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Distribution attributes of natural canopy gaps in the Hyrcanian mixed-oriental beech forests

Asadollah Mataji[1], *Ali-Asghar Vahedi*[2]*

[1]*Department of Forestry, Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[2]*Research Department of Natural Resources, Mazandaran Agricultural and Natural Resources Research and Education Center, AREEO, Sari, Iran*

**Corresponding author: as.vahedi@areeo.ac.ir*

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Abstract: One of the most important issues indicating the quality and quantity of forest ecosystems is the distribution of natural disturbances resulting in canopy gaps (CGs). The present study was conducted in one of the Hyrcanian beech forests in northern Iran in summer 2018. The gap areas were classified into small (< 200 m^2), medium (200–500 m^2) and large gaps (500–1 000 m^2) on the basis of full inventory. The univariate Ripley's L-function was used for introducing the CG spatial pattern. Furthermore, mark correlation function (MCF) and density function (DC) in turns were used for verifying the correlation and frequency of CG size classes in each pattern. The results showed patterns of the gaps in each size class and integrated by the three size classes, they were random and cluster, respectively. Furthermore, the MCF revealed that the gap size classes were independently located in the clusters. The total frequency of the small, medium and large gaps in turns was 32, 49 and 19%, respectively. Although the density share of medium and small gaps in turns was more frequent than the large gap density in the study forest, the results of DC indicated that the frequency of each gap size class was random within each cluster, regardless of their density share. Based on the natural gap aggregations, the base circular mosaic with an area of 5 000 m^2 can be introduced for monitoring and specifying the forest stand dynamics.

Keywords: clustered pattern; disturbance; Hyrcanian forest; stand mosaic

Forest disturbances are all events and occurrences that induce significant changes in structure, composition, and ultimately distribution of canopy trees (Nagel et al. 2017). Disturbance agents in temperate forests include biotic and abiotic drivers such as insects, pathogens, wind, snow, ice, drought and interactions between ecological factors (Stueve et al. 2011; Nagel et al. 2017). Moreover, some events such as fire, landslide, soil erosion, damage caused by mammals and natural mortality of trees can be introduced as other disturbance agents in forest ecosystems. The majority of the disturbances in forest ecosystems are generally manifested in the form of natural canopy gaps (CGs) with various dimensions and shapes, especially in non-managed forests. They influence nutrient cycle, biodiversity, structure and successions (Muscolo et al. 2014). CGs are microsites with favourable conditions for tree regenerations and substantial effects on forest architecture, composition, sociability and competition between different tree species. Thus, the CG characteristics such as size, spatial pattern, locations and frequency reflect future quality and quantity of forest ecosystems. The distribution attributes of the CGs belong to the most important issues that can in-

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dicate the future dynamics of forest ecosystems. The CGs of different dimensions may indicate the trend of biomass reestablishment and biological continuity in forests as Asner et al. (2004) reported that the dispersion of the CGs shows significant interactions with ecological, physiological and biogeochemical processes in the forest ecosystems.

The present study was conducted in one of the Hyrcanian mixed-beech temperate forests in Iran. In the temperate forests, the canopy openings created by catastrophic disturbances on a large scale are absent or very scarce, and it is expected that the dynamics of forests is driven by the formation of CGs on a small to intermediate scale following the mortality of canopy trees (Spies et al. 1990; Garbarino et al. 2012). Therefore, the ecological and biological processes, and developmental stages are driven by distribution patterns of fine-scale disturbances in these forests (Mataji et al. 2008). Gap geometry consisting of size and shape strongly influences regeneration structure, species composition and its diversity (Garbarino et al. 2012). Architecture of forest stands is ordinarily influenced by the gap geometry. Furthermore, spatial patterns within a base area may serve as a descriptor for introducing the stand mosaics in forest ecosystems. Some recent studies acknowledged the distribution of CGs causing different forest patches and stand mosaics with various structures and tree species composition (Frelich, Lorimer 1991; Garbarino et al. 2012). The spatial pattern and correlation interactions between the gap geometry parameters may serve as indicators for separating the forest mosaics from observation distances. Each forest stand mosaic represents a base area for executive management based on the distribution characteristics after the disturbance occurrence. A mosaic is the smallest functional unit area of forest ecosystems, which may vary according to size, type of stands and developmental phase. By using a proper protocol such as clarifying canopy gap distribution attributes for introducing a mosaic with similar size can help foresters to focus on stand dynamics at each patch in forest ecosystems. Although the study forest has been protectively managed and the executive interferences are forbidden in the field, the findings acquired in the present study can be generalized in the Hyrcanian mixed-beech forest stands having similar site conditions such as species diversity and composition, topography, edaphic characteristics and stand structure. It is noteworthy that the size of the above-mentioned forest stand mosaics can be different in various stands or forest sites. In fact, the mosaic size and homogeneity strongly depend on the CG pattern in natural forests.

