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ORIGINAL RESEARCH ARTICLE

Spatial diversity of planted and untended silver birch (*Betula pendula* L.) stands

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Abstract. The aim of this paper was to describe changes in the spatial distribution of living trees in planted and untended birch stands, as well as to determine the spatial differentiation of the diameters and height of their constituent trees. Analysis was performed in 9- and 39-year old stands.

The structural diversity of birch stands was described using the following spatial indices: Clark-Evans index *(CE)*, spatial differentiation index for DBH (*TD*) and height (*TH*). The *CE* index describes the horizontal distribution of trees within a stand and the *TD/TH* indices indicate the size differentiation between neighbouring trees within a stand (DBH and H, respectively). The indices mentioned above concern small spatial scales. Our results indicate a regular spatial distribution of living trees on the ground at age nine, shown by high *CE* index. After 30 further years of stand development *CE* values were distinctly lower and no longer significantly different from the value for a random distribution of trees. At age 39, the 2 stands had a random spatial distribution and in the planted stand living trees still retained a regular spatial arrangement. Analysing the spatial differentiation of diameter and height of trees revealed that there was little differentiation between neighbours in forest stands in neither their diameter and height. The highest average values for the *TD* index decreased for stands during the 30 years since their initial measurement at age nine. A similar trend was observed for height differentiation *(TH)*,which decreased from a maximum at age nine.

Key words: spatial structure of stands, size differentiation of trees, silver birch, plantations, semi-natural forest

1. Introduction

Due to the longevity of trees, a stand is subject to two types of variation: cyclical, relating principally to growth, and continuous, occurring over the very long period of a tree stand's life and primarily related to developmental processes (Szymański 2000). The most important of these include the natural differentiation of trees positions in the stand layers (biosocial position of trees), resulting from the processes of their natural development, the natural process of self-pruning and the process of stand ageing. To these should be added the creation of the stand-specific spatial structure, resulting from various factors, biotic as well as abiotic nature. Natural processes in a tree stand occur with varying intensity during specific stages of development, affecting its dynamic. Understanding the population dynamics of trees in artificially planted forests – whose share in the total area of forests both in Poland and in the world is significant – seems particularly important from the point of view of forest sustainable management.

Until recently, tree stand structure was described most frequently with the use of such parameters as average size (thickness, height, etc.), average density or cross-sectional diameter at breast height. Currently, the spatial aspect is used to describe stand structure with increasing frequency, relating to the horizontal distribution of trees in the stand, spatial size differentiation or the spatial mixing of species in a multi species forest (Gadow, Hui 2002; Aquirre et al. 2003; Boyden et al. 2005; Szmyt, Korzeniewicz 2010). Of particular importance are changes in stand structure occurring during its various stages of

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development. The long life of trees, however, means that studying forest dynamics requires long-term work and analyses, repeated every several or several dozen years (Szymański 1964; Ward et al. 1996; Kenkel et al. 1997; Hessburg et al. 2000; Woods 2000; Szmyt 2004; Wolf 2005; Saunders, Wagner 2008; LeMay et al. 2009). Most research on forest dynamics has been conducted on natural forests; much less so on artificially established forests. The fact that the vast majority of forests in Poland and Europe originate from artificially planted stands is precisely the reason why research needs to be conducted on such populations. This will enable comparisons to be made of the structural variations between managed stands and natural forests, as well as to determine the influence of forest management on the development of the mentioned populations (Commarmot et al. 2005; Bilek et al. 2011).

Managed forests are perceived as wood lands with a simplified structure, in the spatial aspect also however, the dynamics of these populations are relatively poorly understood. Supplementing this knowledge may lead to the development of new rational management principles that take into account naturally occurring ecological processes. Skilfully undertaken management activities may lead to an increased structural diversity of stands, which in the case of artificial populations is especially important, not only ecologically but also economically (Latham et al. 1998; Lähde et al. 1999; Lexerød, Eid 2006). One of the factors determining the dynamics of a tree stand is the way the trees occur on the surface area, as this determines the influence of various ecological processes (e.g. competition, mortality). On the other hand, the same processes can shape the spatial structure of the stand in the next phases of development (Lepš 1990; Stoyan, Penttinen 2000; Comas, Mateu 2007, Eichhorn 2010).

The present paper is on birch forests, initially planted in regular rows and left untended. For this reason, these are as provide good material to study the dynamics of artificially planted, untended tree stands.

