RESPONSE OF SPATIAL POINT PATTERN OF *HALOSTACHYS CASPICA* POPULATION TO GROUND WATER DEPTH

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Abstract

We subjected *Halostachys caspica* populations to three groundwater depths: shallow (< 2.5 m), middle (2.5–4.5 m), and deep (> 4.5 m) in the sample plots, at the diluvial fan of the South Junggar Basin. Both the spatial pattern and spatial association of the population among all three groundwater depths and four growth stages were studied to investigate the impact of groundwater depth on the formation and persistence mechanism of the spatial pattern of *Halostachys caspica* populations. In this study, Ripley's *K* function was utilized to characterize spatial patterns and intraspecific associations of *H. caspica* in three 1-ha plots, as well as to study their relationship with groundwater depth. The seedling supplement severely decreased with increasing groundwater depth, and the population structure changed noticeably due to increased amount of dead standing plants. Different growth stagesof the *H. caspica* population all had aggregated distributions at small scale in the three groundwater depth areas. With increasing scales, the aggregation intensity weakened in all growth stages. Distribution was aggregated at 50 m scales in both the shallow and middle groundwater depth areas, while the deep groundwater depth area followed a random distribution.

Key words: Spatial point pattern, *Halostachys caspica*, Diluvial fan.

Introduction

Desert plants in the arid region are depending on groundwater and play a significant role for indicating variation of groundwater levels; however, groundwater depth directly affects the dynamics of soil moisture and nutrients, which are closely associated with vegetation growth (Zhong *et al.*, 2002; Zhang *et al.*, 2003). Therefore, groundwater is the dominant factor that determines the distribution, germination, and population succession of desert vegetation, as well as desert oasis survival (Zhao *et al.*, 2003; Fan *et al.*, 2004). Through long-term adaptive evolutionary processes, desert vegetation in the arid region has developed unique mechanisms to adapt to groundwater change, which could vary depending on different individuals, populations, communities, and even patches (Chen *et al.*, 2003). Currently, only few reports exist on the effects of groundwater depth on desert riparian forest plants (Zhong *et al.*, 2002; Chen *et al.*, 2003). Zeng *et al.* (2012) further studied the relationship between *Haloxylon ammodendron*and groundwater in the Gurbantunggut Desert.

A point pattern is based on a dot diagram of spatial distribution of plant individuals and could analyze the population spatial distribution pattern and spatial associations between two species (Ripley, 1977; Dale &Powell, 2001; Zhang & Meng, 2004). Hence, the results of this analysis are more accurate, and make up for the deficiencies of traditional analysis methods to a large extent (Zhang & Meng, 2004; Yang *et al.*, 2006). In addition, the *g(r)* function is very sensitive to scale in point pattern analysis, and can effectively reflect the population spatial distribution pattern, providing a lot of underlying ecological information for the further study of forest patterns by analyzing spatial associations among different communities (Zhang *et al.*, 2007; Song *et al.*, 2010; Pillay & Ward, 2012). Point pattern analysis has been used in several studies on the spatial distribution patterns and spatial associations of different desert shrub species, such as *Haloxylon ammodendron*, *Ceratoides ewersmanniana*, and *Anabasis aphylla* in the Junggar Basin (Song *et al.*, 2010; Pillay & Ward, 2012; Jia *et al.*, 2007; Wang *et al.*, 2014; Wang *et al.*, 2015; Chu *et al.*, 2014; Liu *et al.*, 2008).

Halostachys caspica is a chenopodiaceous subshrub that provides a significant plant resource in desert and salt-alkali regions, and is mainly distributed at the Hexi Corridor, the Taklimakan Desert, the Yanqi Basin, the Turpan Basin, and the Tianshan Mountain in the northwestern region of China, in which the groundwater level ranges between 1 and 3 m. The roots of *H. caspica* distribute mainly at a range of 70–130 cm, depending on groundwater and anastatic water availability (Wang, 1964; Tao, 2007). It has unique bioecology characteristics, extensive economic and ecological value, and is also a medicinal plant (Chu *et al.*, 2014). At present, studies on *H. caspica* mainly focused on biological characteristics and medicinal ingredients (Tao, 2007). The spatial distribution pattern of *H. caspica* population was analyzed via distributed index method (Yang *et al.*, 2010), while the content mainly focused on the entire pattern and interspecific association of the population. However, distribution pattern and intraspecific association of the *H. caspica* population at different growth stages have not been reported. In this study, we analyzed the spatial distribution patterns of a *H. caspica* population in response to a groundwater depth gradient using the *g(r)* function in the diluvial fan of the South Junggar Basin. Such studies contribute to our understanding of the response of spatial distribution pattern and intraspecific association of a *H. caspica* population to groundwater depth, and could provide useful information for the development of vegetation recovery and rebuilding.