The presented research aimed (1) to study the natural CG spatial distribution at a specific distance for introducing stand mosaics, and (2) to clarify interactions between the CGs integrated by different dimensions for interpreting the location and frequency of size classes in the mosaics.

MATERIAL AND METHODS

Study area. This study was carried out in the forest of Glandrood district (36°27'30''–36°32'15''N and 51°532'5''–51°57'25''E), located in the north of Iran. The current research was conducted in summer 2018. The elevation of the forest area ranges between 1 050 and 1 250 m a.s.l. Also, according to the report of Forestry Project belonging to the Natural Resources and Watershed Organization of Mazandaran-Nowshahr unpublished and provided in 2008, the bedrock is limestone and the soil type is forest brown soil showing a texture ranging between silty clay loam and clay. Within the district, a reserved 38-ha area known to be a mixed-beech forest, which has not been managed for the last 50 years, was selected for this study. The tree species such as Oriental beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* Lipsky), alder (*Alnus subcordata* C.A. May), Caucasian persimmon (*Diospyros lotus* Lipsky), ironwood (*Parrotia persica* DC. C.A. May), maple (*Acer velutinum* Boiss.), oak (*Quercus castaneifolia* C.A. May), Caspian zelkova (*Zelkova carpinifolia* Pall. Dippel), and ash (*Fraxinus excelsior* Lipskey) were variously distributed in the study forest. The site was chosen because there was no clear evidence of any recent artificial anthropogenic disturbances in the stands for the last 50 years. Also, oriental beech is a dominant tree species in the study area. Meteorological parameters indicated that mean annual precipitation and temperature of this studied area were 1 293.5 mm and 16.1 °C, respectively.

Data collection. In the present study, all canopy gaps were measured based on full callipering (100% inventory) during the summer of 2018 in a natural mixed-beech forest. In total 68 CGs were found in the study forest. Prior to the inventory, the smallest size of a gap was defined as an

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area exceeding 15 m^2 created by the death of one or several trees (Sefidi et al. 2011). Each gap size was quantified according to the two dimensional projections to the forest floor on the basis of one of the descriptions which assume an irregular shape for the gap (Schliemann, Bockheim 2011). According to this description, the gap area with irregular shape was subdivided into smaller sections and each section was measured (Schliemann, Bockheim 2011). The area of each gap was measured on the basis of azimuth and horizontal distances to the bases of the projection of canopy trees surrounding the gap.

Analysis. The canopy gaps were analysed on the basis of three size classes including small (< 200 m^2), medium (200–500 m^2), and large (> 500 m^2) gaps (Sefidi et al. 2011; Mohammadi et al. 2019). In order to analyse the spatial pattern of gaps, univariate Ripley's L-function was used in the current research (Ripley 1976). The statistical significance of all ordination analyses was tested by the Monte Carlo permutation method based on 999 runs with the data. The spatial patterns of CGs based on the analysis of Monte Carlo permutations include random, cluster and regular distributions in the forest. Furthermore, Stoyan's generalized model $K_f(r)$ of the mark correlation function (MCF) was used based on a point process X to analyse a change in the CG size with changes in the observation scale (Equation 1).

$$K_f\left(r\right)=\frac{E_{ij}\times(f\left(M_i\times M_j\right)}{E\times(f\left(M\times M'\right)} \tag{1}$$

where:

E_{ij} – the conditional expected value of the i^{th} and j^{th} gaps at distance r in the point process X;
E – the common expected value;
f – a test function;
M_i, M_j – marks attached to the i^{th} and j^{th} gaps;
M, M' – random markers independently drawn from the edge distribution of the mark.

