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Ecological Insights from Spatial Pattern Analysis: *Halocnemum strobilaceum* and *Climacoptera turcomanica* in Golestan's Saline and Alkaline Rangelands

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ABSTRACT

Halophytes and other salt-tolerant plants in rangeland ecosystems play an important role in environmental protection and food security. The spatial point pattern analyses of these plants in arid and semi-arid areas provide valuable information about how they affect each other and how we can preserve plant species as well as restore and manage the rangeland ecosystems. This advanced tool to interpret ecological processes can provide valuable information on plant coexistence patterns and biodiversity maintenance in arid and semi-arid regions. This research focuses on the investigation of spatial patterns and interactions occurring with two crucial species (*Halocnemum strobilaceum* (Pall.) M.Bieb and *Climacoptera turcomanica* (Litv.) Botsch) characterizing the Inchehboroun rangelands, in Golestan province, Iran. These two salty species dominate the rangeland and influence plant diversity and the relative conservation of rangeland productivity. We used the RTK GPS (Real Time Kinematic Global Positioning System) to record the position of each species in the study area during the field survey. Then, the spatial distribution and interactions between *H. strobilaceum* and *Cl. turcomanica* were determined by summary statistics methods including univariate and bivariate functions; g(r) and O-ring. The results showed that: 1) both investigated species have aggregated spatial patterns. 2) *H. strobilaceum* has a significantly positive correlation with *Cl. turcomanica.* Furthermore, according to the results of this study and the fact that most rangelands in the country are in moderate to poor condition, spatial pattern analyses using statistical functions can be useful in the development of restoration programs and ecological management of rangelands.

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1. Introduction

Rangelands in Iran's arid and semi-arid regions tolerate overgrazing livestock and periodic droughts (Amiri *et al*., 2020). The characteristics of the environment including climatic and topographic elements have an important role in plant diversity and richness (Heshmati, 2007). The spatial patterns analysis of species and their relationships with environmental agents can be useful for the mechanisms of uncovering biodiversity and tracking the fundamental ecological activities of community stability (He *et al*., 2022). However, it is very difficult to understand the ecological processes of the spatio-temporal structure of plant species in arid and semi-arid regions and how they are formed, because complex factors such as the occurrence of sudden changes and environmental heterogeneity are involved in them (Li *et al*., 2020; Pourghasemi *et al*., 2019). The most important reasons for different ecological behaviors between plants are the facilitating effect of one plant for the establishment of another plant, competition for resources, the mechanism of seed dispersal, and environmental heterogeneity that can cause the distance or proximity of plant communities from each other (Ferrante *et al*., 2014). Therefore, ecologists try to better understand plant distribution, their relationships, and the factors controlling them (Dale, 2003).

Based on ecological principles, species coexistence is preserved through niche distinction (Mittelbach & McGill, 2019) and there is a limit (also in spatial terms, vicinity) to how functionally analogous two coexisting species can be, if both have to preserve in the same habitat (Kariminejad *et al*., 2017). If the species have the same environmental requirements (i.e. ecologically equivalent) or need the aid of supporting species for establishment and growth, they can live near each other. The spatial pattern of any random variable, such as plants, can be analyzed via point processes and identified using ecological processes hidden in their spatial distribution. Summary statistics (as g(r) and O-ring) can be progressive forms of quantitative analysis and applied to analyze the plant spatial structure or pattern and their relationships with different effective factors. These functions describe point patterns at different spatial scales (Getzin *et al*., 2015). Spatial pattern analysis is beneficial to illustrate the type and significance of the ecological processes in an ecosystem. Spatial patterns of rangeland's vegetation are fundamental agents for identifying and analyzing ecosystem dynamics. More recently, spatial patterns have been a hot topic for ecosystem research, mostly resulting from the intraspecies and interspecies and related environmental agents (Lv *et al*., 2019). Due to the importance of studying the spatial patterns of tree species, most research has been done on the forests. Cysneiros *et al*. (2018) showed the spatial pattern and interactions of *Dinizia excelsa*, *Astronium lecointei,* and *Peltogyne paniculata* in the Jamari National Forest of the Amazon. Univariate analyses indicated different scale-dependent spatial patterns for the ecological features, such as dispersal limitation. The species *D. excelsa* had a random spatial pattern, explained by specific properties of its establishment, such as the need for clearings due to light requirements. Gu *et al*. (2019) used univariate function g(r) to dissect the dynamic variations in interspecific associations and spatial patterns of *Quercus wutaishanica* and *Pinus tabuliformis* on the Loess Plateau located in North West China. They indicated remarkable aggregation in near intervals and became more random with increasing distance. The spatial pattern varied at different growth periods, maybe because of robust competition between different species. Jiao *et al*. (2021) investigated the spatial distribution of *Tamarix chinensis* in the Yellow River Delta of China using summary statistics. They considered the role of biological and environmental interactions in the spatial pattern of *T. chinensis*. The aggregation distribution pattern at small scales (2-6 m) was a result of interspecific facilitation and seed dispersal through wind, but the pattern at large scales (>10 m) was random. He *et al*. (2022) showed that each dominant species in the forest had a small-scale distribution. The aggregation distribution level of all dominant species was decreased by excluding the influence of environmental discontinuity. The trees mainly indicated a uniform or random distribution (Zhang *et al*., 2022b).

