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EFFECTS OF DIFFERENT THINNING GRADES ON THE SPATIAL STRUCTURE OF PURE BLACK PINE STANDS

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Abstract

Black pine is very widely distributed in Turkey, with most stands managed by periodic harvesting to meet domestic wood demand. However, scientific knowledge about the spatial structure of stands after thinning is lacking. To correct this deficiency, 12 pure black pine stands in the Alaçam Mountains between 61 and 95 years of age were investigated. The stands were mapped according to spatial tree distribution and thinning grades were determined by both number of trees per hectare and basal area. The numbers of trees in the stands were between 590 and 2163 (before thinning) and between 269 and 1422 (after thinning). Spatial-structure analyses were carried out before and after thinning using a pair correlation function. Graphical illustrations were extracted and visually assessed. In addition, the total areas below and above the theoretical line (g=1) of the pair correlation functions were calculated, and the effects of thinning on these were determined. No change was observed in the slightly thinned sample stands (17, 35, 38, and 56) and only slight changes in the moderately thinned stands (18, 21, 49. and 53). The most striking differences were detected in the intensively thinned stands (59, 68, 76, and 78). Regular areas have increased in parallel with increased thinning applications. In other respects; clustered areas did not decrease along with the increased thinning. The pair correlation function provides a comprehensive explanation of the effects of thinning on stand spatial structure.

Keywords: Black Pine, Function area, Pair correlation, Spatial point process, Thinning

Özet

Türkiye'de karaçam çok yaygın olmakla birlikte meşcerelerinin çoğunda yerel talebi karşılamak için dönemsel hasat yapılmaktadır. Yalnız aralama işleminden sonra meşcerenin mekânsal yapısı hakkında bilimsel bulgular yeterli olarak bulunmamaktadır. Bu eksikliği gidermek için Alaçam Dağlarında yaşları 61 ile 95 arasında bireyler bulunan 12 saf karaçam meşceresinde incelemeler yapılmıştır. Ağaçların mekânsal dağılımı ve aralama derecesine göre haritalandırılan meşcereler hem göğüs yüzeyi alanı hem de hektar başına düşen ağaç sayısına göre belirlenmiştir. Meşcerelerdeki ağaç sayısı aralama işleminden önce 590 ile 2163 iken, işlemden sonra 269 ile 1422'ye düşmüştür. Aralamadan önce ve sonra olmak üzere mekânsal yapı analizleri ikili korelasyon fonksiyonu kullanarak yapılmıştır. Grafiksel gösterimler üretilmiş ve görsel değerlendirmeleri yapılmıştır. Ayrıca ikili korelasyon teorik çizginin (g=1) altında ve üstünde olan toplam alanlar hesaplanmış ve aralamanın bunların üzerindeki etkileri belirlenmiştir. Aralamanın az yapıldığı meşcerelerde (17, 35, 38 ve 56) değişikliğe rastlanmayıp, orta düzeyde aralamanın yapıldığı meşcerelerde (18, 21, 49 ve 53) ise küçük değişikliğe tanık olunmuştur. En büyük fark ise aralamanın yoğun yapıldığı meşcerelerde (59, 68, 76 ve 78) görülmüştür. Düzenli (homojen dağılım gösteren) alanlar artan aralama uygulamasına paralel olarak artmıştır. Diğer bir deyişle kümelenmiş bölgeler seyreltmenin arttırılması ile azalmamıştır. İkili korelasyon fonksiyonu seyreltmenin meşcere konumsal yapısı üzerinde kapsamlı bilgi vermektedir.

Anahtar Kelimeler: Karaçam, İkili korelasyon, Mekânsal nokta süreci, Aralama

INTRODUCTION

Forester's most efficient tool for shaping a naturally regenerated forest at the thicket stage is thinning. Three thinning approaches, low, high, and selective, are used in various ecological, silvicultural, and economic contexts (Saatçioğlu 1972, Saatçioğlu and Odabaşı 1979). The objectives of stand management and the stand structure formed in response to site conditions and tree species play a decisive role in the choice of thinning methods and intensity (Odabaşı et al. 2004). By thinning, the species mixture and ratios, stratification, closure, and density are modified to meet management objectives. Moreover, the stand is strengthened against external climatic and biotic effects, and efficient use of soil is ensured (Odabaşı 1985). The species mixture and tree-size differentiation resulting from improvement cuttings can be elucidated by analyzing spatial distributions (Laar and Akça 2009, Pommerening 2002, Aguirre et al. 2003, Kint et al. 2004).

A stand is a part of a forest which is defined by previous land use, complex ecological processes, and forestry activities (Stoyan and Penttinen 2000). Stand structure is a key element in comprehending forest ecosystems. Horizontal and vertical layering, bio-detrital mass, and spatial distribution depend on biodiversity, vegetation composition and tree positions, ecological persistence, competition, and the functioning of the forest ecosystem itself. The theoretical and practical importance of stand structure and development in forestry applications is becoming more widely accepted (Kint et al. 2004).

Stand structure not only affects stand dynamics, growth, and productivity, but also impacts forest functions such as protection and recreation. Stand-structure parameters are also important for analysis and modeling of forest dynamics and are useful as management indicators of forest ecosystem status. Spatial structure, which is the horizontal and vertical arrangement of trees and other vegetation within a defined time frame, provides stability and integrity to the forest.

