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SPATIAL PATTERN OF TREES OF DIFFERENT DIAMETER CLASSES IN MANAGED PINE STANDS (*PINUS SYLVESTRIS* L.) OF DIFFERENT AGE

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Abstract. The present research was conducted in managed stands of Scots pine (*Pinus sylvestris* L.) at different age in Poland. All the investigated stands were planted and thinned according to selection thinning. Analysis of spatial structure concerned trees of different categories (DBH classess) depending on the age of stand. Spatial distribution of trees was investigated using two commonly used methods: Clark-Evans R index and Ripley's L(t) function. In stands of age 43 and 65 the effect of the initial spacing was observed and all living trees were distributed regularly at the smallest distances and at larger spatial scale they were spaced randomly. Random type of spatial structure of trees was observed when smaller and larger trees were taken into consideration, separately. In case of stands at the age 90 the effect of the initial planting on the spatial structure of trees was not observed even at the smallest distances independently of the category of trees taken into account. All living trees in these stands were distributed randomly. Only in two stands clumps of trees were observed and one concerned smaller trees and the other – larger trees. Size differentiation index was small for all stands. The lowest values was ascertained in the oldest stands.

Key words: spatial distribution, pine stands, managed stands, Ripley's function, size differentiation

INTRODUCTION

For better understanding of the dynamics of forests, detailed information on the natural processes is needed. So far, a great attention has been paid to self-thinning and self-pruning and a lot of information on those processes and their effect on the stand structures is available. Data on the spatial horizontal organisation of trees are not so numerous. In a natural population three main types of spatial distribution of trees can be distinguished: random, regular and clumped. Random type of spatial distribution means that trees are distributed independently from each other and the probability of finding

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trees in the whole population is the same. In aggregated population, individuals occur in clumps of different densities and sizes and in case of regular type of spatial distribution objects are evenly spaced in a population over a given area [Reich and Davis 2008].

Spatial structure of forest is a complicated forest characteristic due to the complex factors influencing it. Among the most important factors are: climatic factors, micro-site mosaic, relationships between plants (cooperation as well as competition), methods of regeneration, natural mortality of individuals, biological and ecological characteristics of organisms, natural disasters (fire, wind-throws), human activities etc. [Beaty 1984, Gil 1995, Pretzsch 1996, Vacek and Leps 1996, Falińska 1997]. Human activity is an important factor in managed stands. Different intensities of thinning result in different spatial pattern of the remaining trees [Pretzsch 1996, Bilski and Brzeziecki 2005, Crecente-Campo et al. 2009]. It is known that spatial arrangement of populations is not stable and it changes with time. Falińska [1997] stated that the reasons for changing the spatial structure of population may be connected with its development phase and mortality (self-thinning). Szwagrzyk [1992] stated that the role of self-thinning resulting from mortality and competition is not always clear in shaping the spatial structure of the forests. Dynamics of forests, their regeneration and growth, as well as occuring of natural disturbances are often affected by spatial pattern of trees [Stoyan and Penttinen 2000, Koukoulas and Blackburn 2005]. Most of research focusing on spatial structure dealt with natural forests, mostly mixed and with limited impact of human activity [Leemans 1991, Szwagrzyk 1990, 1992, Kenkel et al. 1997, Hessburg et al. 2000, Bolibok 2003, Paluch 2004, Wolf 2005, Mason et al. 2007, Crecente-Campo et al. 2009, Sanchez Meador et al. 2009]. Information on spatial pattern of individuals in case of managed forests is far less numerous [Kammensheidt 1998, Neumann and Starlinger 2001, Pommerening 2002, Montes et al. 2004, Szmyt 2004, Szmyt and Korzeniewicz 2007, Berbeito et al. 2009, Crecente-Campo et al. 2009, Sanchez Meador et al. 2009].

The aim of this paper was to find out:

1. What is the type of spatial pattern of trees in pure managed pine stands of different age.
2. What is the spatial tree diameter differentiation in such stands.