The $K_f(r)$ function can flexibly measure the spatial correlation of the mark of the i^{th} and j^{th} neighbours at a distance r (Li et al. 2019). The size classes of CGs can be interpreted as so called marks of the considered point process characterizing the points or CGs in some way. The so called MCF describes the spatial correlation of these marks introduced as CG sizes. The spatial correlation of the marks is described using a test function including two parameters $[f(m_i, m_j)]$ for two marks m_i and m_j. This test function attributes the correlation between the marks m_i and m_j at different points on the basis of distance r (Wälder, Wälder 2007). In Equation 1, E_{ij} is the conditional expected value of the i^{th} and j^{th} gaps at distance r in the point process X, and M_i and M_j are the marks attached to the i^{th} and j^{th} gaps (Li et al. 2019). In the denominator, M and M' are random markers independently drawn from the edge distribution of the mark, and E is the common expected value (Li et al. 2019). For gap sizes, $k_{mm}(r) = 1$ indicates that the gap sizes at the scale r are independent of each other, and $k_{mm}(r) > 1$ indicates that the gaps sizes are positively correlated, i.e., similar gap sizes are observed in the specified spatial distribution. If $k_{mm}(r) < 1$, the CG sizes are considered to be negatively correlated, i.e., differently various gap sizes are observed in the specified spatial distribution. Mark variograms and density correlation function are an unbiased way to visualize the autocorrelation structure. Therefore, an observed value within the envelope between the confidence intervals indicates non-correlation, though the observations outside the upper and the lower confidence limit reveal direct and negative autocorrelations, respectively.

RESULTS AND DISCUSSION

Gap size structure. The results indicated that the small, medium and large CGs in turns were 32, 49 and 19% of the total gap frequency in the overall studied area (Table 1). According to the total area fraction contributed to each gap size class, it was found that the total gap fraction in the study forest is 1.76 ha (4.6% of 38 ha), and also the CGs ranged in size from a minimum of 68 m^2 to a maximum of 1 538 m^2 (Table 1). The statistical items observed in the forest are summarized in Table 1. The breast height diameter (*DBH*) and height (*H*) of trees distributed on borders of canopy gaps are given in Table 2. All parameters denote a background associated with the mean and standard error (SE) of the tree biophysical variables (Table 2).

Spatial patterns. Univariate Ripley's L-function for each size class showed a complete random distribution starting at a distance of 1 m (Figures 1–3). The results showed that the spatial distribution of CGs at each size class was approximately similar

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Table 1. Characteristics of canopy gaps in the study forest

	Minimum size	Maximum size	Median size	Frequency	Total area fraction
		(m^{2})		(%)	(m^{2})
Small gap	68	170	140	32	1 877
Medium gap	230	480	311	49	7 675
Large gap	540	1 538	721	19	8 135

Table 2. Mensurational characteristics of border trees of each canopy gap class in the study forest

Canopy gap class (m^2)	*DBH* (cm)	*H* (m)
	mean ± SE	
< 200	51.35 ± 32.35	25.78 ± 8.25
200–500	55.68 ± 35.43	24.61 ± 9.04
500–1 000	53.05 ± 41.25	23.45 ± 9.72

DBH – diameter at breast height; *H* – height of the tree; SE – standard error

to each other (Figure 1). However, the spatial pattern of CGs at the small size scale was exclusively clustered for distances between 14 to 20 m (Figure 1). Univariate Ripley's L-function for all size classes in the study forest showed a cluster distribution deviated from complete spatial randomness starting at a distance of 4 m (Figure 4).

A radius with maximum distance of 40 m was defined as an observation scale for describing the spatial patterns of natural CGs in the forest. Thus, the results corresponding to the random and aggregated (cluster) patterns were found within a circular shape across the radial distance with an area of 5 025 m^2.