Current non-spatial approaches for stand measurement, analysis, and modeling are based on stand parameters such as average diameter, dominant height, and volume per hectare (Kalıpsız 1982). This approach excludes the three-dimensional nature of stands.

Evaluation of stand development stages is crucial for investigating gap development by interactions between trees in the crown layer, as well as for explaining tree-growth characteristics (Longuetaud et al. 2008). Spatial analysis can also factor out the impacts of human interventions (maintenance, thinning, etc.) on stands. Tree species mix and spatial distribution have a clear impact on regeneration, growth, and secession. These processes result not only from natural or human-induced disturbances, but also from the structural heterogeneity of the forest (Uuttera et al. 1998).

Spatial analysis methods have been used in forestry sciences since the 1960's. Examples include comparison of natural tropical forests with plantation areas (Biber and Weyerhaeuser 1998), analysis of *Betula ermanii* stands in Russia (Eichhorn 2010a), comparison of mixed beech-larch forests in Germany (Pretzsch 1997), study of *Quercus brantii var persica* stands in Iran (Fard et al. 2008),analysis of vertical structure under different silvicultural systems (Barbeito et al. 2009),analysis of interaction effects in forest (Walder and Walder 2008), investigation of various tree species in Sri Lanka (Wiegand et al. 2007), analysis of Douglas-fir forest in the Pacific Northwest (He and Duncan, 2000, Getzin et al. 2006), investigation of subtropical forests in China (Li et al. 2008), study of *Quercus pyrenaica* and *Q. faginea* in Spain (Montes et al. 2004), and study of pure Norway spruce and mixed oak-beech plantations in Russia (Sekretenko and Gavrikov 1998). However, the literature is lacking in studies of tree species of the Mediterranean region. Moreover, the study areas are generally located in natural forest lands, not in managed stands.

The wide geographical distribution of black pine gives this species great ecological and economic importance (Bussoti 2002). Black pine is widespread in Turkey, including the Marmara, Aegean, Taurus Mountains, and inner Anatolia regions, with a total area of approximately 4.2 million ha (Figure 1, OGM, 2006; Akkemik et al. 2011). Management of these forests requires an awareness of their structure and its response to various impacts. This response can be measured more precisely once stand spatial structure has been determined. The current study aims to characterize the effects of different thinning grades applied by the local forest directory staff at the managed forests on the spatial structure of pure black pine stands using the pair correlation function.

MATERIAL AND METHODS

Study area

The study site in the Alaçam Mountains includes Akdağ, Ulus Mountain, Eğrigöz, and Alaçam Mountain. It lies between 39° 38' 00" and 39° 07' 30" North latitude and between 29° 15' 30" and 28° 15' 00" East longitude (Figures 1a and b). According to Thornthwaite's climatic evaluation based on meteorological data from nearby stations, a significant "summer drought" occurs in this area, which lasts for five months from June to October. Minimum and maximum precipitation values are 458.2 and 860.3 mm respectively (Sevgi et al. 2010).

Black pine is widespread in the study site. Single-layered black pine forests cover 91,744 ha, and two-layered forests cover 14,722 ha. In addition to pure stands, black pine forms locally mixed stands with many different tree species, such as juniper (*Juniperus ssp.*), umbrella pine (*Pinus pinea*), Scots pine (*Pinus sylvestris L.*), Calabrian pine (*Pinus brutia Ten.*), Oriental beech (*Fagus orientalis Lipsky*), poplar (*Populus tremula L.*), and oak (*Quercus ssp.*) (Sevgi et al. 2010).

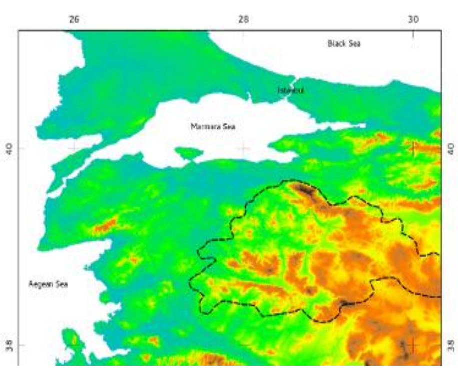

Figure 1. Distribution of black pine worldwide and in the study area.

Data Collection

118 sample plots potentially suitable for long-term ecological studies were determined by GIS and verified by field studies during 2006 and 2007. Twelve of these were selected for the current study. Initially, the corners of the sample plots, of a size (varying between 900 and 2000 m²) determined by tree age and density, were surrounded with plastic tape, and the *X*-, *Y*-, and *Z*-coordinates of each standing tree or stump were determined using a Total Station instrument. Besides the diameter, the height, the lowest dry branch height, and the crown of each tree were measured using a Vertex III laser tree height instrument. These attributes (diameter, height, etc.) and the *X*-, *Y*-, and *Z*-coordinates of the trees were entered into a GIS constructed on the basis of GRASS (GRASS Development Team 2011). Spatial analyses were carried out through an interface between GRASS and the R statistical program so that data transfer was unnecessary (Bivand 2012). The data were analyzed using the Spatstat package, with R modules used in addition as required (R Development Core Team 2008, Baddeley and Turner 2005).

