. 2010, Szmyt 2010, Szmyt and Korzeniewicz 2010). Moreover, different processes can operarte in different spatial scales (Fortin and Dale 2005, Jagodzinski and Oleksyn 2009b).

Recently, spatial structure of forest is of great importance among ecologists and forest practitioners. More diversified forest structure creates suitable habitats for different organisms increasing so-called biodiversity of the ecosystem. Highly structured forests, like primeval and natural ones, are ecologically stable to the greater extent. From the other side, managed forests, the most frequent in Europe, are usually perceived as simple ecosystems, poorly diversified in each aspect. In such stands human operations, e.g. thinning, are very important factor influencing the spatial structure and dynamics of the forest. They may affect the stand in a different ways, decreasing or increasing forest diversity (Lähde et al. 1999, Pretzsch 1996, 1999, Stoyan and Penttinen 2000, Bachofen and Zingg 2001, Hanewinkel 2004, Montes et al. 2004, Bilski and Brzeziecki 2005, Brzeziecki 2005, Juodvalkis et al. 2005, Szmyt and Korzeniewicz 2007, Saunders and Wagner 2008, Crecente-Campo et. al. 2009, Jactel et al. 2009, Szmyt and Korzeniewicz 2010). Description of the spatial structure gives us better insight into the natural processes under human impact and it allows us to create forests more resistant to biotic and abiotic negative factors (Jagodzinski and Oleksyn 2009c). To describe the spatial structure of forest, different statistical methods can be applied. One group includes simple indices (so-called nearest neighbor statistics or first-order statistics) based on counts of individuals on the plot or based on the distances between nearest neighbors. The second group (so-called second-order statistics) is based on the knowledge of the distances between all pairs of trees in the stand. Both groups differ in methodological concepts, information obtained, complexity and inference possibilities.

The main goal of this paper is the presentation of the possibilities of application of different spatially explicit nearest-neighbor indices for description of the forest spatial structure. Their applicability was demonstrated in three natural and managed beech forests. The following aspects were analyzed in details: 1) the horizontal distribution of living trees and future crop trees, 2) the spatial variation of trees dimensions, 3) spatial mixture of tree species. Additionally, spatial relationships between future crop trees and non-future crop trees were done.

Object and methods

Object

European beech (*Fagus sylvatica* L.) is a widely distributed forest tree species in central, southern and western Europe. In Poland it reaches the eastern limit of its natural range (Białobok 1990, Jaworski 1995). Three experimental temporal plots are located in the Dukla Forest Inspectorate, south-eastern Poland in the Beskid Niski Mountains. Climatic conditions are described as typical for the Carpathians with the average annual temperature +7.4°C, and the mean annual precipitation 770 mm. Vegetation period lasts 170–190 days.

Table 1. Description of the spatially explicit nearest neighbors indices of forest structural diversity

Index	Formula	Description
R (Clark, Evans 1954, Kint 2004)	$R = \frac{r_A}{r_E} = \frac{\frac{1}{N}\sum_{i=1}^{N} r_i}{0.5\cdot\left(\frac{A}{N}\right)^{1/2} + 0.0514\cdot\frac{P}{N} + 0.041\cdot\frac{P}{N^{3/2}}}$	r_A – mean distance between trees A – area of the plot (m^2) N – number of trees P – plot perimeter (m)
TD_{ij} (Kint 2004)	$TD_i = \frac{1}{n}\cdot\sum_{j=1}^{n}\left[1-\frac{\min\left(D_{1.3i},D_{1.3j}\right)}{\max\left(D_{1.3i},D_{1.3j}\right)}\right]$	$D_{1.3i}$ – dbh of *i*-th tree $D_{1.3j}$ – dbh of *j*-th tree n – neighbors number (n=3)
TH_{ij} (Kint 2004)	$TH_i = \frac{1}{n}\cdot\sum_{j=1}^{n}\left[1-\frac{\min\left(H_i,H_j\right)}{\max\left(H_i,H_j\right)}\right]$	H_i – height of *i*-th tree H_j – height of *j*-th tree n – neighbors number (n=3)
DM_i (Kint 2004)	$DM_i = \frac{1}{n}\sum_{j=1}^{n} v_{ij}$	v_{ij} = 1 – reference tree and j-tree are different species; v_{ij} = 0 – otherwise n – number of neighbors (n=3)

Measurement plots were rectangular of size 0,35 ha each (70 m × 50 m). Geographical position of the stands (plots) was as follows: stand A – 21°41'26"E and 49°34'54"; stand B – 21°41'25"E and 49°34'44"; stand C – 21°38'39"E and 49°34'35". They were established in homogenous site conditions. Forest site type was described as upland fresh forest with leached brown soils and brown soils in dominance. The stands were at the age: A-82, B-77 and C-77 years old and they were regenerated naturally.