MATERIAL AND METHODS

Objects

Research plots are located in the Wymiarki Forest District, western Poland, within the natural range for all important forest tree species in Poland. Observations and measurements were carried out on nine temporary research plots (three plots for each stand) located in compartments: 218 c, 206 g and 220 d. The age of the stands varied: from 43 years (stands in comp. 218 c), 65 years (stands in comp. 206 g) up to 90 years (stands in comp. 220 d). All stands were monocultures and were planted at the standard initial density (ca. 12 000/ha) and spacing. Forest site type was determined for all stand as fresh coniferous forest.

Different operations (clearing and thinning) were carried out according to the management plans but detailed information on their intensities was not available.

Field measurements

Measurements and observations were conducted on rectangular plots of varying size from 0.18 to 0.21 ha. On each plot there were at least 60 trees. A number of trees in the particular stands are presented in Table 1. Trees were classified into the size classes according to the average DBH for each stand. Following tree categories and size classes were distinguished:

1) all living trees – for all nine plots
2) 3 plots in compartment No. 218 c – trees of diameter: $DBH_{aver.} < DBH \le DBH_{aver.}$
3) 3 plots in compartment No. 206 g – trees of diameter: $DBH_{aver.} < DBH \le DBH_{aver.}$
4) 3 plots in compartment No. 220 d – trees of diameter: $DBH_{aver.} < DBH \le DBH_{aver.}$

Exact coordinates (x, y) of every tree, as well as their diameters at the breast height (DBH) were measured.

Table 1. Characteristic of the pine stands on the measurement plots in the Wymiarki Forest District, Poland
Tabela 1. Charakterystyka drzewostanów sosnowych na powierzchniach pomiarowych w Nadleśnictwie Wymiarki, Polska

Feature Cecha	Stands at age 43 Drzewostan w wieku 43 lat			Stands at age 65 Drzewostan w wieku 65 lat			Stands at age 90 Drzewostan w wieku 90 lat		
	1	2	3	1	2	3	1	2	3
Area, ha Powierzchnia, ha	0.15	0.15	0.15	0.18	0.18	0.16	0.17	0.18	0.19
N (trees/plot) Szt./powierzchnie	346	312	349	152	129	120	60	61	71
BA, m^2/ha Powierzchnia przekroju, m^2/ha	25.2	24.2	25.7	31.2	27.0	23.4	23.6	18.8	19.4
R	1.20*	1.20*	1.10*	1.19*	1.24*	1.30*	1.02	0.90	0.97
TD	0.17	0.20	0.21	0.17	0.20	0.19	0.13	0.13	0.14
DBH (cm) $d_{1.3}$	11.58	11.90	11.68	20.51	20.17	20.05	28.03	27.98	26.80
d (m)**	2.36	2.45	2.34	3.91	4.21	4.26	4.54	5.95	5.69

TD – index of diameter differentiation.
R – Clark-Evans index.
*Significance level, α = 0.05.
**Mean distance between trees in the plot.
TD – wskaźnik zróżnicowania przestrzennego pierśnicy.
R – wskaźnik Clarka-Evansa.
*Poziom istotności α = 0,05.
**Średnia odległość między drzewami na powierzchni.

Methods

To analyse the spatial pattern of trees two commonly used methods were applied: Ripley's K(t) function and Clark-Evans index R. To find out the size differentiation of trees the size differentiation index TD was used [Pommerening 2002].

Ripley's function. This method is based on the knowledge of all distances between all trees taken into consideration. The advantage of it is that it gives information on the spatial type of trees' arrangement at different spatial scale [Haase 1995, Moeur 1997, Szwagrzyk and Ptak 1991, Bolibok 2003, Li and Zhang 2007]. K(t) function is calculated:

$$K'(t) = \frac{A}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{1}{w_{ij}} I_t(u_{ij})$$

where:

- A – area, m^2,
- n – number of trees,
- u_{ij} – distance between 'i'-th tree and 'j'-th tree,
- $I_{ij} = 1$ for $u_{ij} \le t$ – tree belongs to the area under study,
- $I_{ij} = 0$ – otherwise,
- w_{ij} – edge correction index [Haase 1995, Salas et al. 2006].

Besag [1977] proposed to use the L'(t) modification against K'(t) that stabilizes its variance and linearizes its curve:

$$L'(t) = \sqrt{K'(t)/\pi} - t$$

In case of randomly distributed population the function L(t) = 0. For aggregated population the L(t) > 0, and L(t) < 0 if the population is arranged regularly. Significance of departures from CSR (complete spatial randomness = null hypothesis) is evaluated using Monte Carlo test [Haase 1995, Szwagrzyk and Ptak 1991]. To make analysis of the spatial pattern of trees SPPA software [Haase 2004] was used.