Thinning grades and stand properties

Thinning from below was performed in the sample stands under investigation. The thinning applications in the study site, that is a production forest, were applied by the local Forest Directory staff. The issued thinning was applied at once. The percentage of trees removed varied between 3% and 88% (stems per hectare) and between 1% and 70% (basal area per hectare). Basal-area parameters of forest stands have been widely used in studies based on non-spatial analysis. However, in this study, the effects of thinning on stand structure were evaluated based on the positions and numbers of trees, without any additional stand parameters such as dbh or tree height. This approach can discriminate between stands with the same basal area, but different numbers of trees. Accordingly; we used number of trees and basal area to explain the thinning grades.

Stand ages varied between 71 and 95 years, with one exceptionally at 61 years (Table 1). Stems per hectare in the stands varied between 590 and 2163 before thinning and between 269 and 1422 after thinning. Stand basal areas varied between 35.25 and 68.39 m² before thinning and between 10.45 and 63.71 m² after thinning (Table 2).

Pair correlation function

Modern point process statistics use functions instead of indices or empirical distributions. These functions are based on distances between trees. The output of the pair correlation function is not a number, but a graph which describes the diversity of the tree distribution. Trees are commonly characterized numerically by density. If an infinitesimal circular area is denoted by *d*F, then the probability that a single tree exists in that area can be denoted as λ*d*F. Pairs of trees should be recorded together when describing relationships between trees and stand variation (Pommerening, 2002).

Table 1. Sample stand size, age, height, slope, and site class of stands.

Sample Stand No.	Area (m^2)	Age (y)	Mean Height (m)	Elevation (m)	Aspect	Slope (degrees)	Site class
76	1225	61	15.3	1180	NE	20	III
78	1225	71	22.6	973	NE	39	II
59	1024	71	18.4	1379	E	23	II
68	975	90	17.1	1285	NW	21	III
18	900	74	14.5	1099	E	20	IV
21	900	71	20.5	1219	N	33	II
49	957	72	15.4	1231	SE	30	III
53	1000	82	18.3	1521	W-SW	23	III
17	900	95	27.4	1151	N-NW	65	I
35	2000	77	16.6	1600	NE	13	III
56	1024	76	22.6	898	S-SE	36	I
38	900	81	14.8	1422	SE	38	IV

Table 2. Stems per hectare, basal areas, and mean diameters of stands before and after thinning.

Stand no.	Stems per hectare		Thinning grade (%)	Basal area		Thinning grade (%)	Mean diameter		Change at DBH (%)
	BT	AT		BT	AT		BT	AT	
76	2163	269	0.88	35.25	10.45	0.70	18.5	21.7	0.15
78	1086	367	0.66	37.45	25.10	0.33	24.6	29.1	0.15
59	1885	986	0.48	57.10	47.61	0.17	21.6	24.2	0.10
68	1692	954	0.44	52.68	44.72	0.15	21.8	23.9	0.09
18	1400	844	0.40	38.92	31.07	0.20	20.3	21.2	0.04
21	1089	667	0.39	48.17	38.33	0.20	25.5	26.1	0.03
49	1536	951	0.38	39.71	35.04	0.12	19.3	21.0	0.08
53	1100	760	0.31	58.92	51.02	0.13	27.7	28.8	0.04
17	978	711	0.27	68.39	63.71	0.07	30.9	32.8	0.06
35	590	500	0.15	39.56	38.32	0.03	28.9	29.9	0.03
56	967	830	0.14	59.21	58.09	0.02	27.0	28.0	0.04
38	1467	1422	0.03	57.26	56.73	0.01	21.6	21.6	0.00

BT=before thinning, AT=After thinning.

Assume that dF_1 and dF_2 are two concentric infinitesimal circular areas; then P(r) represents the probability that both circles contain a particular tree:

$$P(r) = \lambda^2 \cdot g(r) \cdot dF_1 \cdot dF_2.$$

g(r) is called the pair correlation function and represents the change in density with increasing distance, revealing small deviations in spatial pattern according to the K and L functions (Pretzsch 2009). This function identifies any deviation from a random distribution and detects whether any clustering or regularity is present (Pretzsch 2009). In a random distribution, g(r) is equal to one; values less than one indicate regularity, and values greater than one indicate clustering.

Analysis

Measurements were carried out throughout the sample stands, but only those individuals with DBH >8 cm were accepted for the current study. Pair correlation function analysis was used to evaluate the status of trees before thinning (standing trees and stumps) and after thinning (only standing trees). Both situations were analyzed using the pair correlation (Gest) function in the Spatstat package of R statistical software and were illustrated on a single graph. Ripley's isotropic edge correction was applied. Borders were defined by the corner points of the quadrats stakeout during the field studies with the Total Station instrument. The radius r was used with the analysis mode automatically selected by the software package according to the size of the sample stand.

Determination of thinning effects using pair correlation area

Spatial distribution before and after thinning was calculated using the pair correlation function (Figure 2). Subsequently, the calculation data set was transferred to a spreadsheet. The areas under the curves were calculated, thus converting the graphical data into numerical form to provide a better understanding of thinning effects. The formulae used to calculate areas are given below. The calculation is based on distance from the function g=1. In Figure 2b, g=1 represents randomness; functions plotted above this line represent clustering and those below represent a regular distribution. Therefore, the sums of the areas above and below the line will provide indices of clustering and regularity respectively.

a1 area = $((\hat{g}1 + \hat{g}2) / 2) * \Delta r$

Total area (gta) = a1 + a2 + a3 ....an

Total effect of thinning
Area before thinning = (gbta)= regular area (gbra) (a + b + c + f) + clustered area (gbca)(g + l +m + n) (Figure 2)

Area after thinning (gata) = regular area (gara) (a + c + d + h) + clustered area (gaca)(e + l + k +n) (Figure 2)

Total effect of thinning (gdta) = gata - gbta
Regular-area effect of thinning (gdra) = gara - gbra
Clustered-area effect of thinning (gdca) = gaca - gbca
Sum of differences (gtda) = (gtra) + (gtca) (absolute values)

Pair correlation functions help to describe stand spatial structure according to the distances between individual trees. The area of the pair correlation function provides one single value for the whole stand, which makes it possible to compare stands.