The following tree species were recorded in the stands: European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* L.), pedunculate oak (*Quercus robur* L.) and sycamore maple (*Acer pseudoplatanus* L.). Beech was the main tree species in each stand and other tree species formed small admixture. All stands are of natural origin. No large gaps caused by natural disturbances were observed.

Methods

On each plot the diameter at the breast height (DBH, cm) and the total height (H, m) of each tree were measured. Coordinates (x, y) of all individuals were determined using theodolite and measurement tape starting from the plot corner with (0,0) coordinates.

To analyze the spatial diversity of stands the following structural indices were applied: Clark-Evans index (R in text), index of spatial differentiation of DBH (TD) and height (TH) and mingling index (DM). Indices were calculated for: all living trees taken together nevertheless of the species (in text: LT), future crop trees (FCT), and other species (OS) if they were represented in the stand. Future crop trees referred only to beech because only trees of this species were selected as FCT. The abbreviation OS means all species other than beech.

R index is the measure of the extent to which the observed population differs from random one in respect to the horizontal distribution of trees (Clark and Evans 1954, Kint 2004). This index can take the values from 0 to 2.1419. If $R=1$ individuals are distributed randomly, whereas $R\neq1$ indicates other types of their spatial arrangement. Then, $R>1$ indicates regularity and $R<1$ – aggregated type of distribution. Donnelly's modification for R was applied (Donnelly 1978). Spatial differentiation index for DBH and height (TD, TH, respectively) reflects the differentiation in size between neighboring trees and the values vary between 0 (no differentiation of sizes) and 1 (completely differentiation) (Brzeziecki 2002, Pommerening 2002, Kint 2003, Kint at al. 2004, Crecente-Compo 2009). More informative than a single mean value for a stand is the distribution of the index in the differentiation classes. In this paper the following classification was applied: 0.00–0.20 – very small differentiation, 0.20–0.40 – small differentiation, 0.40–0.60 – obvious differentiation, 0.60–0.80 – large differentiation and 0.80–1.00 – very large differentiation (Kint 2004, Vorcak at al. 2008). Mingling index (DM) was applied to find out how the different tree species were intermingled (Aguirre et al. 2003, Kint et al. 2003, Pommerening 2006). The index gives the proportion of neighbors of the reference tree which are not the same species as the reference tree. Hence, in case of 3 neighbors the index can take 4 values: 0, 0.33, 0.67, and 1, depending on the spatial pattern and relative frequency of the species. Strongly represented or segregated species result in low DM values and less frequent or regularly spaced species have higher values of DM index (Aguirre et al. 2003, Kint at al. 2003). Low values of the index indicate the homogenous groups of species and low mingling while high values indicate complete mixture of the species. The same DM index (abbreviations in text: DM_{FCT}) was applied to describe how future crop trees are distributed in relation to the other living trees. It was done by coding FCT as 1-type of points and remained living trees coded as 2-type of points. If $DM_{FCT}=1$ it means that future crop trees have as the neighbors non-future crop trees while $DM_{FCT}=0$ indicates that the neighboring trees of FCT are other FCTs.

All nearest neighbor indices were calculated using SIAFOR ver. 1.0 software (Kint 2004).

Results

Spatial distribution of trees

In terms of horizontal distribution of trees in the forest stands it can be stated that – despite the tree category – values of R index were larger than 1 for random population. In case of living trees R values varied: 1.03 (stand A), 1.11 (stand B) and 1.19 (stand C) indicating non-random distribution in the stand. This thesis was proved in stand B and C where R values were significantly different from random hypothesis (H_0) ($a=0.05$). In case of living trees (non-FCT) in the stand A such statement was not proved by significance test. Index R values for the FCT only were the highest in B and C stand, showing very strong regularity in their distribution. Again, in stand A FCT were not regularly spaced. The OS showed random (stand B) or aggregated (stand A) type of spatial distribution in the forest (Table 2). In stand C no other species than European beech were present.