Clark-Evans index R. R index was calculated with modification made by Donnelly [Clark and Evans 1954, Donnelly 1978]. In this method the average distance between trees and their nearest neighbours is compared with the expected mean distance. The index is calculated according to the formula:

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

where:

- A – area, m^2,
- N – number of trees,
- P – perimeter, m.

The null hypothesis $H_0 = 1$ so in case of randomly distributed population index R = 1. Value of R < 1 indicates the aggregated population whereas R > 1 means that trees are regularly spaced on the plot. The null hypothesis is tested using the standard, normally distributed test value c:

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

where: $\sigma_{r_E} = \frac{0.26136}{\sqrt{N \cdot \rho}}$, where: N – number of trees, ρ – density.

This single index informs about the distribution of trees only at the fine spatial scale.

Size differentiation index. Size differentiation index (TD) describes the dissimilarity of the tree sizes (diameter in our case) in the stand. The formula for it is [Pommerening 2002]:

$$TD = \frac{1}{3} \cdot \sum_{j=1}^{3} \left[1 - \frac{\min(DBH_i, DBH_j)}{\text{maks}(DBH_i, DBH_j)} \right]$$

The index can take the values between 0 and 1 and its value increases with increasing size differentiation between neighbouring trees. To find out about the average size differentiation in the whole stand, the TD values were summed and divided by the number of trees.

Both R and TD indices were calculated using the Crancod 1.3 software [Pommerening 2004].

RESULTS

Stands at the age of 43 years

In all stands investigated, all the live trees showed regularity at the distances up to 2 m. For larger distances trees were distributed randomly in two stands with clear deviations toward clumping. In the third stand clumping could be seen at the distances greater than 7 m. Ripley's function demonstrated that trees of smaller diameters (DBH < $DBH_{aver.}$) were randomly distributed. Regularity was observed only at the smallest spatial scale in two stands. Observed deviations from the randomness, not significant statistically, tended toward clumping. Larger trees (DBH > $DBH_{aver.}$) in all investigated stands were also randomly distributed. Similarly to smaller trees regular distribution can be found only at the smallest distances. Tendency of the observed deviations from CSR was the same as in case of smaller trees (Fig. 1).

The results obtained by using R index indicated regular type of all living trees distribution (Table 1 and 2). Trees of smaller and larger DBH than the average for the stand showed mainly random distribution but in one stand they were regularly spaced. DBH differentiation index for all stands at this age was low, and it did not exceed 0.21, indicating that neighbours were similar in sizes (Table 1).