Since few researchers used summary statistics to investigate the interaction of rangeland species, in the present study, to better understanding the dynamics of the rangeland ecosystems and to give information about the interactions between species, we examine the spatial patterns of dominant species by using point pattern analysis methods. Relationships between plant species in order to manage the arid and semi-arid rangelands were determined. To the best of our knowledge, this is the first attempt to compare the distribution and interactions of two dominant plant species, including *H. strobilaceum* and *Cl. turcomanica* using univariate and bivariate g(r), L(r), and O-ring functions in saline and alkaline rangelands. Over the 500,000 ha of rangelands in Golestan province, Iran are salty and alkaline. Inchehboroun is the representative of saline rangelands in the province. Halophytes and other salt-tolerant plants in this rangeland ecosystem in addition to their importance in the protection of wind erosion, have a high potential for forage production and are considered as an appropriate and practical solution for the fodder shortage (Arrekhi *et al*., 2021).

We believe that assessment of such spatial patterns will provide crucial information to better interpret the plant biodiversity of this rangeland and provide new original efforts to manage its conservation.

2. Materials and methods

2.1. Study area

Our study was carried out in Inchehboroun winter rangeland (37° 13' N to 54° 29' E) Golestan province located north east of Iran. The rangeland with an area of more than 10 ha has an elevation of -10 m of Sea level., which has an arid climate (Fig. 1). The general landscape of this saline and alkaline rangeland includes uniform and flat terrain with a low slope less than 5%. The annual mean precipitation in the study area is 181.5 mm, with the most rain recorded in June and the least rain recorded in July. The mean annual temperature is recorded at 17.7 °C (Dianati Tilaki *et al*., 2022).

2.2. Field sampling

The studied species included *H. strobilaceum* and *Cl. turcomanica*. *H. strobilaceum* (Amaranthaceae) is a small foliated succulent shrub or subshrub (height 20-60 cm) that occurs in saline habitats. The root system is shallow to deep, with a poorly extended central axis and a sidelong low depth of 10-35 cm. Its older stems are wooden, interweaved with brownish bark; stems are succulent and jointed with many branches, and stand straight to ascend with opposite circular buds. The bisexual flowers are positioned in inflorescences sidelong, short, terminal, opposite, sessile, and funnel-like or orbicular to elongated. The seeds are compressed, brown, and flattened to slightly tuberculate (Gintzburger, 2003; Nasernakhaei & Zahraei, 2021; Qu *et al*., 2008). *Cl. turcomanica* (Amaranthaceae) is an annual and fast-growing xero-halophyte. This species has rigid branches and maturity of interwind, fine hairs (arachnoid indumentum) on its leaves; nevertheless, these vanish when it becomes an adult plant (Gürsoy *et al*., 2017; Mohammadi Jahromi *et al*., 2019). They are common in the arid and semiarid regions of our planet (Zarka *et al*., 2018). Based on randomly method across the regions, the position of all bases of the two species was recorded separately using RTK GPS (Real Time Kinematic Global Positioning System) (Fig. 1). The used GPS produces a precise position, often within 0.04 m horizontally (Safrel *et al*., 2018). In the RTK technique, two receivers were used. RTK receivers can calculate the baseline (dx,dy,dz) between the base station and the moving station. The base receiver was set to a point with specific coordinates and data was collected at this receiver. These data are sent to the mobile receiver immediately. The base station at a 10 km could achieve an accuracy of a centimeter in position determination. Since the base station has specific coordinates and the position of the mobile station (i.e. sampler) can be calculated with an accuracy of less than one centimeter, we reduced the margin of error by using a trial-and-error method and achieved the centimeter positioning accuracy.