Tree size differentiation

DBH differentiation

In 3 beech stands the average value for the differentiation index indicated rather low spatial variability of this tree characteristic and the TD value ranged

Table 2. Mean values for Clark-Evans (R), differentiation index for DBH (TD) and height (TH) and species mingling index (DM) in investigated *European beech* forests

	R			TD			TH			DM	
	LT	FCT	OS	LT	FCT	OS	LT	FCT	OS	LT	OS
A	1,03	1,03	0,63**	0,32	0,15	0,40	0,19	0,07	0,28	0,16	0,85
B	1,11*	1,24**	0,78	0,24	0,15	0,26	0,07	0,08	0,12	0.19	0,89
C	1,19**	1,28**	–	0,22	0,14	–	0,10	0,08	–	–	–

Explanation: LT – living trees, FCT – future crop trees, OS – other tree species; * – significant differences at a=0.05; ** – significant differences at a=0.01

from 0.32 (stand A) to 0.22 (stand C) for living trees taken together. The average values for FCT were distinctly lower than for all living trees and almost the same in all beech stands analyzed (varied from 0.14 up to 0.15). Other tree species demonstrated a little bit higher average values of TD (Table 2).

Distribution of the index TD showed that the diameter differentiation between nearest neighbors do not exceed 40% for living trees taking together. Cases with higher differentiation are rather sparse with only exception of the A stand, where ca. 20% of nearest neighbors differed more than 40%. Results indicated that OS were either similarly differentiated (B stand) or higher (>40%, A stand) comparing to living trees (Fig. 1). When FCT are analyzed it can be seen more than 70% of them demonstrated differentiation up to 20%. Only 20–30% of nearest neighbors of FCT revealed the differentiation in DBH at the level of 20–40%, and 10% showed even higher differentiation. The latter case was observed only in one stand (C) (Fig. 3).

Height differentiation

Height of trees in all 3 beech stands demonstrated much lower spatial differentiation than DBH. The average TH value varied from 0.07 to 0.19 (Table 2) for all living trees. Future crop trees revealed distinctly lower average values (0.06–0.07) of this index comparing to all living trees, and values were similar in all

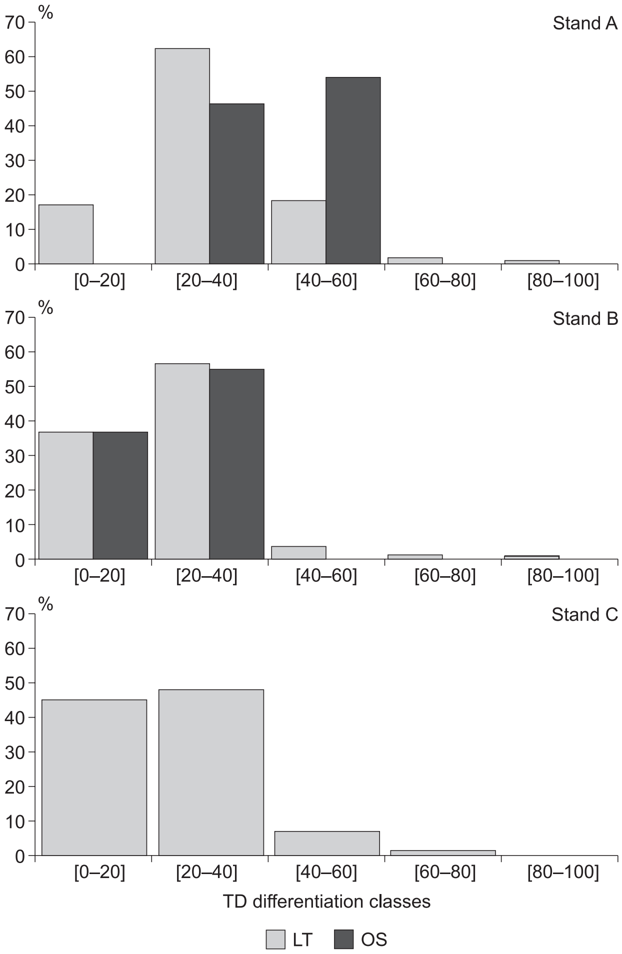

Fig. 1. Distribution of the TD index in differentiation classes for investigated beech forests