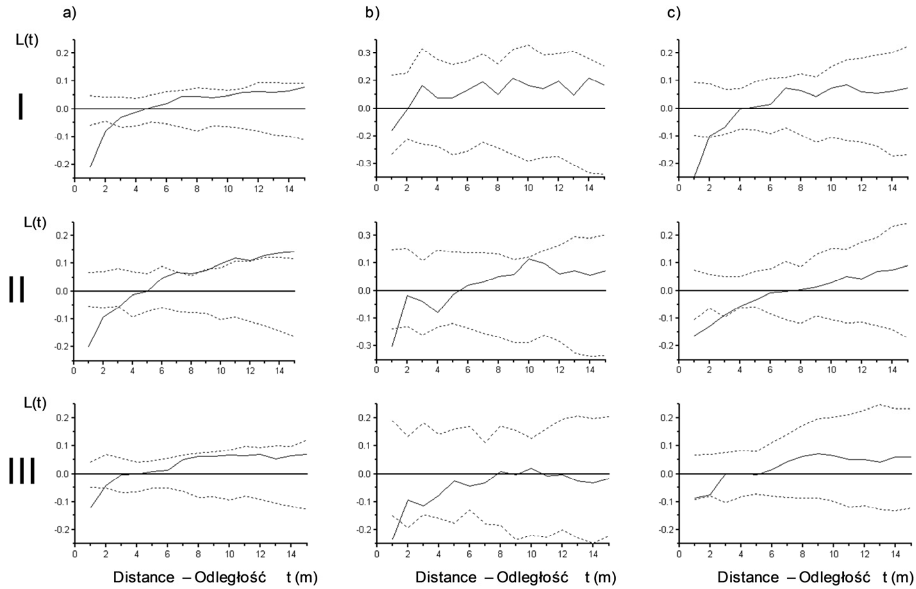

Fig. 1. Ripley's L(t) function for all living pine trees (a), trees of DBH ≤ DBH $_{aver.}$ (b), and trees of DBH > DBH$_{aver.}$ (c) in stands aged 43 years (plot I, II, III). Explanations: solid line – L(t) function for empirical data, dotted lines: 95% upper and lower confidence limits, L(t) = 0 – L(t) function for random population

Rys. 1. Funkcja Ripleya L(t) dla drzew żywych (a), drzew o $d_{1,3} \leq d_{1,3śred.}$ (b) i drzew o $d_{1,3} > d_{1,3śred.}$ (c) w drzewostanach sosnowych w wieku 45 lat (powierzchnie I, II, III). Objaśnienia: linia ciągła – funkcja L(t) dla danych empirycznych, linie przerywane: 95% górny i dolny przedział ufności, L(t) = 0-L(t) – funkcja L(t) dla rozmieszczenia losowego

Table 2. Values of Clark-Evans index R for trees of different size categories in particular compartments under investigation

Tabela 2. Wartości indeksu R Clarka-Evansa dla drzew różnej kategorii w poszczególnych analizowanych drzewostanach

Object Powierzchnia	Age, years – Wiek, lata					
	43		65		90	
	DBH ≤ DBH$_{aver.}$ $d_{1.3} \leq d_{1.3śr.}$	DBH > DBH$_{aver.}$ $d_{1.3} > d_{1.3śr.}$	DBH ≤ DBH$_{aver.}$ $d_{1.3} \leq d_{1.3śr.}$	DBH > DBH$_{aver.}$ $d_{1.3} > d_{1.3śr.}$	DBH ≤ DBH$_{aver.}$ $d_{1.3} \leq d_{1.3śr.}$	DBH > DBH$_{aver.}$ $d_{1.3} > d_{1.3śr..}$
Plot 1 Powierzchnia I	1.11*	1.05	1.08	1.12*	0.94	0.99
Plot 2 Powierzchnia II	1.06	1.16*	1.07	1.12	0.77*	0.97
Plot 3 Powierzchnia III	1.05	1.00	1.10	1.30*	0.89	0.82

*Statistically signifficant, α = 0.05.
*Statystycznie istotne, α = 0,05.

Stands at the age of 65 years

All live trees were randomly distributed except for the smallest spatial scale where trees were regularly spaced, revealing the inhibition zone between neighbours. Observed deviations from CSR were not so clear, except for one stand where they ran toward aggregations. Trees of DBH ≤ $DBH_{aver.}$ characterised random type of spatial arrangement with distinct deviations toward clumping in two stands. No regularity was found. Trees of DBH > $DBH_{aver.}$ were mostly randomly distributed at all distances. Regularity was observed only at the smallest distances. In one stand trees classified to this DBH class showed clumps at the distance larger than 18 m (Fig. 2).