The purpose of this paper is to investigate the dynamics of the spatial structure of birch stands during the intensive growth stage of young trees, thus in a period when proportions are rapidly changing. In particular, the analysis included: 1) the placement of live trees and b) the spatial differences in tree height and thickness. The spatial variations of tree stands are defined with the help of indices of structural variation that can be used in forestry practice, such as in performing a forest inventory.

2. The study subject and methodology

The study was conducted at the experimental plots of the Department of Silviculture, Faculty of Forestry of the University of Life Sciences in Poznań, founded in the spring of 1970 by Prof. Stanisław Szymański. Administratively, the study area is located inthe southern part of the Wielkopolskie Voivodeship in Kępińsk County at the Forest Experimental Station of the University of Life Sciences in Poznań within the Wielisławice Forestry District in sections 25 hand 25i. The geographical coordinates of the area are: λ = 18° 03'E, φ= 51° 12'N.

According to the regionalisation for natural and forested areas adopted in the country, the site is part of the Krainy Śląskiej (Land of Silesia), Wrocław District, Równina Oleśnicka (Oleśnicka Plain) mezzoregion (V.2.g) (Trampler et al. 1990). The average rain fall for the year is in the range of 550–600 mm (Schmuck 1959; Ceitel, Wawro 1999). The birch stand selected for the study are growing on post-agricultural red podzolic soils formed from loose glacial sands. In all three areas (marked in the text as I, II and III), fully prepared soils and similarly aged planting stock (1-year old seedlings) were used with an initial spacing of 1.0×1.0 m. To date, the stands were left untended.

Methodology

In order to analyse the spatial differentiation of birch stands, the following measurements were taken during field work: root collar thickness of 10-year-old young tree stands (cm), diameter at breast height of older stands (D_{13}, cm) and total height (*H*, *m*) of all live trees. The position of each tree was described using rectangular coordinates. Measurements and observations were carried out in the autumn of 1978 and 2009 at three square areas with a side length of 20 m. The following spatial indices of structural diversity of the stands were calculated: the Clark-Evans index of aggregation (*R*), spatial differentiation index for diameter at breast height (*TD*) and spatial differentiation index of height (*TH*).

The Rindicator enables the type of horizontal distribution to be specified of the studied population, based on the distance between the nearest neighbouring trees in a stand (Clark, Evans 1954; Brzeziecki 2002; Kint 2004). The method is based on comparing the average distance between nearest neighbours in the test stand and the expected (theoretical) average distance between them at their random distribution. The mathematical formula for the *R* index with Donnelly's modifications is as follows (Kint 2004; Szmyt, Ceitel 2011):

$$R = \frac{r_A}{r_E} = \frac{\frac{1}{N}\sum_{i=1}^{N} r_i}{0{,}5\left(\frac{A}{N}\right)^{1/2} + 0{,}0514\frac{P}{N} + 0{,}041\frac{P}{N^{3/2}}}$$

where:

r_A – average distance between nearest neighbours,

r_E– average expected (theoretical) distance between nearest neighbours,

r_i– distance between an individual tree and its nearest neighbour (m),

N – number of individual trees in the measured area,

A – size of the area (m^2),

P – diameter of the area (m).

Tree stand with a random distribution of trees is characterised by an index of *R*=1; when trees are arranged in clusters, then *R*<1. The value of *R*>1 indicates an even distribution of trees in the test stand. The significance of deviations of the calculated index from the theoretical pattern can be determined using the standard *Z* normal distribution (Kint 2004):

$$c = \frac{r_A - r_E}{\sigma_{r_E}}$$

$$\sigma_{r_E} = \frac{0{,}26136}{\sqrt{N \cdot \rho}}$$

where:

σ_{rE} – the standard deviation r_E fora random distribution of density ρ.

The index of spatial diameter and height differentiation of the trees (*TD* and *TH*, respectively) determines the similarity in the diameter or height of trees in the stand at the smallest spatial scale, i.e. the scale of the immediate neighbour. The mathematical formula for the index involving three nearest neighbours is denoted by (Pommerening 2002; Aguirre et al. 2003; Kint 2004; Szmyt, Ceitel 2011):

$$TD_i = \frac{1}{3}\sum_{j=1}^{3}\left[1 - \frac{\min(s_i, s_j)}{\max(s_i, s_j)}\right]$$

where:

i – indicator for the reference (central) tree,

si – size (DBH or height) of tree *i*,

sj – size (DBH or height) of tree *j*.