Empirical mark correlation function and density correlation. The MCF analysis indicated an independent spatial correlation of marks (Figure 5). In general, there was no spatial correlation between the CG size classes at any distance from 1 to 100 m in the study forest (Figure 5). Also, the mark variogram for canopy gap size characteristics was in accordance with Figure 5, implying accurately randomly contiguous locations of the gap size classes within each cluster with a minimum distance of 40 m. Furthermore, using the DC revealed that the frequency of marks considered as different canopy gap sizes was randomly found at the observation scale up to 100 m (Figure 6). According to the spatial pattern for all CG size classes, the frequency of each gap size class was random within each cluster up to a minimum distance of 40 m.

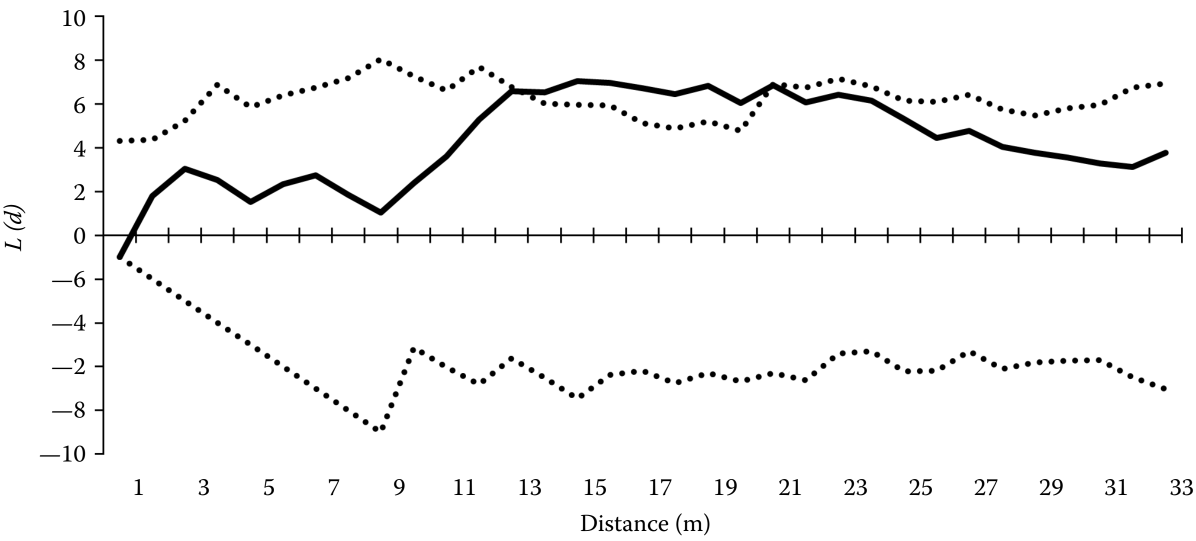

Figure 1. Univariate Ripley's L-function of the small canopy gaps in the forest

dot lines – Monte Carlo permutation; continuous line – spatial pattern

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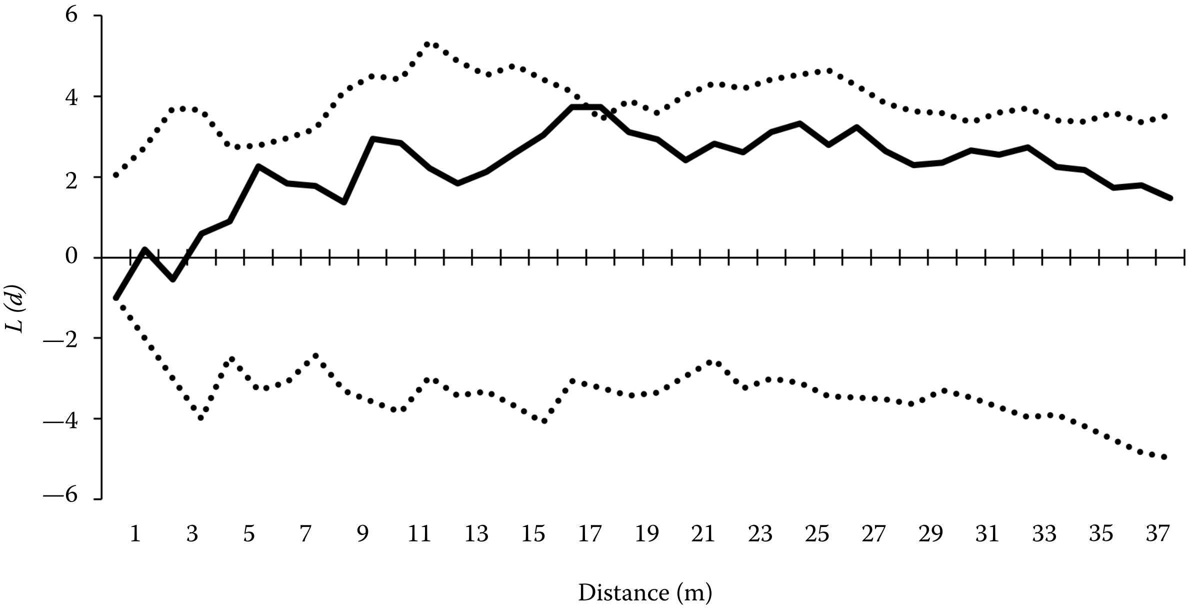