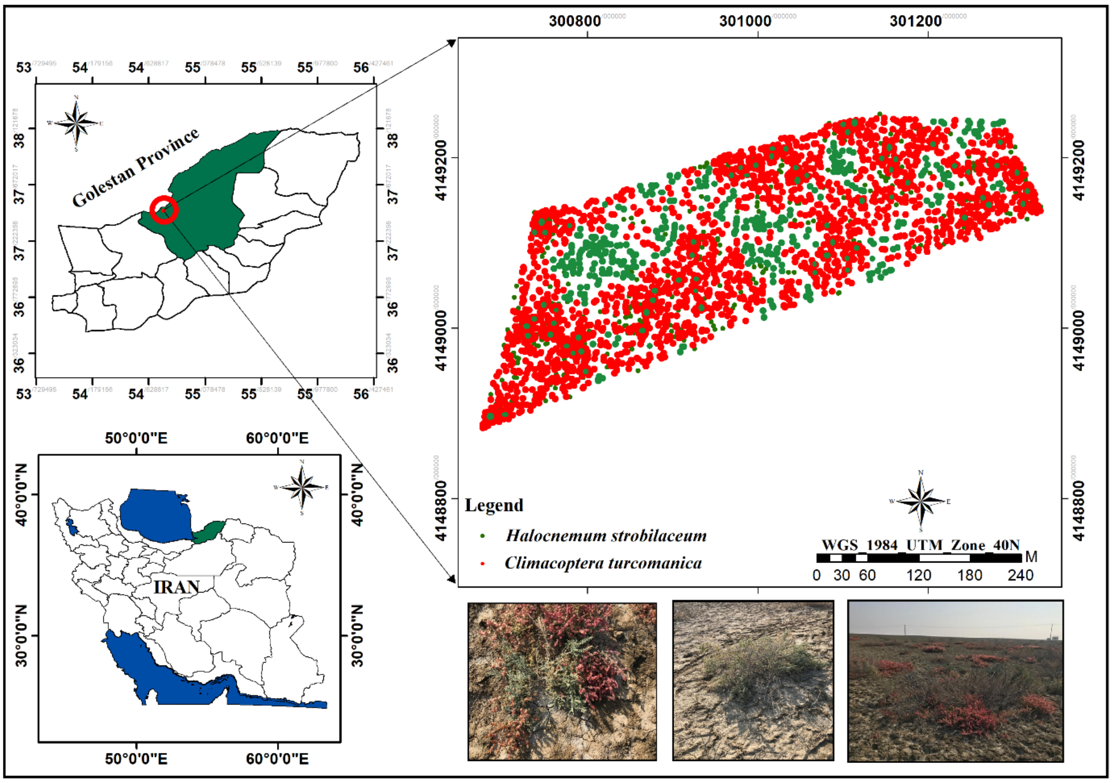

Fig. 1. The geographic location of the study area in Inchehboroun rangeland, Gonbad-e-Kavus city, Golestan province

2.3. Statistical tests

In the first stage of spatial pattern analysis, the Kolmogorov-Smirnov (KS) statistical test was checked for the normality of the sampled data. According to Mamoon and Rahman (2019), the KS test is applied to specify if a sample has come from a supposed continuous probability distribution. This test relies on the empirical cumulative distribution function (ECDF) given as:

$$F_n(x) = 1/n\,[\text{Number of observations} \leq x] \tag{1}$$

The parameter D or KS test statistic is presented by the most difference between the theoretic function and ECDF:

$$D = \max\big(F(x_i) - i - 1/n\,,\, i/n - F(x_i)\big) \tag{2}$$

Less values of D show the distributions are the same and more values show the distributions are probably to be dissimilar. The p-values (α=0.05) were also calculated (Thornley *et al.*, 2022). Then, a point map of species presence was prepared in ArcMap 10.3 based on Universal Transverse Mercator (UTM) coordinate. In the end, information processing and spatial data analysis were done using univariate and bivariate pairwise correlation functions as well as O-ring functions in Programita software (Wiegand & Moloney, 2004). In this software, a simulation envelope by the Monte Carlo test with 199 replications, with a probability level of 95% for the random distribution of the plants, and the results of each summary statistic were studied at the mentioned interval. Fig. 2 depicts the flowchart of the research.