The index value is calculated for each tree in the stand, and then averaged to indicate the average spatial differentiation of the size of the trees within the stand. The index can have values from 0 to 1, with 0 indicating no spatial variation in thickness and that the trees are all the same size, where as the value of *TD*=1 indicates a very high variation in the dimensions of the trees (Kint 2004; Bilek et al. 2011; Szmyt, Ceitel 2011).

In the case of the spatial differentiation index values (*TD* and *TH*), the following class differentiations were adopted: 0.00–0.20, very small variation (nearest neighbour difference in size is not more than 20%); 0.20–0.40, small variation (difference in size is 20–40%); 0.40–0.60, medium variation (difference of 40–60%); 0.60–0.80, high variation (difference of 60–80%); and 0.80–1.00, very high thickness variation (difference of 80%) (Aguirre et al. 2003; Kint 2004; Vorcak et al. 2008).

All calculations in this study were carried out using the SIAFOR ver.1.0 software (Kint 2004).

3. Results

The horizontal distribution of the trees

The value of the aggregation index *R* indicates a significant change in the horizontal distribution of live trees over a 30-year period in all three stands. The initial value of the index (for trees at 9 years of age) clearly indicated a very regular distribution of individuals in each stand (*R*>1, α =0.05). Specific stands of this age were characterised by a similar value of the Clark-Evans index (Table 1). During 30 years of further development, the index value of these stands decreased significantly. In their 39th year of life, a random distribution of live trees was determined for two stands (*R*=1.05 and *R*=1.00), while trees in another stand continued to be regularly distributed (R=1.19).

Table 1. Average value of spatial diversity indices of distribution (*R*), DBH differentiation (*TD*) and height differentiation *(TH)* in untended birch stands at different ages

Forest stand	9 years			39 years		
	R	*TD*	*TH*	*R*	*TD*	*TH*
I	1.75**	0.30	0.22	1.05	0.26	0.23
II	1.72**	0.37	0.26	1.19**	0.29	0.17
III	1.73**	0.39	0.30	1.00	0.29	0.20

** level of significance α=0.01

Table 2. Statistical characteristics of DBH (*D*) and height (*H*) of live trees in untended birch stands at 9 and 39 years of age

Forest stand	Tree age	Number of trees	G_{ha}	Survival	Average		Min		Max		Standard deviation		Coefficient of variation	
	years		m²	%	*D* (cm)	*H* (m)	*D* (cm)	*H* (m)	*D* (cm)	*H* (m)	*D* (cm)	*H* (m)	*D* (%)	*H* (%)
I	9	323	20.6	100.0	5.4**	4.2	0.5	0.8	11.3	6.4	1.84	10.92	33.54	25.79
II		312	23.4	96.6	5.7**	4.7	0.6	2.2	12.1	8.3	2.46	14.42	43.41	30.51
III		314	17.2	97.2	4.8**	4.1	0.6	4.0	10.8	7.6	2.23	14.55	46.73	35.20
I	39	48	13.7	14.9	11.8	17.1	7.0	4.5	18.0	21.8	2.71	3.92	23.06	22.85
II		45	17.9	13.9	13.7	20.2	8.0	14.4	21.0	25.7	3.73	3.10	27.23	15.32
III		38	16.4	11.8	14.1	20.5	7.0	12.8	24.5	28.0	4.33	3.84	30.55	18.73

* – root collar thickness

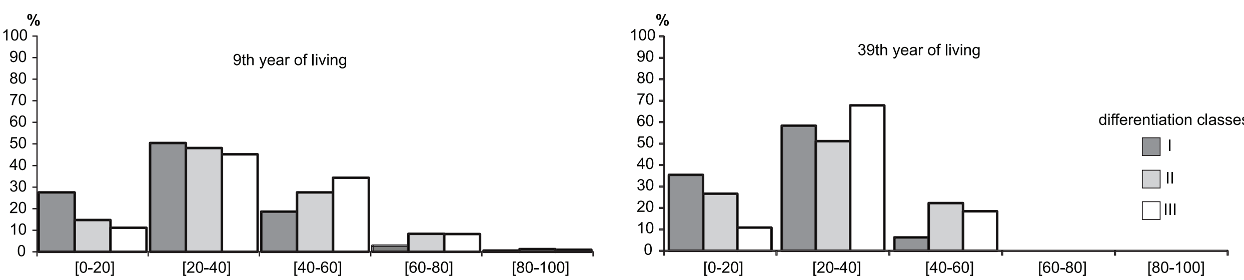

Figure 1. Distribution of the spatial differentiation index for DBH *(TD)* in particular classes of differentiation at different ages in untended birch stands