Figure 2. Univariate Ripley's L-function of the medium canopy gaps in the forest

dot lines – Monte Carlo permutation; continuous line – spatial pattern

Based on the inventory carried out in the forest, all the disturbances occurred within the minimum and maximum areas of approximately 70 and 1 500 m^2, respectively. Main disturbance agents were wind, snow, thunderstorm and natural mortality, though other some evidences like human interferences such as trimming and cutting thick branches of trees constituted the canopy gaps in the study forest. All the CGs observed in the forest had variously irregular shapes, and no matching geometric characteristics were found between these shapes.

The results showed that the CGs at each size class were randomly distributed in the study forest. Only the small CG distribution was clustered at a specified distance (14–20 m), which was likely due to the particular circumstances of topography,

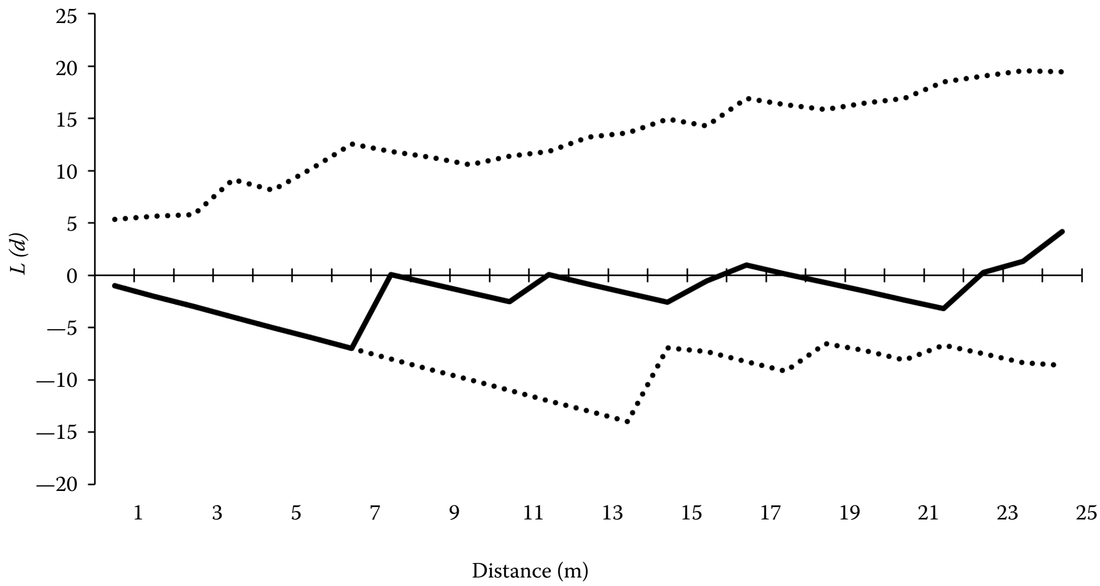

Figure 3. Univariate Ripley's L-function of the large canopy gaps in the forest

dot lines – Monte Carlo permutation; continuous line – spatial pattern

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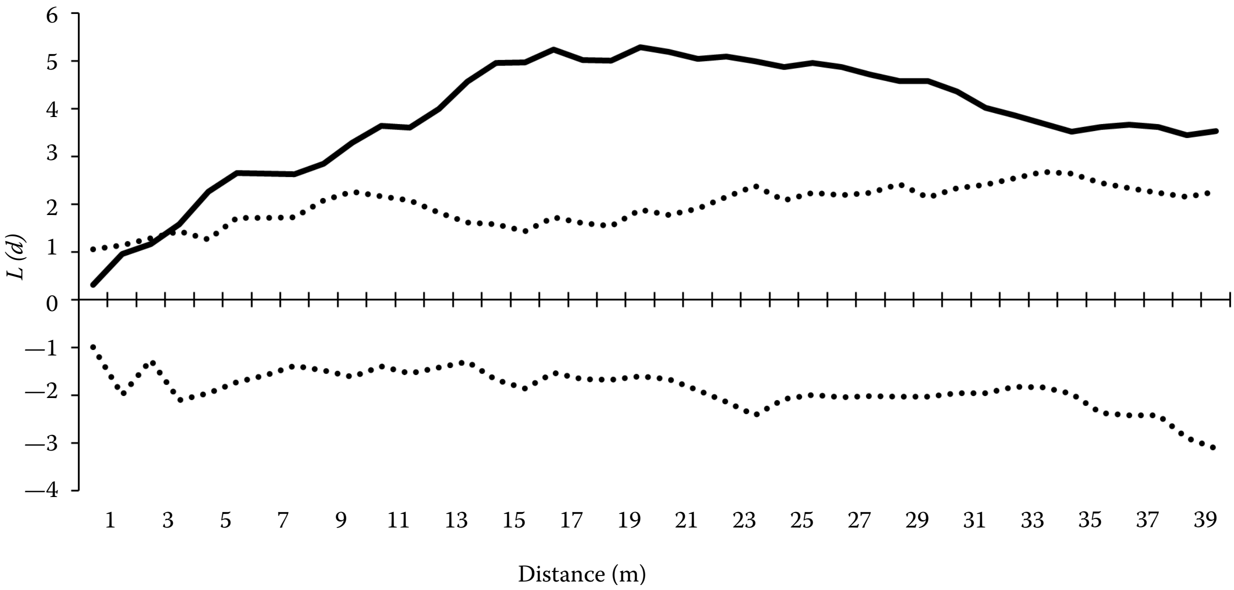

Figure 4. Univariate Ripley's L-function of all canopy gaps in the forest

dot lines – Monte Carlo permutation; continuous line – spatial pattern

forest stand structure and disturbance cause. Analyses of all CG size classes indicated that the distribution of CGs including different sizes was totally clustered. Garbarino et al. (2012) declared that the random distribution of natural gaps in forest ecosystems may likely be due to the relative environmental homogeneity of the area, lack of recent higher severity disturbance events, and mortality of large canopy trees. Although this reason can be particularly specific to the CG spatial pattern at each size class, it is in contrast with the achievement in association with the whole CG distribution attributes in the study forest. The results obviously imply that the disturbances of different intensities and with various causes have randomly influenced the opening formation in the forest. Consequences of all forest disturbances induced the clustered pattern of CG distribution. Integration of all CGs with different sizes showed an aggregated distribution at a radial distance of 40 m in the study forest. In this regard, Parhizkar et al. (2020) found that natural CGs taking into account all size classes including areas of 2 R to 10 R had cluster distribution in a case study of protected field within the mixed-beech Hyrcanian forest. They reported that the CG distribution was aggregated at a specific distance of 360 m, and they introduced this pattern under tree species mixing, tree age, topography and edaphic conditions in the study forest. According to the observations in the forest, the majority of the CGs was created because of tree mortality and of somewhat wind thrown gaps. In spite of these two agents as gap makers, trees species composition and stand structures may be other affecting drivers for the natural CG distribution patterns in the forest. The first question was about the gap size classes which were located in the clusters of the studied forest: did clusters include the specified gap size?