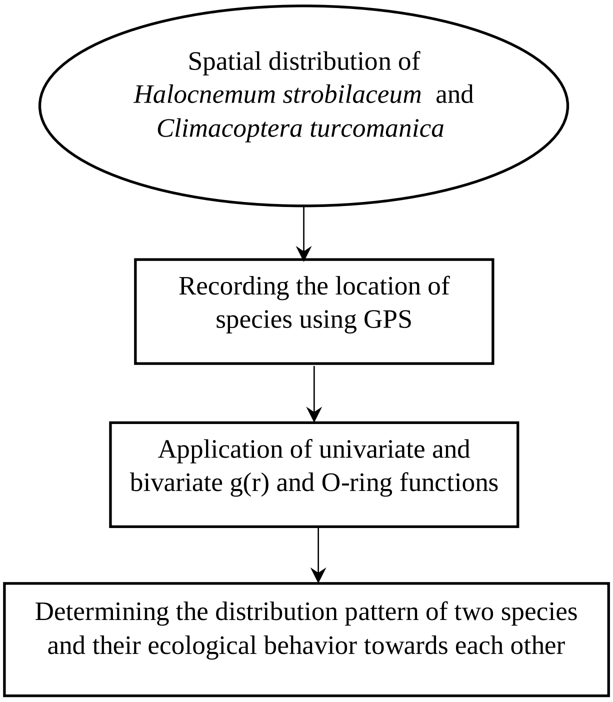

Fig. 2. Flowchart of the present study

2.4. Summary statistics

Summary statistics describe a brief distribution pattern, they condense explicit spatial information but inevitably lose the information included in the pattern. Therefore, the simultaneous use of several functions is important to fully understand the complex nature of the spatial pattern (Wiegand *et al*., 2013).

2.4.1. Pair correlation function g(r)

The g(r) function was applied to specify the spatial distribution pattern of the studied species in this research. By using the g-function, which is the derivative of Ripley's *K*-function, the analysis of the spatial point pattern (the studied phenomenon) is performed in different scales (Eq. 3). This function shows the changes in different spatial distances better than the K function (Fig. 3).

$$\mathrm{g(r)} = 1/2\pi\mathrm{r}\,.\,\mathrm{dK(r)}/\mathrm{dr} \tag{3}$$

where, $dK(r)$ is the derivative of the Ripley's *K*-function, π is 3.14 and r is the radial distance from one point to another point (Getzin & Wiegand, 2007). Based on distances between species, the g-function characterizes regularity and clumping at a certain radius r, by a standard intensity. Therefore, g(r)=1 is under complete spatial randomness (CSR), while g(r) > 1 shows aggregation, and g(r) < 1 shows regularity (Getzin *et al.,* 2011).

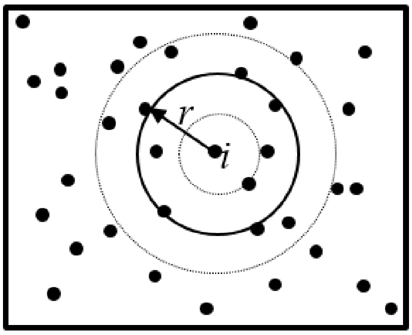

Fig. 3. Measuring plant intensity in circles with a variable radius (r) on each plant (i) in g function

2.4.2. O-ring function

One of the latest methods to determine the spatial pattern and species' interactions is the use of O-ring function. In O-ring function, the defects of Ripley's *K*-function and the related linear form (L) have been corrected. This function is related to Ripley's *K*-function and pair correlation function g(r), and for a specific point pattern, it is calculated as below (Illian *et al.*, 2008):

$$\mathrm{O(r)} = \lambda \mathrm{g(r)} \tag{4}$$

where, $\mathrm{O}(r)$ is the univariate function O-ring, λ is intensity, and $g(r)$ is derivative of Ripley's *K*-Function (Ripley, 1976; Ripley, 1981). One basis of $\mathrm{O}(r)$ is the average number of points (species) placed on rings with radius r from the central points (species) within the studied site. Replacing circles in O(r) instead of circles in *K*-Function enables this function to discover patterns in different distance classes (Illian *et al.*, 2008). While the *K*-Function and its linear form- *L* function are not able to do this and are mostly cumulative in nature. Another advantage of the O-ring function is that it is a probability distribution function describing the intensity of neighbors and adjacent points, which increases the power of pattern discovery and analysis and also interaction compared to cumulative *K*-Function (Stoyan & Penttinen, 2000) (Fig. 4).