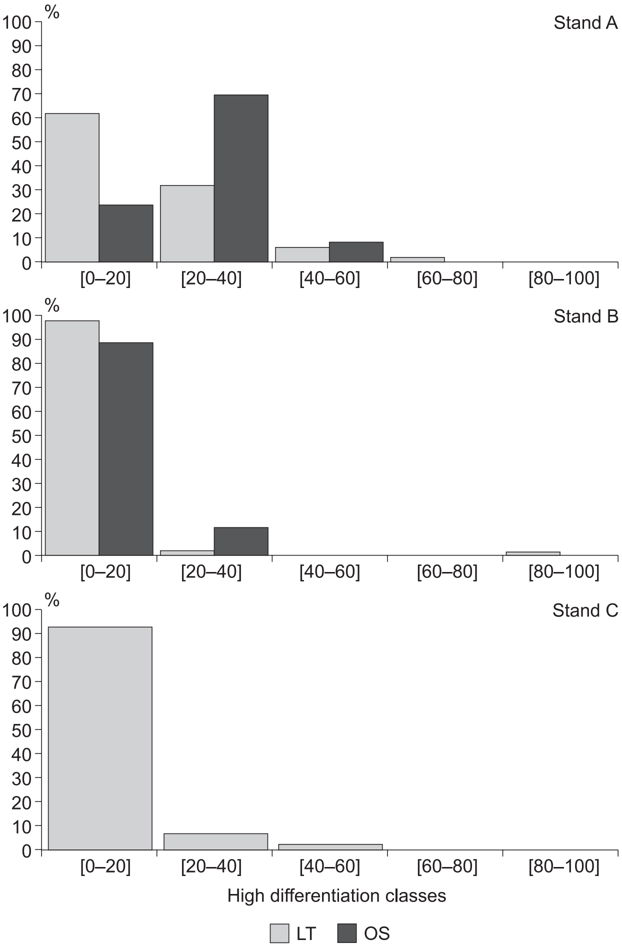

Fig. 2. Distribution of the TH index in differentiation classes for investigated beech forests

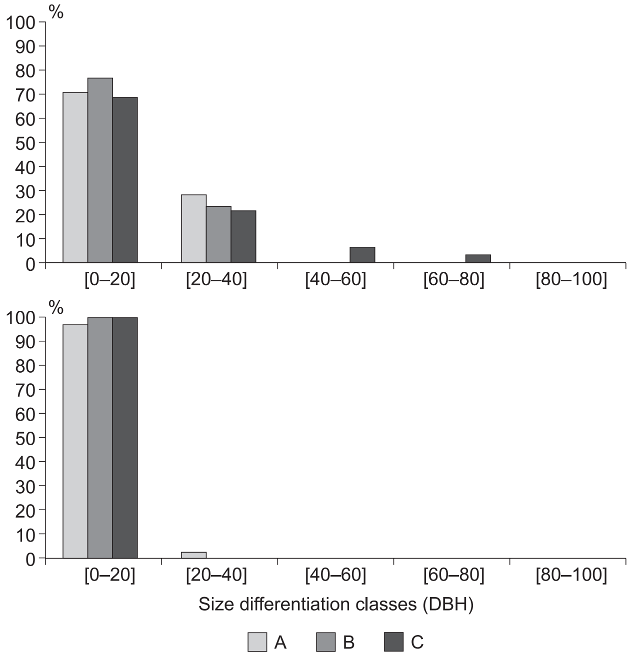

Fig. 3. Distribution of TD and TH indices for future crop trees (A-stand A, etc.)

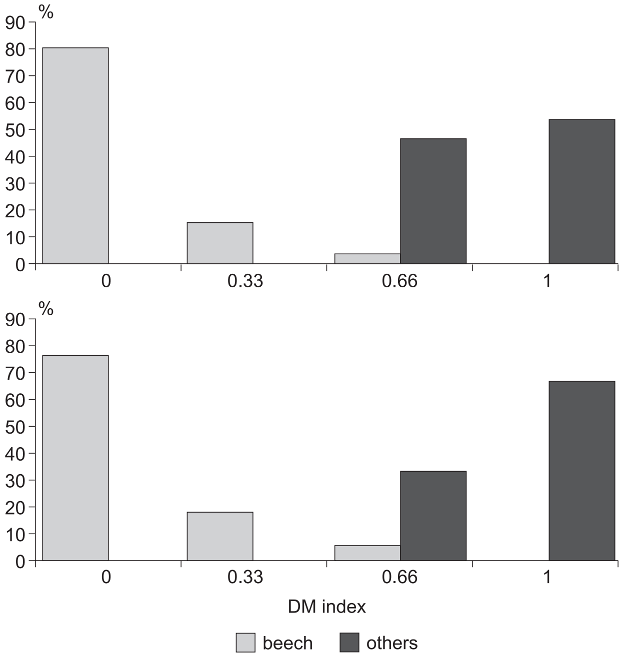

Fig. 5. Distribution of DM index in mingling classes in two forest stands, A and B

stands. Trees of other species showed higher differentiation in terms of their height and the values for 2 stands was 0.28 and 0.12.