The result of MCF indicated that the natural CGs with different size classes were randomly created and located in each cluster, implying that each gap size class location in the clusters was independent of the other size classes. There is a strong assumption that some smaller openings themselves were large gaps in previous years and now because of the tree advanced regeneration establishment as gap fillers they have been transformed to smaller gaps over years. Generally, identifying the opening age can be another key driver to perceive more comprehensive description and interpretation for distribution and mark correlations of the CG size classes, though the age was excluded in the current research because of impossible accurate measurement and estimation on the basis of highly dynamic trends in the study forest. Mataji et al. (2008) declared that the distribution of CGs in natural

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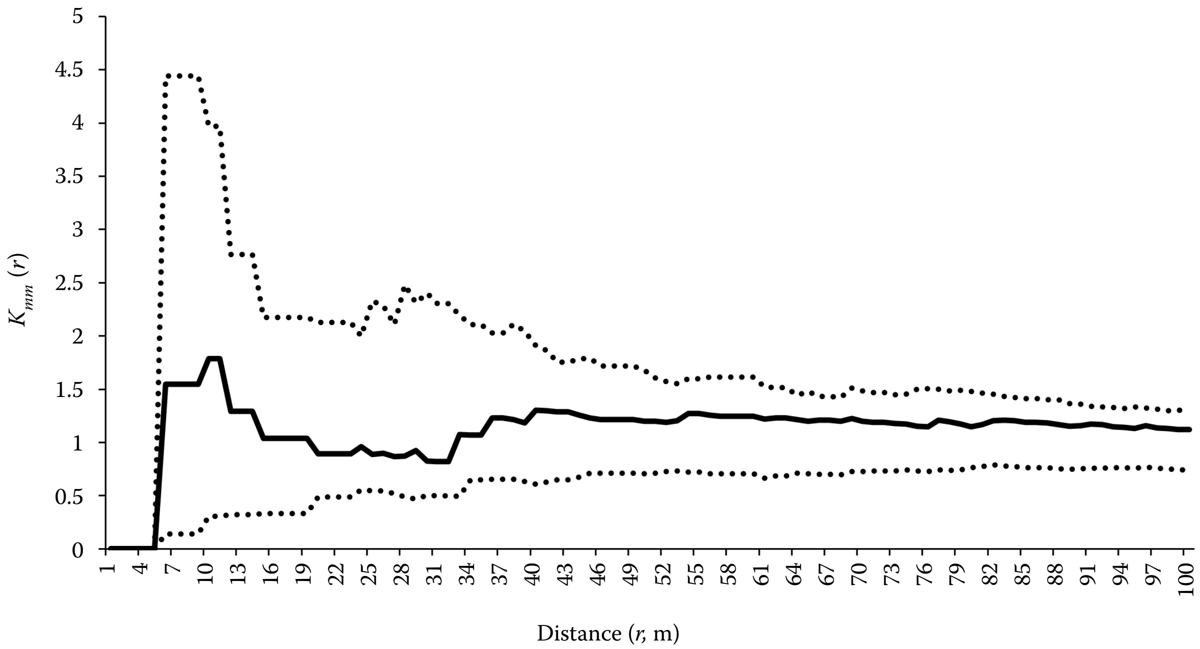

Figure 5. Mark correlation function of the canopy gaps in the forest
dot lines – Monte Carlo permutation; continuous line – mark correlation

forests can be severely influenced by the developmental stages and phases. Besides, we assume that climatic characteristics particularly microclimate sovereignty in the forest would be substantial drivers for occurring disturbances and CG distribution. Otherwise, Garbarino et al. (2012) stated that aggregated distribution of CGs in forest ecosystems is due to topographic characteristics and human causes. In this regard, the human causes were not a significant agent for the CG creation in the study forest although the topographic attributes could be taken into account for their creation and distribution.