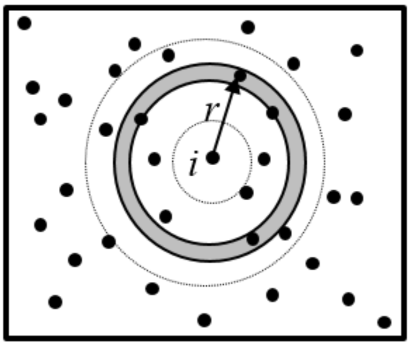

Fig. 4. Measuring plant intensity in circles with variable radius (r) on each plant (i) in O-ring function

2.4.3. Bivariate pair-correlation function ($g_{12}(r)$)

By transforming the univariate version, it is possible to use the bivariate pair-correlation function to analyze the spatial relation between two groups of points. It is the estimated density of points in pattern 2 at distance r from an optional point of pattern 1, divided by the intensity λ_2 in pattern 2 (Hai & Hung, 2016). The function $g_{12}(r)$ examines the interactions between species groups or their sociability according to the distances between different species or the distances between the plants of each species (Hosseinalizadeh *et al*., 2018).

$$g_{12}(r) = 1/2\pi r \,.\, dK_{12}(r)/dr \tag{5}$$

In Eq. (5), $K'(r)$ and r are the derivative of the Ripley's K-Function, and the radius, respectively. $g_{12}(r) = 1$ indicates no interaction (independence), $g_{12}(r) > 1$ shows that at distance r from points of pattern 1 there are on average more points of pattern 2 than expected under independence, thus representing attraction between two-point patterns at distance r. Reversely, $g_{12}(r) < 1$ shows repulsion between the two patterns at distance r (Hai & Hung, 2016) (Fig. 5).

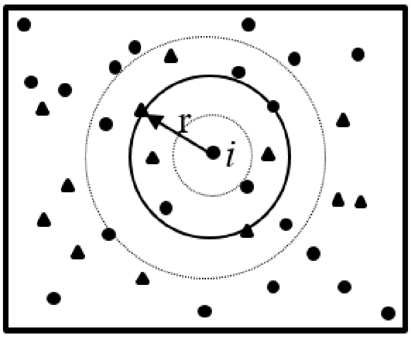

Fig. 5. An overview of the bivariate function *g* expressing the plant interactions in circles and triangles with a variable radius (r) on each plant (i)

2.4.4. Bivariate O-ring function ($O_{12}(r)$)

The $O_{12}(r)$ can be univariate or bivariate. Univariate in conditions that the points in the spatial map display the location of the point (species) or their interactions only in one group and lack any other information. On the other hand, the points in the spatial map may show the interaction between species groups based on the distance or distances between plants of the same species with different dimensions, which in this case is bivariate (Wiegand & Moloney, 2004).

The approach of the bivariate $O_{12}(r)$ function which is shown in the form of Eq. (4), is the number of trees in group 2 (for example, group B) that are placed on rings of radius r centered on the trees of group 1 (for example, group A) which is divided by λ_2 (Kariminejad *et al*., 2017). In other words, the quantity $g_{12}(r)$ is the ratio of the observed average density of species 2 plants in the rings around species 1 plants to the expected average density of species 2 plants in these rings. In this case, the corresponding neighborhood density function yields the Eq. (6):

$$O_{12}(r) = \lambda_2 g_{12}(r) \tag{6}$$

In this equation, $O_{12}(r)$ is a bivariate O-ring function, λ_2 is the density of the point pattern of group 2, and $g_{12}(r)$ is the bivariate form of the function g(r). We obtain $O_{12}(r) = \lambda_2$ for independent patterns, $O_{12}(r) < \lambda_2$ for repulsion, whiles $O_{12}(r) > \lambda_2$ for attraction (Lan *et al*., 2012). That is, in attraction, the number of trees neighboring the central tree is more than the expected average, and in repulsion, the number of trees is less than the expected number due to unfavorable habitat factors and competition (Miao *et al*., 2014) (Fig. 6).