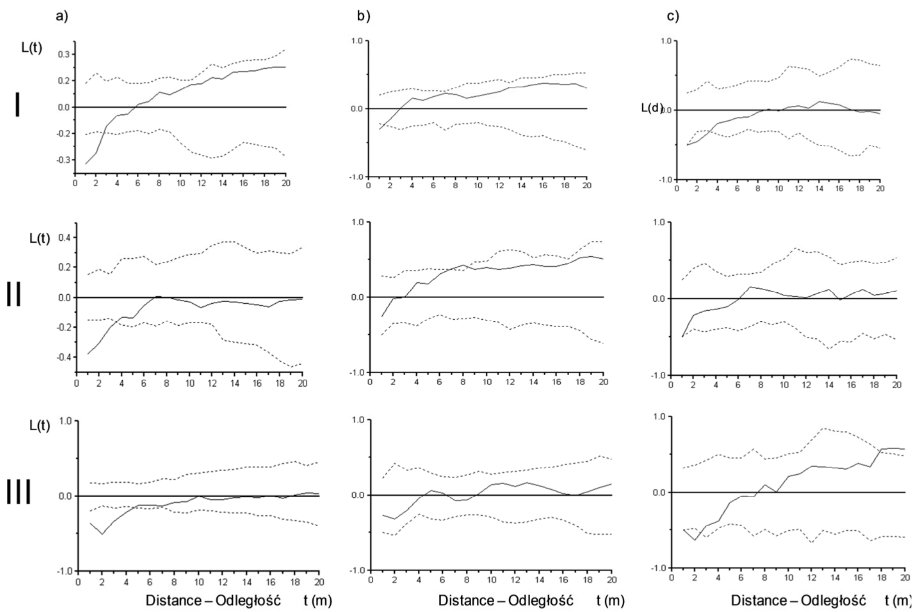

Fig. 2. Ripley's L(t) function for all living pine trees (a), trees of DBH ≤ $DBH_{aver.}$ (b) and trees of DBH > $DBH_{aver.}$ (c) in stands aged 65 years (plot I, II, III). Explanations: see Figure 1

Rys. 2. Funkcja Ripleya L(t) dla drzew żywych (a), drzew o $d_{1,3} \leq d_{1,3śred.}$ (b) i drzew o $d_{1,3} > d_{1,3śred.}$ (c) w drzewostanach sosnowych w wieku 65 lat (powierzchnie I, II, III). Objaśnienia jak na rysunku 1

R index for all living trees' distribution in all stands of 65 years old showed regular type of spatial arrangement (Table 1). In case of small trees (DBH ≤ $DBH_{aver.}$) they were randomly dispersed within the stands. Distribution of larger trees in two stands indicated regularity and in the third one they were randomly spaced (Table 2). Differentiation index indicated very small differentiation of DBH (values 0.17; 0.20 and 0.19) what suggests that nearest neighbours are the same sizes (Table 1).

Stands at the age of 90 years

In the oldest stands all living trees analysed together showed random type of spatial arrangement. Ripley's function for smaller trees (DBH ≤ $DBH_{aver.}$) showed randomness in two stands. In the third one L'(t) exceeded the upper confidence limits at the distances > 4 m indicating clumping. For trees of DBH > $DBH_{aver.}$ analysis showed that in two stands they are distributed randomly with deviations toward clumping and in one stand larger trees were distributed randomly up to the distance of 10 m and above that distance they formed clumps (Fig. 3).

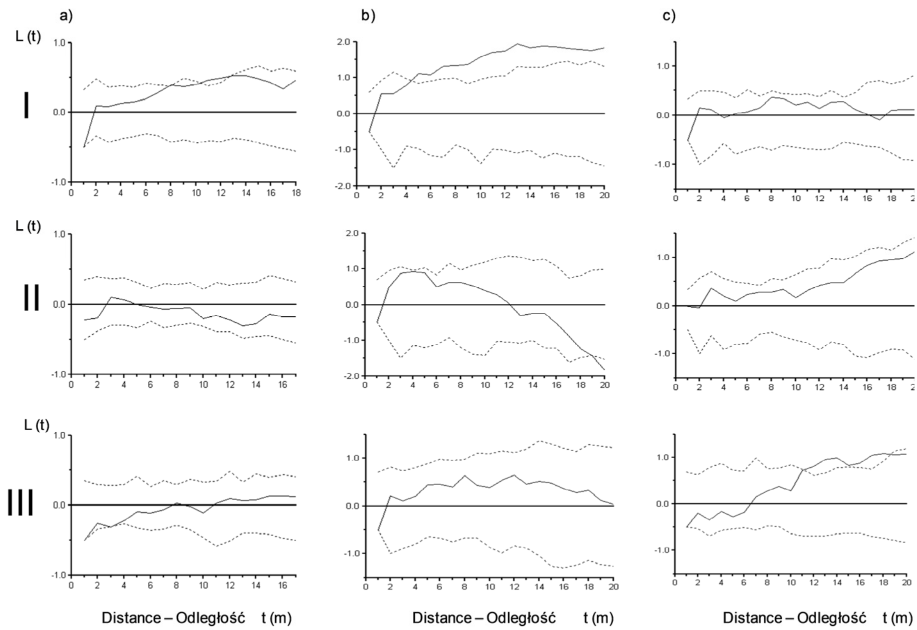

Fig. 3. Ripley's L(t) function for all living pine trees (a), trees of DBH ≤ $DBH_{aver.}$ (b) and trees of DBH > $DBH_{aver.}$ (c) in stands aged 90 years (plot I, II, III). Explanations: see Figure 1