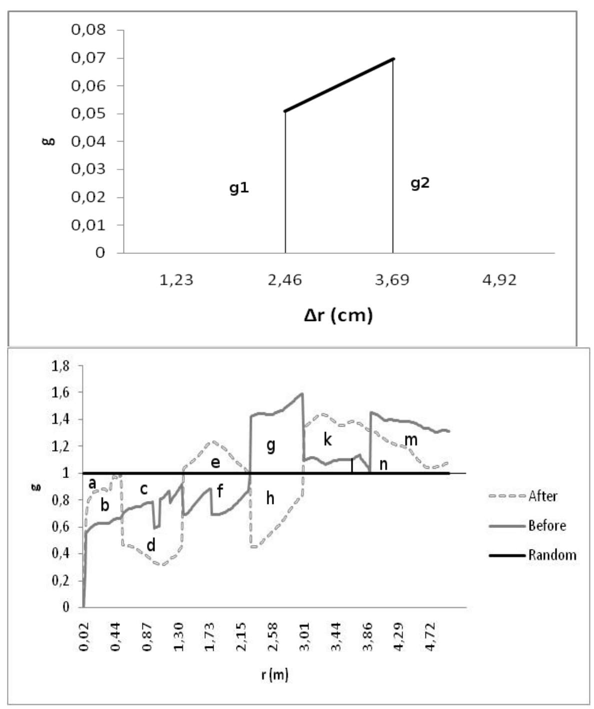

Figure 2: Calculation of pair correlation functions: (a) calculation of micro units; (b) areas before and after thinning and total areas.

Different g(*r*) values calculated from the spatial distributions of various stands can efficiently distinguish clustered, regular, and random stands. For comparison of different stands, g(*r*) should have a constant value, which was set to 7.5 m in this study.

RESULTS

Effects of thinning grades were determined using the pair correlation function and expressed both graphically and numerically.

For sample stands 17, 35, 38, and 56 where the changes in the number of stems per hectare were 27%, 15%, 14%, and 3%, and the changes in stand basal area were 7%, 3%, 2%, and 1% respectively. The g(*r*) radius changed from 10 to 12 m (Figure 3). Except for some differences at small distances in sample stand 56, no differences in spatial structure were recorded, and both curves coincided. The initial regular spatial structure of sample 17 changed to random and clustered structures at distances greater than 1.5 m. In sample stand 35, the g(*r*) radius increased to greater than 12 m due to the large stand area. In sample stand 35, the most highly clustered structures were detected at 2 m and 4.5 m. Regular structures were detected at small distances before thinning and at 6 m both before and after thinning. In sample stand 38 where the least amount of thinning was used, the initial, intensively regular structure changed to clustered and random structures at distances greater than 2 m. The maximum degree of clustering was detected at a distance of 3 m. In sample stand 56, the g(*r*) radius increased to 11 m. The clustered and random structures observed before thinning changed to regular structures at small distances and remained unchanged at greater distances. The greatest clustering tendency was detected at a distance of 1.5 m (Figure 3). After thinning, regular structures decreased by 2% in sample stand 38 and increased by 35%, 3%, and 42% in sample stands 17, 35, and 56 respectively. Clustering tendencies decreased by 49%, 5%, and 60% in sample stands 17, 35, and 56 respectively and increased by 20% in sample stand 38 (Table 3).

For sample stands 18, 21, 49, and 53 where the changes in the number of stems per hectare were 40%, 39%, 38%, and 31%, and the changes in stand basal area were 20%, 20%, 12%, and 13% respectively. In these stands, only slight differences were detected in spatial structures. In sample stand 18, the initial intensive regular structure changed to a mixture of regular, clustered, and random structures at distances greater than 3 m (Figure 4). After thinning, substantial increases in differentiation of regular structures were detected at distances of 1 and 6 m. The clustering initially observed at 3 m moved to 4 m, and the most intensive clustering was detected at 7.5 m. No significant difference was detected in the spatial structures of sample stand 49 before and after thinning, where only slight differences were detected at 3, 4, and 6 m distances. In sample stand 53, random distributions became clustered after thinning (Figure 4). After thinning, regular structure increased by 36%, 68%, 23%, and 22% in sample stands 18, 21, 49, and 53 respectively. Clustering decreased by 39% and 45% in sample stands 18 and 53 and increased by 16% and 20% in sample stands 21 and 49 respectively (Table 3).