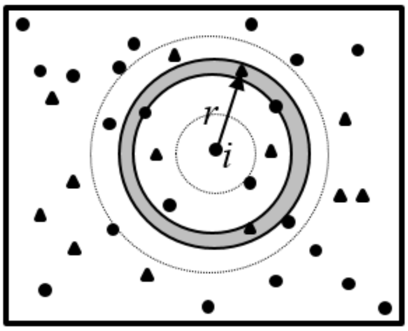

Fig. 6. An overview of the $O_{12}(r)$ function expressing the plant interactions in circles and triangles with variable radius (r) on each plant (i)

3. Results

The field sampling indicated that there were 2884 plant individuals related to *H. strobilaceum*, 2641 plant individuals related to *Cl. turcomanica* in the studied area.

Also, the K-S goodness of fit test showed that the spatial pattern of these species in the studied area followed a homogeneous Poisson distribution.

The quantity of the g(r) function was applied to specify the spatial pattern of *Cl. turcomanica* the results of using this univariate function indicated that the *Cl. turcomanica* has a clustered spatial pattern up to a distance of 5 meters. The non-significance of this distribution was confirmed up to a distance of 5 meters at a confidence level of 0.95. Because in these distances, the value of the function was outside the limits of Monte Carlo, and in this distance, the density of *Cl. turcomanica* is about four times higher than the random state. At distances greater than 5 meters, the patterns of distribution are random (Fig. 7). The O(r) function is also significant in confirming the *g*(r) function at distances of 0-5 meters at the confidence level of 0.95. At distances greater than 8 meters, the pattern is random.

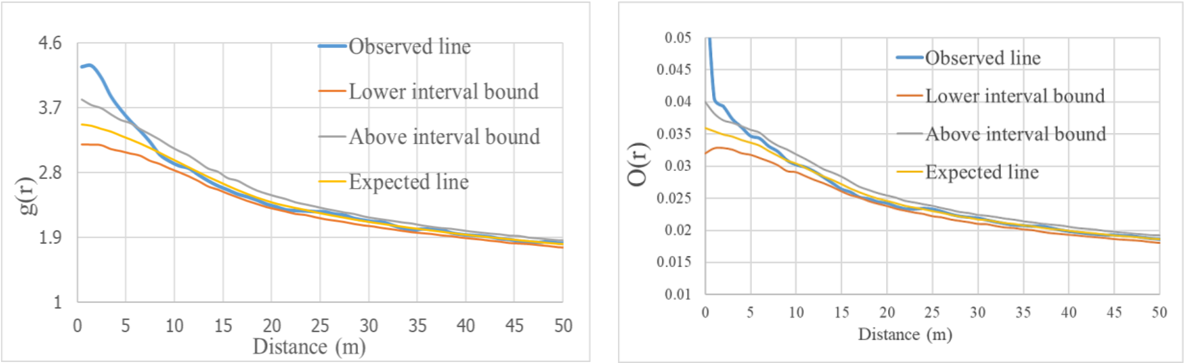

Fig. 7. Changes in the spatial distribution of *Cl. turcomanica* in the study area using univariate functions (g-r and O-ring).

The results of using univariate functions to investigate the spatial pattern of *H. strobilaceum* indicated that the value of the function *g*(r) was higher than the baseline of the function at distances 0-5 meters, and consequently, the spatial pattern of this species was aggregation. Also, the significance of this distribution was confirmed at a 0.05 confidence level at distances of approximately 0-5 meters, because at this distance, the value of the function was outside the limits of Monte Carlo envelopes. The distribution pattern was random at distances greater than

5 meters (Fig. 8).