Spatial variation of tree diameter

The average rate of variation in the diameter of trees in the stand exhibited little diversity from the very beginning, with trees not differing more than 40% from their nearest neighbours (Table 1). Over 30 years, this difference significantly declined even further in all three stands. The reduced variation in thickness was also confirmed by the coefficient of variation of this characteristic, whose values also significantly decreased in the 39-year-old stands (Table 2).

Figure 1 shows the proportion of trees in the adopted classes of diameter differentiation. The largest number of trees in the studied stands at 9 and 39 years of age were in the class of 20–40% diversity. At the beginning of the study period, a distinct proportion of trees were in the medium class of 40–60% diversity in two stands, whereas at the end of the study period, the proportion of trees in this class decreased in favour of the class with the least diversity of diameter between immediate neighbours. The figure shows that in the 9th year of age, only the thickness of a small number (%) of trees differed significantly from their nearest neighbours (difference of 60%). After the stands developed for a further 30 years, trees exhibiting such a difference in diameter at the breast height were not found.

Spatial variation of tree height

Table 1 shows the average value of the spatial diversity index of tree height for individual stands. It shows that tree height variation in both the 9- and 39-year-old stands is small and decreases with age. Only in Stand I the average index value increased slightly from 0.22 to 0.23 at the end of the analysed period. The decrease in height was also confirmed by the coefficient of variation calculated for the height of the trees (Table 2).

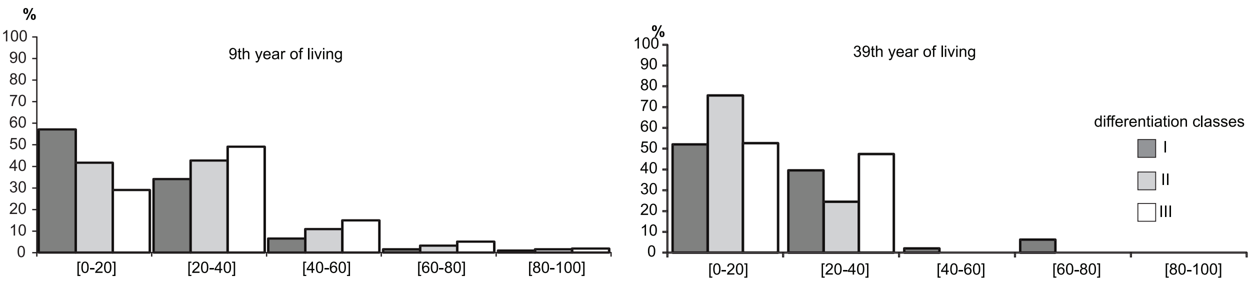

Figure 2. Distribution of the spatial differentiation index for height *(TH)* in particular classes of variations at different ages in untended birch stands

The proportion of trees in each class of height differentiation in comparison with its neighbours is shown in Figure 2. Both at the beginning and at the end of the analysed period, the highest number of trees belonged to the class of up to 40% of height diversity. With age, the proportion of trees in the class with the lowest diversity increased in two stands, at the expense of the other classes. The figure also shows that the proportion of trees significantly differing in height compared with their neighbours decreases with age, reflecting a reduction in the height variation of the tree stands. At the age of 9, the proportion of young trees differing in height by more than 40% ranged from 8.9% to almost 22%. At the end of the study period, only one stand exhibited this variation (40%) in about 8% of its trees.

4. Discussion

An initial regular spatial distribution of trees is typical of untended stands planted in a specified pattern, and the results confirm previous studies. The regular spatial distribution of live trees in plantations and young stands is confirmed by, for example, Szmyt (2004), who analysed the spatial structure of artificially planted, untended pine, spruce and oak established in various patterns of rows. Regardless of the pattern used in planting, all the analysed stands exhibited a distinctly regular spatial distribution at the time of harvesting, which resulted from the initially imposed pattern. However, this need not be a permanent feature, as it may vary in subsequent phases of stand development. The direction of these changes in artificially planted stands is not sufficiently understood and requires further studies (Szwagrzyk 1992; Sekretenko, Gavrikow 1998; Szmyt 2004; Szmyt 2010).