For sample stands 59, 68, 76, and 78 where the changes in the number of stems per hectare were 48%, 44%, 88%, and 66%, and the changes in stand basal area were 17%, 15%, 33%, and 70% respectively. Only slight changes were detected in the spatial structure of sample stand 59, but considerable changes were detected in the other three sample stands (Figure 5). In sample stand 59, the extent of clustering increased at a distance of 8 m. The extent of regular structure in the tree distribution increased after thinning in sample stand 68. Remarkable differences was detected in sample stand 76, where clustered and random structures were observed at 1 m before thinning, but changed to regular structures at distances of less than 5 m, intensive clustering at 7 m, and regular structures once again at 10 m. Hard-core was detected at distances of less than 1.5 m in sample stand 76. In sample stand 78, the spatial structure was clustered at distances greater than 3 m before thinning, but changed after thinning to an intensively regular structure at 2 m and again to regular structures at distances greater than 5 m (Figure 5). After thinning, regular structure increased by 35%, 79%, 313%, and 313% in sample stands 59, 68, 76, and 78 respectively. Clustering decreased by 47% and 71% in sample stands 68 and 78 and increased by 24% and 10% in sample stands 59 and 76 respectively (Table 3).

Comparison of pair correlation area

The total areas of the pair correlation functions were between 0.841 and 1.731 before thinning and between 0.791 and 3.474 after thinning (Figure 6a). In other words, the range of extreme values was extended by increases in the maximum value and decreases in the minimum value (Figure 6a). Even though the total areas of the pair correlation function for the 17, 35, 38, and 56 sample stands decreased from 1.248 to 1.141, the magnitude of the areas before and after thinning were similar (Figure 6a). However, the total area increased from 1.478 to 1.868 for the 18, 21, 49, and 53 sample stands and from 1.134 to 2.078 for the 59, 68, 76, and 78 sample stands (Figure 6a). The greatest differences were detected in sample stands 76 and 78, which were the most heavily thinned stands (Figure 6a). Although total area was affected by differentiation of regular areas, no relationship was found between clustered and total area (Figure 6a-6c). Regular areas had increased and clustering decreased in all sample stands (Figures 6b, 6c). In addition, a direct proportionality was detected between thinning grade and regular area (Figure 6b), while no clear relationship was found with clustering because clustered area decreased in three sample stands and increased in nine sample stands (Figure 6c).

The established equation relating thinning percentage based on tree numbers (TPBN) and difference in total area is: gdta = 0.025*(thinning rate (%)) - 0.567 with R^2 = 0.768 (Figure 6d). The equation relating thinning percentage and difference in regular area is: gdra = 0.026*(thinning rate (%)) - 0.437 with R^2 = 0.853. No relationship could be established between TPBN and difference in clustered areas (Figure 6d). The equation relating TPBN and the absolute values of the sum of differences between regular and clustered areas is: gtda = 0.022*(thinning rate (%)) - 0.468 with R^2 = 0.624 (Figure 6d).

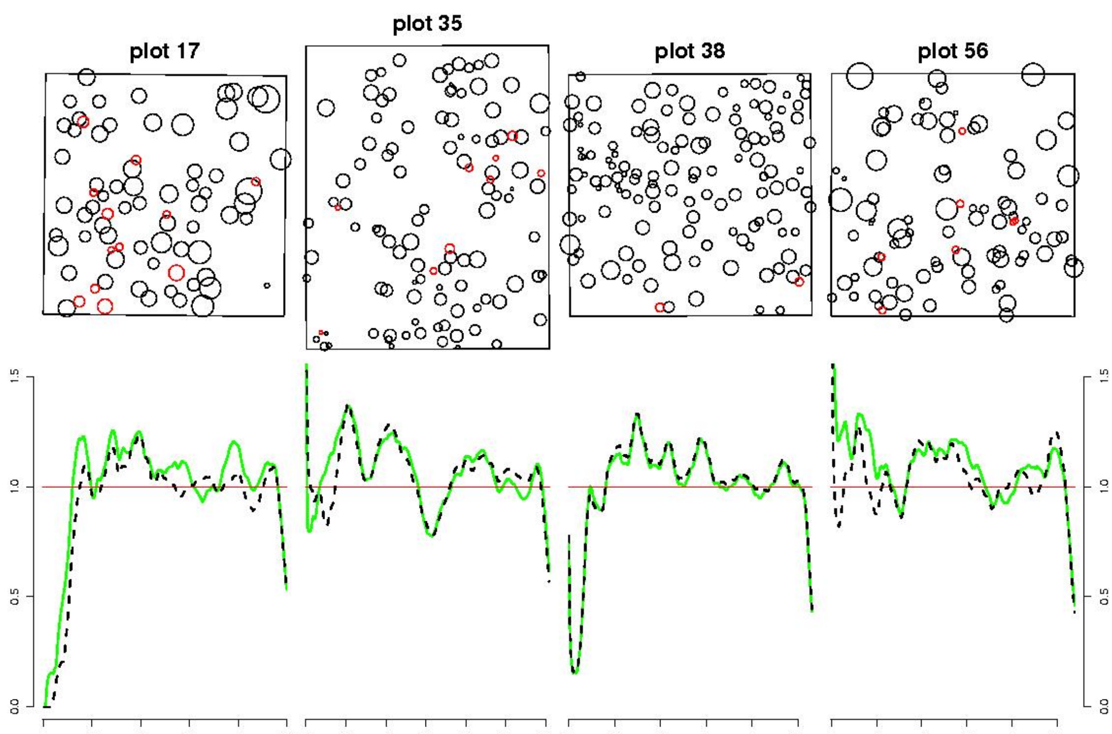

Figure 3. Stem maps (above) and pair correlation function plots (below) of 17,35,38, and 56 sample stands before and after thinning (red circles = stumps).