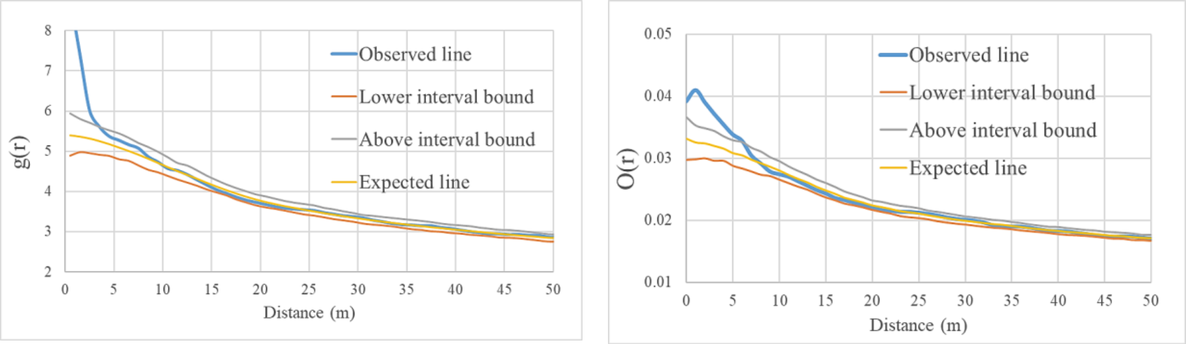

Fig. 8. Changes in the spatial distribution of *Halocnemum strobilaceum* in the study area by using univariate functions (g-r and O-ring).

The bivariate function $g_{12}(r)$ was used to investigate the interaction of *Cl. turcomanica* and *H. strobilaceum*. If the value of this function exceeds 1, it is concluded that these two species have positive interactions and have a facilitating effect on each other's growth. Therefore, they provide the conditions for establishing each other. Values less than 1 for this function indicate the negative effect of these species on each other; In other words, there was a competition between them for resources.

The results of $g_{12}(r)$ function indicate that these two species have a positive interaction with each other at distances between 0-5 meters and they influence each other's distribution, which is consistent with the aggregation spatial pattern of these species up to the distance 5 m. In other words, this range has created facilitating conditions for these species, which can be due to the inappropriate environmental and soil conditions or insufficient nutrients in the study area, which plays the role of a nurse for another species. The $O_{12}(r)$ function was also used to confirm the $g_{12}(r)$ function and showed the same results as those used in the bivariate pair-correlation function (Fig. 9).

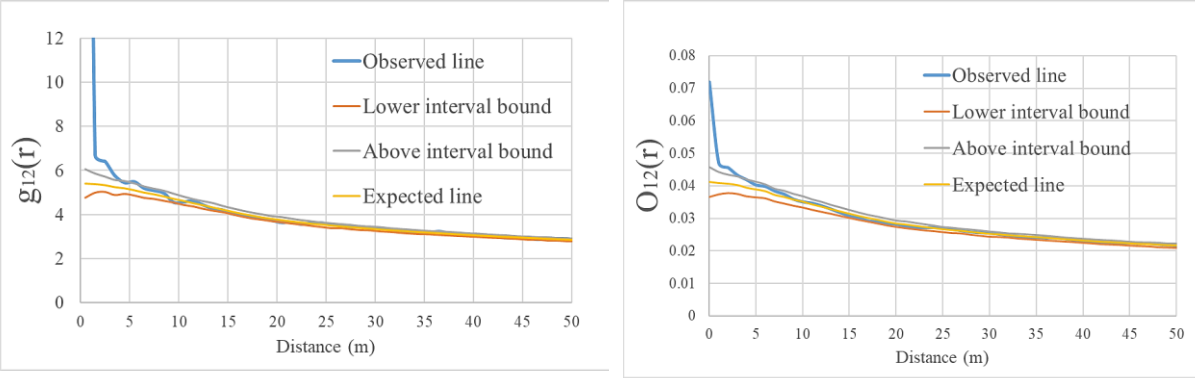

Fig. 9. The interaction of *H. strobilaceum* and *Cl. turcomanica* in the studied sample using the bivariate g-function and O-ring

According to the results obtained regarding the spatial analysis of the two studied species, it can be concluded that the spatial pattern of these species is clumped, there are in close vicinity of each other and have a facilitating effect on the growth of each other. On the other hand, at all distance scales, *Cl. turcomanica* and *H. strobilaceum* had positive relationships; wherever there was *H. strobilaceum*, there was also *Cl. turcomanica.* So, it is concluded that *H. strobilaceum* plays the role of nurse and protector for *Cl. turcomanica*, and had a positive interaction with it, which the investigated functions also confirm this point. The interaction of two studied species in this research was evaluated from two different aspects. First, the spatial pattern of these two species was studied using univariate summary statistics, and afterward with the bivariate functions $g_{12}(r)$ and $O_{12}(r)$, the interactions of the two species were investigated in the study area.