In the case of naturally regenerated forests, the dynamics of tree distribution is much better known and most often starts with a clustered distribution in the regeneration phase, then goes to a random distribution and finally a regular distribution in older age-class forests (Gavrikow, Stoyan 1995). In the early developmental phase of artificially planted tree stands, the clustering of individuals should not be expected, and this was confirmed by our research. However, in older stands, when the effect of the initial spacing lessens due to natural processes, the future direction of changes can occur as it does in natural forests (Szmyt 2004; Szmyt, Korzeniewicz 2010). A random distribution of live trees in older stands of artificial origin was observed by Szwagrzyk (1992) and Szmyt (2010). However, Sekretenko, Gavrikow (1998), Pommerening (2002), Kint et al.(2003), Mason et al. (2007) and Szmyt, Ceitel (2011) found a regular distribution of trees in stands of similar origin.

The reasons for the regular distribution of trees in stands are seen primarily as the result of competition between individuals, but competition is not always the most important process occurring in populations, as often many other factors and ecological processes play a more significant role in the formation of the characteristic spatial structure (Kenkel 1988; Szwagrzyk 1992; Murrell 2009). The impact of competition resulting from the high density of individuals in naturally regenerating tree stands is especially visible in natural forests, when the intensity of individual growth is greater in areas with a higher density, often leading to the random or regular distribution of the remaining trees. In artificially planted, managed stands, the choice of initial planting pattern and density may limit competition among individuals. As Szmyt (2004) noted, the sparser the initial plantings, the more durable the regular distribution of trees in the stand.

Often, single species and similarly aged stands are considered to have little structural differences. Our results support this view in the diversity of both the thickness and height of the trees. In untended birch stands, the coefficient of variation of thickness and height, as well as the spatial diversity indices of both these characteristics, indicate little variation throughout the 39 years of the analysed period. This diversity was greater in stands of young birch trees and significantly decreased with age. During cultivation, before the tree canopy closed, the growth of young trees was individual in nature and resulted from the interaction of genotype and environment. As soon as the tree canopy closed, competitive interaction between individuals took on greater significance. As a result of this competition, the weakest individuals are eliminated, usually those with a small diameter at breast height and low height.

The study results presented of the birch stands are consistent with other research on artificially planted stands (Pommerening 2002; Szmyt, Korzeniewicz 2010; Szmyt, Ceitel 2011). In examining the diameter variation of artificial pine stands of different ages, Szmyt (2010) found that the least variation occurred in the oldest stands (90-year-old), but it was also small in 43- and 65-year-old stands. Little variation of diameters was found in the artificially planted pine stands analysed by Mason et al. (2007). Dröβer and Lüpke (2004) observed a similar trend in single species managed stands of beech aged 148 and 166 years. Younger stands (80 and 120 years) were more varied in this feature. Little height variation was found by Kint et al. (2003) in artificially planted pine tree stands. As Brzeziecki (2005) noted, the diversity of tree stands depends not only on various ecological processes, but also on how they are managed (e.g. thinned). The author found that in a sample pine stand, diameter variation was small before thinning, while thinning from below, thus preceding the natural removal of trees, decreased variability even more. On the other hand, selective thinning, the recommended practice, promotes the formation of greater spatial variation in a stand.

Crecente-Campo et al. (2009) analysed the impact of thinning on the structural diversity of 50- to 60-year-old artificially regenerated pine stands. The control plot (no thinning) had a random distribution of trees, and indicators of the structural diversity of thickness and height decreased as a result of the natural elimination of trees from the stand. The influence of thinning on the aforementioned characteristics depends, among other things, on its intensity (Crecente-Campo et al. 2009). Similar conclusions were reached earlier by Pretzsch (1999) who analysed the effect of different management practices on the diversity of mixed spruce and beech stands.

5. Conclusions

The results obtained allow the following conclusions to be proposed.

Despite the initial pattern of distributing seedlings during planting, horizontal distribution can become random as a result of the natural processes eliminating trees from the stand. If left untended, this processis the main one influencing the horizontal distribution of trees in a stand.

The results presented confirm the thesis that the lack of tending in birch stands during the initial stage of their development leads to a decrease in thickness and height diversity. Based on the natural ecological processes occurring in birch stands, increasing their diversity is not possible.