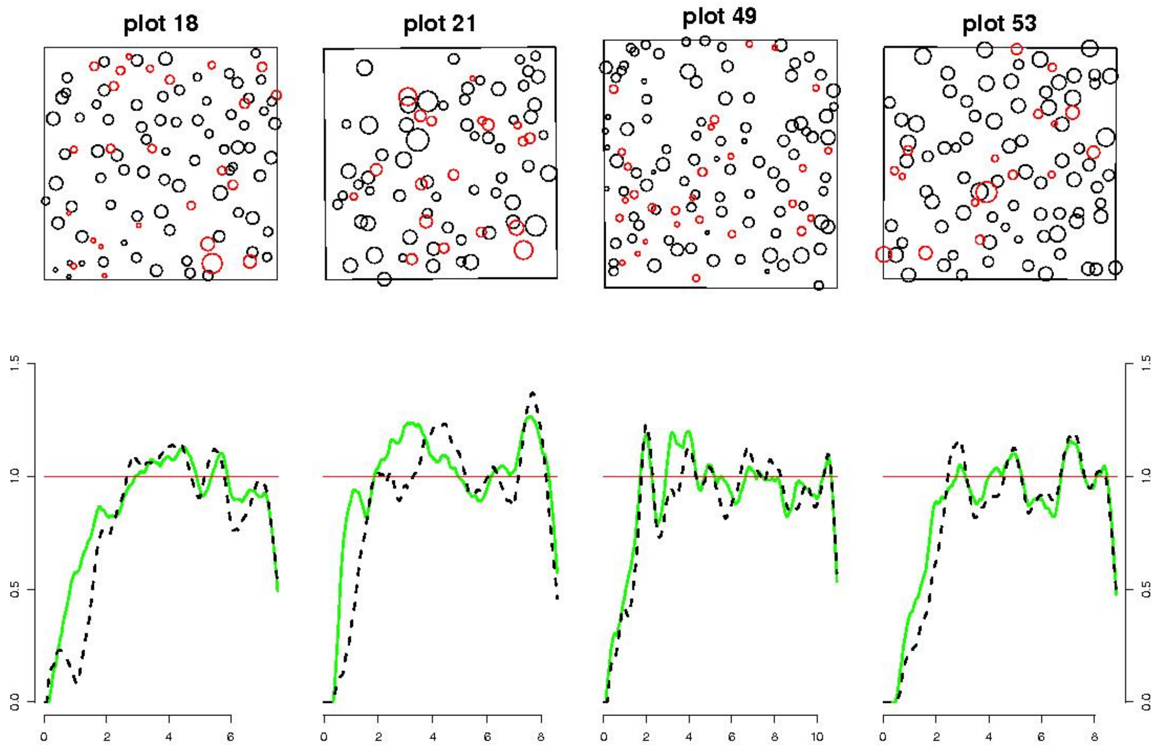

Figure 4. Pair correlation functions of 18, 21, 49, and 53 sample stands before and after thinning.

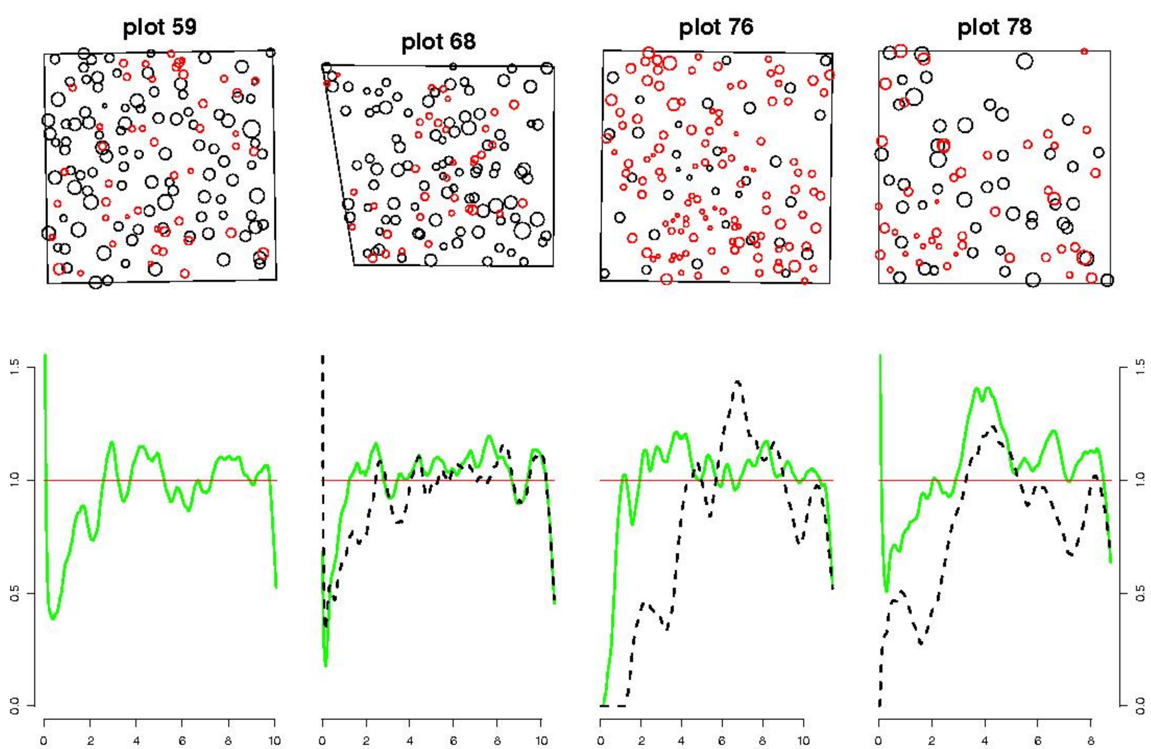

Figure 5. Pair correlation functions of 59, 68, 76, and 78 sample stands before and after thinning.