The statistical results showed that the medium and small canopy gaps in turns were more frequent than the large canopy gaps. In accordance with the current result, Amanzadeh et al. (2015) found the same frequency for the canopy gap size classes; however, Sefidi et al. (2011) and Nasiri et al. (2018) indicated that the frequency of small canopy gaps was highest compared to the other gap size classes. Nasiri et al. (2018) reported that 70% of all identified CGs were smaller than 200 m^2 in size, and only 3% were larger than 500 m^2. All these results indicate that naturally fine-scale disturbances much more likely occur in these forests, and also the occurrences are mainly significantly continuous components of this forest dynamics. According to the results of DC at the specified distance *r* (100 m), the frequency of each CG size class was independently random with respect to the other size classes, indicating the frequency of each gap size class was random in the clusters within the designed stand mosaics. The density of each gap size class was random within a cluster located in a circular area of 5 025 m^2. Furthermore, it was not expected that the frequency of small gaps in each cluster was surely higher than that of the other size classes. Thus, based on a plausible assumption concerning the observations in the study, we can state that the probability of fine-scale disturbance occurrence is higher than in large-scale ones in the forest although the frequency of small openings may be lower than the other CG size classes in some clusters distributed in the forest. In addition, some ecological and biological phenomena can be effective key drivers for constructing the CG topology and architecture introduced in the current research. For instance, Karami et al. (2013) found that the dynamics of CG size and their spatial pattern in the mixed-beech Hyrcanian forests was strongly correlated with tree species diversity. In fact, the natural CG spatial pattern and their density function can be similar in the forest stands including the same tree species and plant diversity indices.

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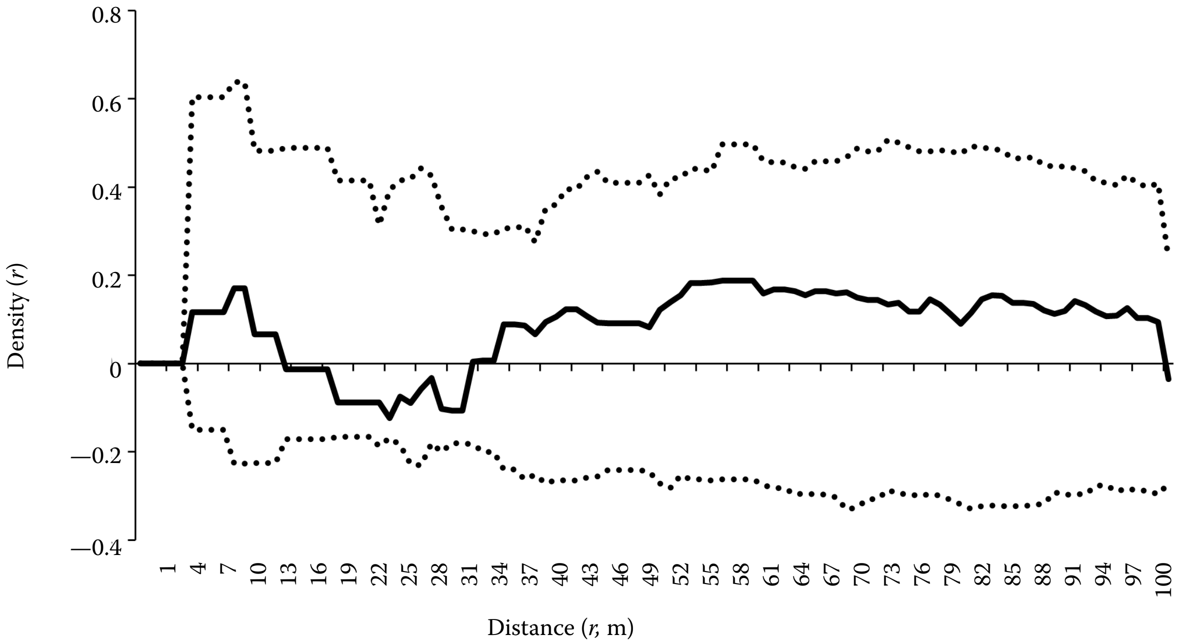

Figure 6. Density correlation of the canopy gaps in the forest
dot lines – Monte Carlo permutation; continuous line – density function

CONCLUSION

Our results show that distribution attributes of CGs can be considered as a key item in the forest executive management. As CGs represent base areas with optimal conditions for forest ecosystem rehabilitation, distribution attributes of these openings of different sizes clarify the regeneration establishment and the ecological and physiological niche extent of standing tree species. On the basis of the aggregated pattern of natural CGs with 40 m radius, the base circular area with an area of 5 025 m^2 can be introduced for partitioning the forest stands. As the location and frequency of each gap size class within each mosaic were exclusively random based on the results of MCF and DC, each mosaic may include specified tree stands with various developmental stages and structures in the forest. Each mosaic may be a representative of specific stand structure, tree species composition and developmental stage.

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