Rys. 3. Funkcja Ripleya L(t) dla drzew żywych (a), drzew o $d_{1,3} \leq d_{1,3śred.}$ (b) i drzew o $d_{1,3} > d_{1,3śred.}$ (c) w drzewostanach sosnowych w wieku 90 lat (powierzchnie I, II, III). Objaśnienia jak na rysunku 1

R values indicated random spatial pattern of all living trees in all three stands taken into consideration. Despite its values were below 1.0, they were not statistically significant (Table 2). Only in one stand and only for trees of smaller DBH than the average, R index pointed clusters (R = 0.77). Trees of larger DBH were randomly dispersed, despite the valuse were below 1.0 too.

In case the oldest stands being investigated values of differentiation index did not exceed 0.14 showing a very small size differentiation between neighbouring trees (Table 1).

DISCUSSION

Despite the large difference between 43 and 65-year old stands in respect to the number of live trees, they did not reveal differences in terms of their spatial pattern. In these stands R index and L(t) function showed statistically significant regularity in treir dispersion at small spatial scale. Contrary, the oldest stands – where the number of living trees was the smallest – both methods demonstrated random distribution of live trees. The obtained results confirmed the earlier opinions on the influence of planting on the spatial distribution of trees and that this stand characteristic is changing in time. Sekretenko and Gavrikov [1998] observed the regular pattern of tree in spruce stands established by planting. Similar observation was made by Pommerening [2002] in Dougflas-fir plantation and Mason et al. [2007] in pine plantation. In naturally regenerated stands regular distribution of live trees can be also observed and it results from the self-thinning process and competition between individuals [Kenkel 1988, Gavrikov and Stoyan 1995]. However, self-thinning does not always lead to regular spatial pattern of remained trees but randomness in their dispersion can be observed quite frequently [Szwagrzyk 1990, Szwagrzyk and Czerwczak 1993, Gavrikov and Stoyan 1995, Mason et al. 2007, Szmyt and Korzeniewicz 2007]. Even if trees were planted in regular spacing, e.g. in managed stands, the initial regularity of trees dispersion can be easily lost [Szwagrzyk 1990, Kint et al. 2003] and results presented in this paper confirmed this opinion.

Trees of different size classes showed random or regular type of spatial distribution. Younger stands differed clearly from the oldest ones. In their case the values of R index varied from 1.0 to 1.16 showing the trend for regular distribution. In four stands the values of R were significantly different from randomness. Thicker trees of DBH above the average for the particular stands showed more often regular pattern than smaller ones. These results partly confirmed the opinions that regularity can be observed with increasing sizes of trees [Moeur 1997, Sekretenko and Gavrikov 1998, Mason et al. 2007]. Smaller trees, DBH below the average for the stands, were randomly dispersed and they never formed clumps. Clumping in case of trees of smaller DBH observed Szmyt and Korzeniewicz [2007] in 80-years old managed spruce stands. Similar trend was observed by Bolibok [2003] in the forests located in the Białowieża National Park in Poland. In the oldest stands the indices are not the same. Both catergories of trees showed a random distribution most frequently, and values of R index were always below 1.0 indicating a trend towards clumping. However, only one stand characterised the value of R index significantly different form randomness ($R = 0.77$, $\alpha = 0.05$), and it referred only to trees of DBH smaller than the average for this stand. Clumping is rather surprising in managed stands but it does not mean that it is imposible in such stands. Selective thinning carried out in this stand could promote this type of spatial distribution. Possibility of creating random or clumped dispersion by selective thinning in managed forests was stated by Pretzsch [1996, 1999].