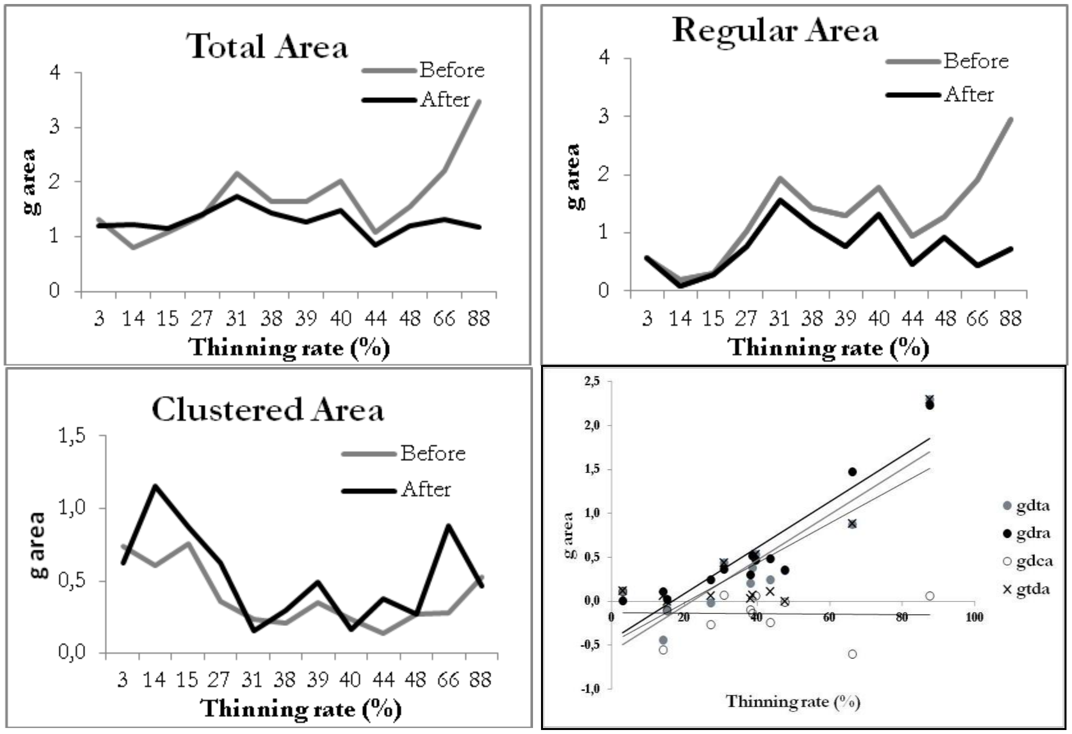

Figure 6. (a) Total area before and after thinning; (b) regular area; (c) clustered area; (d) changes in differences due to thinning grade. g(*r*) was assumed to be 7.5 m when calculating these areas.

Table 3 . Sum of pair correlation function areas for sample stands.

			Area Before			Area After			Differences			
Sample Stand No	Δr (cm)	g(r) (m)	Regular(gbra)	Clustered (gbca)	Total (gbta)	Regular (gara)	Clustered (gaca)	Total (gata)	Regular (gdra)	Clustered (gdca)	Total (gdta)	Sum of differences (gtda)
38	2.07	10.61	0.710	0.696	1.406	0.699	0.833	1.532	-0.011	0.137	0.126	0.148
56	2.10	10.76	0.236	1.356	1.591	0.335	0.810	1.145	0.099	-0.545	-0.446	0.644
35	2.38	12.17	0.400	1.138	1.538	0.411	1.081	1.492	0.012	-0.058	-0.046	0.070
17	1.95	9.98	0.871	0.818	1.689	1.177	0.419	1.596	0.306	-0.399	-0.093	0.705
53	1.73	8.83	1.684	0.169	1.853	2.058	0.245	2.302	0.374	0.076	0.450	0.450
49	2.13	10.92	1.373	0.317	1.690	1.692	0.254	1.946	0.318	-0.062	0.256	0.380
21	1.68	8.58	0.849	0.627	1.476	1.425	0.526	1.951	0.576	-0.101	0.475	0.677
18	1.46	7.50	1.313	0.167	1.480	1.784	0.232	2.016	0.471	0.065	0.536	0.536
68	2.07	10.61	0.617	0.587	1.205	1.107	0.310	1.417	0.490	-0.277	0.212	0.767
59	1.97	10.08	1.000	0.413	1.412	1.352	0.512	1.864	0.352	0.100	0.452	0.452
78	1.71	8.75	0.505	0.991	1.496	2.085	0.283	2.368	1.580	-0.708	0.872	2.288
76	2.23	11.43	0.811	0.654	1.465	3.347	0.717	4.064	2.536	0.063	2.599	2.599

DISCUSSION AND CONCLUSION

The spatial structure of black pine stands shows wavelike clustering and regular structures around a random distribution before thinning (Figures 3, 4, 5). Generally, the structure is clustered at distances greater than 2 m; the clustering tendency reaches a maximum at 4 m, after which wavelike structures predominate. The stand basal areas of some sample stands were similar, but were found to have a different spatial structure (e.g., sample stand pairs 17-56, 76-78, and 18-35).