4. Discussion

Results showed the difference in the number of individuals between *H. strobilaceum* and *Cl. turcomanica*. For a general overview, it can be attributed to several ecological and biological factors related to their life forms and adaptations to their environments. *Halocnemum* typically exhibits a more robust growth form, often forming dense stands in salt marshes. This can lead to higher density of individuals due to clonal propagation through vegetative means, allowing one plant to contribute to a larger number of shoots or individuals in a given area. In contrast, *Climacoptera* may have a more conservative growth strategy with lower reproductive output or more specialized habitat requirements. Khatir Namani (2008) and GNWM (2015) have also highlighted the higher number of individuals in *Halocnemum* compared to *Climacoptera* can be explained by their differences in life form, habitat adaptability, reproductive strategies, environmental tolerance, and competitive dynamics within their ecosystems.

The K-S goodness of fit test was used to evaluate the spatial pattern of species in regions with arid and semi-arid climate. Thornley *et al*. (2022) also used the KS test in analyzing the spatial pattern in grasslands to check the normality of the collected data. Bakhshi Khaniki and Mohammadi (2012) studied the ecology of some *Climacoptera* species in Golestan province and concluded that *Cl. turcomanica* can be found together with *H. strobilaceum* as a community.

Wang *et al*. (2016) investigated the usage of the O-ring statistic to examine the spatial pattern and association of *Haloxylon ammodendron* and *Anabasis aphylla* population in the southern border of Junggar Basin located in Xinjiang. Their results confirmed that the spatial association of *H. ammodendron* and *A. aphylla* reflects a tense negative interaction between woody plants. Shaw *et al*. (2020) and Rudge *et al*. (2022) also considered the role of spatial patterns of plant species in designing appropriate management plans, and the description of ecosystem stability and restoration measures as an important tool in environmental and protection planning. Zhang *et al*. (2022a) also used the $O_{12}(r)$ function to examine the interspecific relationship between *Sarcocephalus xanthoxylon* and *Ammopiptanthus mongolicus*. Their results indicated a positive relation at small scales under various grazing intensities, which is compatible with strong moisture competition in arid regions.

The results of the univariate function showed the clustered spatial pattern for *Climacoptera* species. van Mantgem *et al*. (2011) and Shin *et al*. (2017) introduced the reason for the change in the clustered spatial pattern to a random spatial pattern with increasing distance as the impossibility of reproduction. According to the results obtained regarding the spatial analysis of the two studied species, it can be concluded that the spatial pattern of these species in the study area is clumped, they are in close vicinity of each other and have a facilitating effect on the growth of each other. Hosseini and Shahmoradi (2011) studied the behavior of *H. strobilaceum* in saline and alkaline rangelands of Golestan province and stated that this species protects *Puccinellia distans* and *Climacoptera turcomanica* within its canopy cover. One of the reasons for the accumulation of species next to each other is the existence of appropriate and suitable conditions for plant growth (such as being supported by another species) which forms a cluster spatial pattern (Peralta *et al*., 2023).

Knowledge of the type of spatial ecological relationship of plants and their interactions using univariate and bivariate statistical functions contributes significantly to the proper range management. The results of this research showed that both species of *Cl. turcomanica* and *H. strobilaceum* had a positive interaction with each other at a short distance (0-5 m). The univariate pair-core function indicated that at the 0-5 m intervals, the distribution pattern of these two species was aggregation, because the results of the bivariate g-function were at scales outside the Monte Carlo and the distribution pattern has been random as distance increases, which can be attributed to the impossibility of reproduction. Considering that the spatial pattern of complications in nature is a main characteristic in understanding the dynamic of the ecosystem and provides useful information about establishment, growth, regeneration, mortality, use of resources by the occupants of the field, and finally in the development and spatial conditions of point complications, it is necessary to determine the general trend of changes in the spatial pattern and interaction of plant species through expanding the current study in different ecological and physiographic conditions in other plant habitats.

Author Contributions

Azimi M. and Kariminejad N. designed the study, carried out the simulations and verified the analytical methods. Ebrahimi O. and Riyazinia V. contributed to field sampling and sample preparation. Amiri M. aided in interpreting the results and wrote the manuscript in consultation with Campetella G. All authors discussed the results by providing critical feedback and helped shape the research, analysis and manuscript.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The study was approved by the Ethics Committee of the University of Tehran (COPE). The authors avoided from data fabrication and falsification.

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Conflict of Interest

The authors declare that they have no conflicts of interest. Also, the funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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