Low spatial variability of total trees height was confirmed by the distribution of the TH index in differentiation classes (Fig. 2). In 2 stands (B, C) more than 90% of nearest neighbors belonged to the lowest class of height differentiation represented the differentiation lower than 20% in height. In one stand (A) 60% of trees showed the same class and ca. 38% of trees demonstrated higher height differentiation, whereas in stand B and C the share of trees of higher differentiation was much lower (<8%). Trees of other species exhibited low differentiation as well but stands differed between each other. In stand A the most abundant differentiation class was the class where nearest neighbors differ about 20-40% in height, then 23% of nearest neighbors differed less than 20%. In stand B the most abundant class is class of the lowest differentiation (<20%). Almost 100% of future crop trees belonged to the lowest class of height differentiation (Fig. 3).

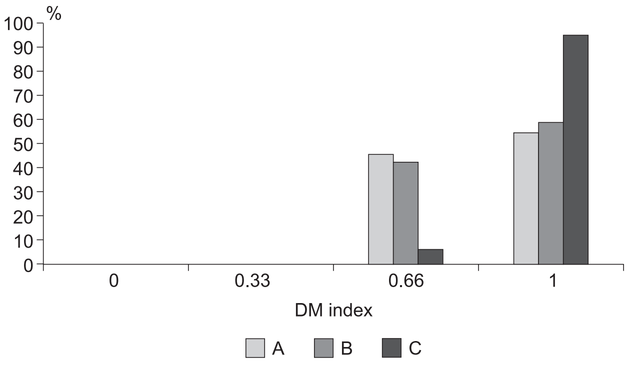

Fig. 4. Distribution of DM index for FCT and non-FCT (A-stand A, etc.)

Spatial organization of future crop trees

The average values of mingling for DM_{FCT} varied from 0.85 to 0.98 and indicated that the nearest neighbors of FCT are non-FCT trees and results are similar for each analyzed beech stand. It was confirmed by the distribution of DM_{FCT}. In 45.71% and 41.94% of FCTs their two neighbors were non-FCT trees in stand A and B, respectively. Three neighbors belonging to non-FCTs were observed for 54.29% and 58.06% of FCT (stands A, B respectively). In case of stand C more than 93.75% of FCT had 3 neighbors of non-FCTs (Fig. 4).

Species mingling

In stands A and B other tree species than European beech were present and both stands showed low mingling of species. The mean values for DM index were 0.16 for stand A and 0.19 in stand B. Distribution of DM index (Fig. 5) indicated that beech formed homogenous groups and each beech is surrounded by 3 or 2 other beeches. Other tree species occurred more often alone so they were very well intermingled with beech.

Discussion

Tree positioning

Presented results indicate that managed mature beech stands can reveal regular distribution of trees, also future crop trees, making the spatial structure more homogeneous than unmanaged stands. Pommerening (2002) observed regularity in tree dispersion in planted Douglas fir stand as well as in mixed forest consisted of beech with some pines and oaks. Zingg and Ramp (2004) stated that managed pure and mixed beech stands are characterized by regular distribution of living trees and other types (random or clumping) were very rare. Regularity in spatial positioning of trees in managed beech stands in Slovenia was reported by Boncina et al. (2007). They noted also that future crop trees were more uniformly dispersed in the stands than all living trees. This paper's results support their conclusion. Analyzing pine stands established by planting and managed, Crecente-Campo et al. (2009) observed that thinning regimes lead to more or less regular distribution of remaining trees. They noted that different thinning intensities influence the spatial distribution of trees in different ways. Regularity in tree dispersion was observed also by Bilek et al. (2011). Regular type of distribution of individuals observed in managed stand is usually attributed to density-depended mortality, also. In stands where human interventions are limited, e.g. forests in reserves, the main factors influencing the spatial organization of individuals are competition and mortality. Random mortality leads very often to random distribution of living trees, whereas competition is usually responsible for their regular spacing. Because forests considered here were managed it can be assumed that thinning treatments played important role in creating the spatial pattern of trees. Such a role of thinning on spatial structure of forest was reported by others (Pretzsch 1999, Kint et al. 2003, Brzeziecki 2005, Crecente-Campo et al. 2009, Bilek et al. 2011). As noted by Pretzsch (1999) the effect of the influence of thinning depends on the method and its intensity. Thinning method is important because it describes which trees are removed from the stand. Selective thinning or thinning from above creates more diversified (heterogeneous) spatial structure of the stand than thinning from below does. Also Kint et al. (2003) observed more regular distribution of trees in pine stands after intensive thinning. Bilek et al. (2011) observed random or regular distribution in unmanaged stands and regular one in case of managed ones. Crecente-Campo et al. (2009) reported random regular distribution of trees after heavy and very heavy thinning in planted Scots pine stands what makes them similar to naturally regenerated forest. In analyzed beech stands future crop trees were mostly surrounded by non-future crop trees what could be expected because they are managed (thinned) according to silvicultural rules recommending regular spacing between them. Regularity in distribution of future crop trees were observed in managed beech stands in Slovenia by Boncina et al. (2007). Such spatial positioning of such trees was attributed to selective thinning method.