According to the illustrations presented here, the results from the 17, 35, 38, and 56 sample stands were almost the same before and after thinning, except for sample stand 56 (Figure 3). For the 18, 21, 49, and 53 sample stands, remarkable differences were detected between the two plotted lines, resulting in visible changes in area (Figure 4). The areas for 59, 68, 76, and 78 sample stands increased after thinning (Figure 5), except for sample stand 59 (Figure 5).

The total areas of the pair correlation functions showed some variation in the final results for different thinning grades: slight decreases for 17, 35, 38, and 56 sample stands and significant increases for the rest of the sample stands (Table 3, Figure 6a). The most striking increases were observed in sample stands 76 and 78, where thinning was applied most intensively (Figure 6a). Linear relationships were found between TPBN and changes in total and regular areas, with R^2 values of 0.768 and 0.853 respectively. Regular areas increased with increasing thinning grade. This can be explained by noting that initially randomly distributed stands became more regular by intensive thinning from below, which eliminated understory and intermediate trees and left satisfactory dominant trees in the stands (Pretzsch 1998). The nature of the thinning operation led to an increase in regular structure throughout the stands because it focused mainly on the denser parts of the stands. On the other hand, clustering was moved towards greater g(*r*) distances, especially in intensively thinned stands. Although clustering showed a slight increase in sample stands 38, 53, 18, and 76, a decrease in clustering was common in the rest of the stands. Montes et al. (2004) found results similar to these for spatial structure in *Quercus pyrenaica* and *Q. faginea* stands. Interestingly, removal of individual trees from natural stands tends to move the stand structure from clustered to regular, passing through a random structure (Yu 2009). A similar evolution was observed in the present research. In other cases, the succession sequence of spatial structure may alternate, as in up to 110-year-old Norway spruce (*Picea abies*) stands, which when modeled, revealed a sequence from regular to clustered, passing through random (Hanewinkel and Pretzsch 2000). These variants may result from stand properties such as the presence of even-aged or uneven-aged trees (Hanewinkel 2004) or pure or mixed species (Sekretenko and Gavrikov 1998). Other possible causes include the ecological demands of species, thinning methods (Pretzsch 1998), the period over which stand spatial structure was investigated (Brumelis et al. 2005), and variation in (*r*) distances (Dessard et al. 2004). Therefore, generalization of spatial analysis results may not be possible (Li et al. 2008). Pretzsch (1998) found different results after application of various thinning methods in mixed spruce-beech stands.

Forest structure is defined in three dimensions, while height and radius are one-dimensional, various indices and functions are two-dimensional, and structural complexity indices define three-dimensional parameters (Zenner 2000, Zenner and Hibbs 2000). In this study, stand spatial structure was defined by a two-dimensional parameter, the pair correlation function. One-dimensional parameters such as height, radius, canopy closure, and others have been widely used in various classical approaches. Spatial analysis uses mainly empirical functions and indices to describe the stands. Spatial stand structures (horizontal tree distribution patterns) are analyzed using two major approaches (Pretzsch 2009): (I) indices representing parameters of the whole stand (Clark and Evans, 1954) and (II) functions using one point or tree as a starting point, such as Ripley's K and L, pair correlation, and mark correlation functions. Additional functions have also been developed (Stoyan and Penttinen 2000, Eichhorn 2010b, Law et al. 2009). In this study, in addition to graphical illustrations, three single numbers were generated by calculation of function areas. Not only could the spatial structural distribution pattern be perceived in detail from the graphical illustrations, but also the regular area (gra), the clustered area (gca), and the total area (gta) could be calculated. Although the graphical illustrations do not permit easy comparison of stands from different locations or at the same location but at different times, this is possible using the regular area (gra), clustered area (gca), and total area (gta) calculated from pair correlation graphs.

The number of stems per hectare and the average stand diameter are closely related. The excess numbers of trees in a given radius are removed naturally by self-thinning (Pretzsch 2002, 2005). The ecologically effective distance is close to that caused by competition due to self-thinning (Antonovics and Levin 1980, Kenkel 1988, He and Duncan 2000). Therefore, in black pine stands, natural negative selection is interfered with by managed cutting, resulting in decreased clustering and conversion of a random distribution to a regular distribution. Not only does the resulting yield improvement return economic benefit, but also the remainder of the stand consists of better-quality individuals (Pretzsch 1997, Odabaşı et al. 2004). Cutting to achieve thinning should avoid intensifying clustering or modifying the g(*r*) distance.

It can be concluded that in managed pure black pine stands, thinning causes an increase in regular area that can be explicitly seen from both the pair correlation plots and the numerical values generated from the plots. Regular areas have increased in parallel with increased thinning applications. In other respects; clustered areas did not decrease along with the increased thinning. Although the calculated values reveal a better understanding of the effects of thinning than the graphical illustrations, investigations of the effects of single trees on the spatial structure remain to be performed.

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