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References

Aquirre O., Hui G., Gadow H. V., Jimenez J. 2003. An analysis of spatial forest structure using neighbourhood-based variables. *Forest Ecology and Management,* 183: 137–145.

Bilek L., Remes J., Zahradnik D. 2011. Managed vs. unmanagedstructure of beech forest stands *(Fagus sylvatica* L.) after 50 years of development, Central Bohemia. *Forest Systems,* 20: 122–138.

Boyden S., Binkley D., Shepperd W. 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. *Forest Ecology and Management,* 219: 43–55.

Brzeziecki B. 2002. Wskaźniki zróżnicowania struktury drzewostanu [Indices of stand structural diversity]. *Sylwan,* 4: 69–79.

Brzeziecki B. 2005. Wpływ trzebieży na zróżnicowanie strukturalne drzewostanów sosnowych [Impact of thinning on structural diversity of Scots Pine stands]. *Sylwan,* 10: 11–19.

Ceitel J., Wawro T. 1999. Wyniki obserwacji meteorologicznych z terenu leśnictwa doświadczalnego Wielisławice (LZD Siemianice) za okres 1988–1997. *Roczniki Akademii Rolniczej w Poznaniu, Leśnictwo,* 37: 3345.

Clark P., Evans F. 1954. Distance to the nearest neighbor as a measure of spatial relationships in populations. *Ecology,* 35 (5): 445–453.

Comas C., Mateu J. 2007. Modelling forest dynamics: a perspective from point process methods. *Biometrical Journal,* 49: 176–196.

Commarmot B., Bachofen H., Bundziak Y., Bürgi A., Ramp B., Shaparyk Y., Sukhariuk D., Viter R., Zingg A. 2005. Structure of virgin and managed beech forests in Uholka (Ukraine) and Sihlwald (Switzerland): a comparative study. *Forest Snow and Landscape Research,* 79: 45–56.

Crecente-Campo F., Pommerening A., Rodriguez-Soalleiro R. 2009. Impacts of thinning on structure, growth and risk of crown fire in a *Pinus sylvestris* L. plantation in northern Spain. *Forest Ecology and Management,* 257: 1945–1954.

Dröβer L., von Lüpke B. 2004. Quantitative description of forest structure in a virgin beech forest and a comparison with managed beech forest. Teheran, Iran, Proceedings from the *7-th International Beech Symposium.* IUFRO Research Group 1.10.00. 10–20 May 2004, 37–47.

Eichhorn M. P. 2010. Spatial organisation of bimodal forest stand. *Journal of Forest Research,* 15: 391–397.

Gadow K. von, Hui G. 2002. Characterising forest spatial structure and diversity, in: Sustainable forestry in temperate regions (ed. L. Bjoerk). Lund, Materiały konferencyjne IUFRO, pp. 20–30.

Hessburg P. F., Smith B. G., Salter R. B., Ottmar R. D., Alvarado E. 2000. Recent changes (1930s–1990s) in spatial patterns of interior northwest forests, USA. *Forest Ecology and Management*, 136: 53–83.

Kenkel N., Hendrie M. L., Bella I. E. 1997. A long-term study of *Pinus banksiana* population dynamics. *Journal of Vegetation Science,* 8: 241–254.

Kenkel N. C. 1988. Pattern of self-thinning in jackpine: testing the random mortality hypothesis. *Ecology,* 64: 1017–1024.

Kint V., Van Meirvenne M., Nachtergale L., Geudens G., Lust N. 2003. Spatial methods for quantifying forest stand structure development: a comparison between nearest-neighbor indices and variogram analysis. *Forest Science,* 49 (1): 36–49.

Kint V. 2004. SIAFOR 1.0 - user guide. Laboratory of Forestry, Ghent University.

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

Lähde E., Laiho O., Norokorpi Y., Saksa T. 1999. Stand structure as the basis of diversity index. *Forest Ecology and Management,* 115: 213–220.

LeMay V., Pommerening A., Marshall P. 2009. Spatiotemporal structure of multi-storied, multi-aged interior Douglas fir *(Pseudotsuga menziesii* var. *glauca)* stands. *Journal of Ecology,* 97: 1062–1074.

Lepš J. 1990. Can underlying mechanisms be deduced from observed patterns in spatial processes in plant communities? (F. Krahulec, A. D. Q. Agnewand, J. H. Willems, eds.) 1–11. Academia, Prague.