Size differentiation

Greater homogeneity in terms of tree size variation in managed stands comparing to unmanaged ones is well known (Pretzsch 1999, Pommerening 2002, Dröâler and Lüpke 2004, Montes et al. 2004, Barbeito et al. 2009, Crecente-Campo et al. 2009, Jagodzinski and Oleksyn 2009a, Szmyt 2010, Bilek et al. 2011). Structural diversity of analyzed beech stands in terms of DBH and height of trees was rather low confirming their homogeneity. It referred to all living trees as well as future crop trees. Especially the later ones showed high homogeneity in DBH and – even more – in the height. This homogeneity could result from the thinning treatment conducted in all investigated stands. Brzeziecki (2005) stated that thinning from below imitating natural thinning leaded to lower DBH differentiation between the neighbors than in case of selective thinning. Low variation in DBH was found by Dröâler and Lüpke (2004) in managed old-growth beech stands in Germany while Bilek et al. (2011) pointed at low DBH differentiation in managed stands in Bohemia. In un-managed beech forests the differentiation index showed higher values (Bilek et al. 2011). Homogeneity in DBH differentiation among the nearest neighbors was stated by Szmyt (2010) in managed Scots pine stands of different age. Apart from low DBH differentiation observed in analyzed natural beech stands, they were also characterized by very low height diversity, both for living trees and future crop trees. It shows that neighbors only a little differ from each other in terms of this tree parameter. Kint et al. (2003) observed similarly low values of TH in managed Scots pine stands.

Species mingling

Obtained results confirmed high homogeneity of beech stands. Other tree species, like pedunculate oak and silver fir in this case, usually formed single mixture. Beech in both stands was surrounded by 3 neighbors of the same species and other species were surrounded mostly by 3 or 2 trees of beech. It points out that the other tree species are single mixtures to beech. In old-growth beech stands it is quite natural because beech makes strong shadow below the canopy in order to let the other species in-growth in the forest canopy. Other species may establish in gaps created by natural small disturbances or formed by human interventions. Bilek et al. (2011) found similar mingling in old-growth beech forest with an admixture of hornbeam where the latter formed single mixture. Groups of beech found Pommerening (2002) in 120 year old oak-beech forest and oaks were surrounded usually by 4 or 3 beeches. Gadow and Hui (2007) observed similar mingling in beech-ash forest in Bovenden, Lower Saxony. Beech formed pure groups whereas ash was single mixture and trees of this species were surrounded by other species.

Conclusion

This paper presented different nearest neighbor indices suitable to describe the spatial structure of forest in horizontal (positioning, DBH differentiation) and vertical aspects (height differentiation). Mingling index, describing mutual spatial positioning of different species, gives information how different tree species are intermingled (association or segregation of species). All presented indices have one important thing in common. First, they describe spatial aspects in the smallest spatial scale (nearest neighborhood). Secondly, they do not need exact maps of stems location in the stand and they can be successfully applied in the field by foresters.

For scientists who are involved in comparison of structure diversity of natural and managed forests they can be a suitable tools for such research.

Answering the questions included in the aim of the paper it can be stated that:

1. Mature and naturally regenerated beech forests reveal rather simple spatial structure in terms of each aspect taken into consideration. It can be assumed that human interventions, like thinning, were among the main factors causing low diversity of them.
2. Because the future crop trees showed the lowest spatial diversity comparing to the all living trees, it can be predicted that thinning regimes lead to further decreasing of the spatial structure of beech forests.
3. Managed beech forests are rather poor in terms of tree species richness.

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