The DBH differentiation index showed small or very small differentiation in size of trees in all stands being investigated. It means that neighbouring trees did not differ from each other in terms of their DBH. The smallest differentiation showed the oldest stands. Low differetiation of sizes was observed by Mason et al. [2007] in pine stands and the lowest index they observed in case of a pine plantation. They compared a plantation with other semi-natural pine stands and they stated only the minor differences between stands in terms of DBH differentiation. Similarly, low variation in trees dimension (DBH) was observed in young Douglas-fir plantation and in beech forests [Pommerening 2002]. Brzeziecki [2005] stated that the DBH differentiation index for planted pine stands (*P. sylvestris* L.) is naturally low and thinning operations [thinning from below] may lead to a farther decrease of it. Contrary, the differentiation thinning can lead to an increase in the size differentation of trees [Bilski and Brzeziecki 2005].

CONCLUSIONS

In managed pure pine stands spatial pattern of trees is changing with time.

Applied initial spacing can impose regularity in trees' distribution for a long time.

Human activity expressed in tending operations can affect structural differentiation of managed pine stands in terms of size differentiation and spatial pattern of trees.

Regular initial spacing makes difficult the formation of clumps of trees. Clumping of trees can be due to micro-site variation.

Size (DBH) differentiation in managed pine stands was decreasing with time, however, in every stand the differentiation was described as small.

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WZORZEC PRZESTRZENNEGO ROZMIESZCZENIA DRZEW RÓŻNYCH KLAS GRUBOŚCI W GOSPODARCZYCH DRZEWOSTANACH SOSNOWYCH (*PINUS SYLVESTRIS* L.) W RÓŻNYM WIEKU

Streszczenie. Celem pracy było określenie wzorca przestrzennego rozmieszczenia drzew na powierzchni oraz przestrzennego zróżnicowania ich pierśnic w drzewostanach gospodarczych (*Pinus sylvestris* L.) sosny zwyczajnej zlokalizowanych w Nadleśnictwie Wymiarki, RDLP Zielona Góra. Analiza dotyczyła drzewostanów w wieku 43, 65 oraz 90 lat, rosnących na siedlisku BMśw, w których były prowadzone zabiegi pielęgnacyjne zgodnie z regułami obowiązującymi w Lasach Państwowych. Typ poziomego rozmieszczenia osobników określono z wykorzystaniem dwóch popularnych metod: indeksu Clarka-Evansa (R) oraz funkcji Ripleya [Clark i Evans 1954, Donnelly 1978, Moeur 1993]. Analizie poddano wszystkie drzewa żywe, drzewa cieńsze od średniej pierśnicy oraz drzewa grubsze od tej średniej dla poszczególnych drzewostanów. Przestrzenne zróżnicowanie pierśnic określono na podstawie indeksu zróżnicowania przestrzennego TD [Pommerening 2002]. W drzewostanach w wieku 43 i 65 lat obie metody określenia typu poziomej organizacji przestrzennej pozwoliły stwierdzić regularne ich rozmieszczenie w małej skali przestrzennej. W drzewostanie najstarszym (90 lat) nie wykazano istotnych odchyleń od wzorca teoretycznego populacji rozmieszczonej losowo (tab. 1, rys. 1, 2). W drzewostanach w wieku 43 i 65 lat rozmieszczenie drzew należących do kategorii drzew cieńszych niż średnia, w większości nie różniło się od losowego. Stwierdzana regularność była obserwowana jedynie w najmniejszej skali przestrzennej. Drzewa grubsze od średniej pierśnicy w tych drzewostanach były rozmieszczone równie często losowo, co regularnie.

Podobnie jak w drzewach cieńszych, regularność przejawiała się jedynie w skali przestrzennej odpowiadającej najbliższemu sąsiedztwu (tab. 1, rys. 1, 2). W drzewostanach najstarszych (90-letnich) drzewa cieńsze i grubsze od średniej najczęściej były rozmieszczone losowo. Mimo że wartości indeksu R wskazywały na rozmieszczenie grupowe drzew obu kategorii, zostało ono potwierdzone statystycznie tylko w jednym drzewostanie i tylko dla drzew cieńszych (tab. 2, rys. 3). Przestrzenne zróżnicowanie pierśnic najbliższych sąsiadów było niewielkie i z wiekiem malało we wszystkich badanych drzewostanach (tab. 1).

Słowa kluczowe: rozkład przestrzenny, drzewostany sosnowe, drzewostany gospodarcze, funkcja Ripleya, zróżnicowanie wielkości

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