Lexerřd N., Eid T. 2006. An evaluation of different diameter diversity indices based on criteria related to forest management planning. *Forest Ecology and Management,* 222: 17–28.

Mason W. L., Connoly T., Pommerening A., Edwards C. 2007. Spatial structure of semi-natural and plantation stands of Scots pine (*Pinus sylvestris* L.) in northern Scotland. *Forestry,* 80 (5): 567–586.

Murrell D. J. 2009. On the emergence spatial structure of size-structured populations: when does self-thinning lead to a reduction in clustering? *Journal of Ecology,* 97: 256–266.

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

Pretzsch H. 1999. Structural diversity as a result of silvicultural operations, in: (ed. A.F.M. Olsthoorn). Management of mixed-species forest: silviculture and economics, pp. 157–174. ISBN 9076095086.

Saunders M. R., Wagner R. G. 2008. Long-term spatial and structural dynamics in Acadian mixed wood stands managed under various silvicultural systems. *Canadian Journal of Forest Research,* 38: 498–517.

Schmuck A. 1959. Zarys klimatologii Polski. Warszawa, PWN.

Sekretenko O. P., Gavrikov V. L. 1998. Characterization of the tree spatial distribution in small plots using the pair correlation function. *Forest Ecology and Management,* 102: 113–120.

Szmyt J. 2004. Wpływ więźby początkowej i wieku na kształtowanie się poziomego rozmieszczenia drzew w niepielęgnowanych drzewostanach sosnowych, świerkowych i dębowych. Praca doktorska, Katedra Hodowli Lasu, Uniwersytet Przyrodniczy w Poznaniu.

Szmyt J. 2010. Spatial pattern of trees of different diameter classes in managed pine stands *(Pinus sylvestris* L.) of different age. *Acta Scientiarum Polonorum Silvarum Colendarum Ratio et Industria Lignaria,* 9: 37–49.

Szmyt J., Korzeniewicz R. 2010. Przestrzenne zróżnicowanie drzewostanów daglezjowych *(Pseudotsuga menziesii* (Mirbel) Franco) odnowionych sadzeniem na siedliskach BMśw i LMśw [Spatial diversity of Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands planted on fresh mixed coniferous and fresh mixed broadleaved sites]. *Sylwan,* 154 (11): 791–800.

Szmyt J, Ceitel J. 2011. Zróżnicowanie przestrzenne i grubościowe drzew w niepielęgnowanych drzewostanach sosnowych o różnym zagęszczeniu początkowym [Spatial and size diversity of trees in untended pine stands of different initial density]. *Sylwan,* 155: 749–759.

Szwagrzyk J. 1992. Small-scale spatial patterns of trees in a mixed *Pinus sylvestris-Fagus sylvatica* forest. *Forest Ecology and Management,* 51: 301-315.

Szymański S. 1964. Dynamika rozwoju niekierowanych młodników sosnowych [Dynamics of development of untending Scots pine thicket]. Poznańskie Towarzystwo Przyjaciół Nauk, *Prace Komomisji Nauk Rolniczch i Komisji Nauk Leśnych,* 15 (3): 341–404.

Szymański S. 2000. Ekologiczne podstawy hodowli lasu. Warszawa. Powszechne Wydawnictwo Rolnicze i Leśne. ISBN 8309017286.

Stoyan D., Penttinen A. 2000. Recent applications of point process methods in forestry statistics. *Statistical Science,* 15: 61–78.

Trampler T., Kliczkowska A., Dmyterko E., Sierpińska A., Matuszkiewicz W. 1990. Regionalizacja przyrodniczo-leśna na podstawach ekologiczno-fizjograficznych. Warszawa, Powszechne Wydawnictwo Rolnicze i Leśne.

Ward J. S., Parker G. R., Ferrandino F. J. 1996. Long-term spatial dynamics in an old-growth deciduous forest. *Forest Ecology and Management,* 83: 189–202.

Wolf A. 2005. Fifty year record of change in tree spatial patterns within a mixed deciduous forest. *Forest Ecology and Management,* 215: 212–223.

Woods K. 2000. Long-term change and spatial pattern in a late-successional hemlock-northern hardwood forest. *Journal of Ecology,* 88: 267–282.

Vorčak J., Merganič J. Saniga M. 2006. Structural diversity change and regeneration processes of the Norway spruce natural forest in Babia hora NNR in relation to altitude. *Journal of Forest Science,* 52 (9): 399–409.

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