Materials and Methods

Study site: The study area was located at the diluvial fan on the southern edge of the Junggar Basin in Xinjiang (84°50′–85°20′E, 45°22′–45°40′N), bordering on the Jayer mountain and the Chenjisihan mountain. The area is very rugged, and

tilted from southeast to northwest, spanning an elevation range of 258–285 m. Main soil types were brown desert soil and gray-brown desert soil with local saline soils, sandy soils, and dry bog soil. The study area has a typical arid continental climate with a mean annual temperature of 8°C. January was the coldest with a mean temperature of -16.7°C, while July had the highest temperature with 27.4°C. The mean temperature varied from 5 to 9°C, minimum winter temperatures varied from -30 to -41°C, and maximum summer temperatures varied from 30 to 40°C. Snowmelt at the end of winter, combined with the rainfall, amounted to an annual precipitation of 100–150 mm. Annual potential evaporation was more than 2000 mm. The sample plots were mainly distributed with xerophytic and salt-alkali tolerant desert plants, which were dominated by *H. caspica*. Other woody plant species in the area included *Halocnemum strobilaceum*, *Nitraria roborowskii*, *Reaumuria songarica*,and *Tamarix ramosissima*.

Data collection: Three study plots were established in summer 2014, according to groundwater depth and the distribution of the *H. caspica* population. These included deep groundwater depth (underground water level > 4.5 m), middle groundwater depth (underground water level 2.5–4.5 m), and shallow groundwater depth (underground water level < 2.5 m), respectively. Each plot covered an area of 1 ha (100 × 100 m) in horizontal distance, and was divided into contiguous 10 × 10 m quadrates, as a basic unit for the vegetation survey. All woody plants were investigated, including living and dead standing individuals. The species names, relative location of each individual, height, crown width (the greatest diameter of the vertical projection of the crown in the two directions north-south or east-west), and microhabitat (e.g. soil surface or depression patch) were recorded.

Data analysis

According to research objectives and biological characteristics (such as germination and fructification), *H. caspica* plants were classified into seedling ($H \leq 20$ cm), juvenile (20 cm $<H \leq 35$ cm), small adult plants (35 cm $<H \leq 50$ cm), big adult plants ($H>50$ cm), and dead standing plants.

Spatial distribution patterns and associations of *H. caspica* population in different groundwater depths were analyzed using Ripley's $g(r)$ function, which is a point calculation to the ring area with fixed width. The function $g(r)$ uses a dimensionless ratio of the actual distribution density to a random distribution in the study area, and its mathematical expectations should follow published literature (Ripley, 1977). The function $g(r)$ has the additional advantage that it is a probability density function, which is an alternative statistic to estimate the number of points within concentric rings at the distance and within the radius r. The function relationship between Ripley's $g(r)$ and Ripley's $K(r)$ could be shown via equation (Wiegand & Moloney, 2004):

$$g\ (r) = (2\pi r)^{-1}dK\ (r)\ /dr$$

where $dK\ (r)$ = the differential $K\ (r)$, dr = the differential r.At a given distance r, if $g(r)$ were above the upper (or below the lower) limit of the confidence envelope, this

would indicate aggregated (regular) distributions. However, the function $g(r)$ is within the confidence intervals, indicating random distributions.

A pair correlation function is also used for bivariate point pattern analysis as follows:

$$g_{12}\ (r) = (2\pi r)^{-1}dK_{12}\ (r)\ /dr$$

where $dK_{12}\ (r)$ = the differential $K_{12}\ (r)$, the function $g_{12}\ (r)$ estimates the number of species 2 within fixed width concentric rings at each individual of species 1 as the center and within radius r, by which the spatial association of the population at many specific scales were defined. For bivariate analysis and for a given distance r, $g_{12}(r)$ is above the upper (or below the lower) limit of the confidence envelope, this indicates that species 2 is positively (or negatively) associated with species 1 at the distance r. Function $g_{12}(r)$ ranges within the confidence intervals, indicating that there is no interaction between species 1 and 2.

All analyses were conducted with the Programita software package (Wiegand & Moloney, 2004). The spatial analysis scale was 0–100 m in the present paper, and the utilized step size was 1 m. A Monte Carlo simulation was used to test calculation envelope line up and down, which was fitted to 100 times,and estimated a 99% confidence interval.

Results

Population characteristics: In the plot, the coverage of *H. caspica* population was increasing with decreasing groundwater level. The coverages of the *H. caspica* population in the deep and shallow groundwater depth were 2.63% and 25.62%, respectively. Seedling recruitment in shallow groundwater depth was mass, and more than for middle groundwater depth, while seedling recruitment was only 24 for deep groundwater depth (Table 1). Dead standing plants of *H. caspica* population in the three plots had high density. Particularly for deep and middle groundwater depths, dead standing plant densitywas even more than living plant density due to the harsh environment and deeper groundwater level (Table 1). In the deep, middle and shallow groundwater depth areas, the dead standing plant density of the *H. caspica* population was 6873 hm^{-2}, 5396 hm^{-2}, and 1015 hm^{-2}, respectively.

Spatial pattern: For the *H. caspica* population, the aggregation intensity in the seedling, juvenile, small adult plant, and big adult plant reduced successively, while it was decreasing in shallow, middle, and deep groundwater depth in turn (Fig. 1). The seedling, juvenile, small adult plant, and big adult plant of *H. caspica* population at shallow groundwater depth were significantly aggregated at 0–50 m, 0–51 m, 0–51 m, and 0–47 m, respectively, and tended toward regular spatial distribution at > 55 m, > 61 m, > 54 m, and > 49 m, respectively, while it tended to random spatial distribution at other scales (Fig. 1).

Table 1. Population characteristics of *H. caspica* in the diluvial fan of the South Junggar Basin.

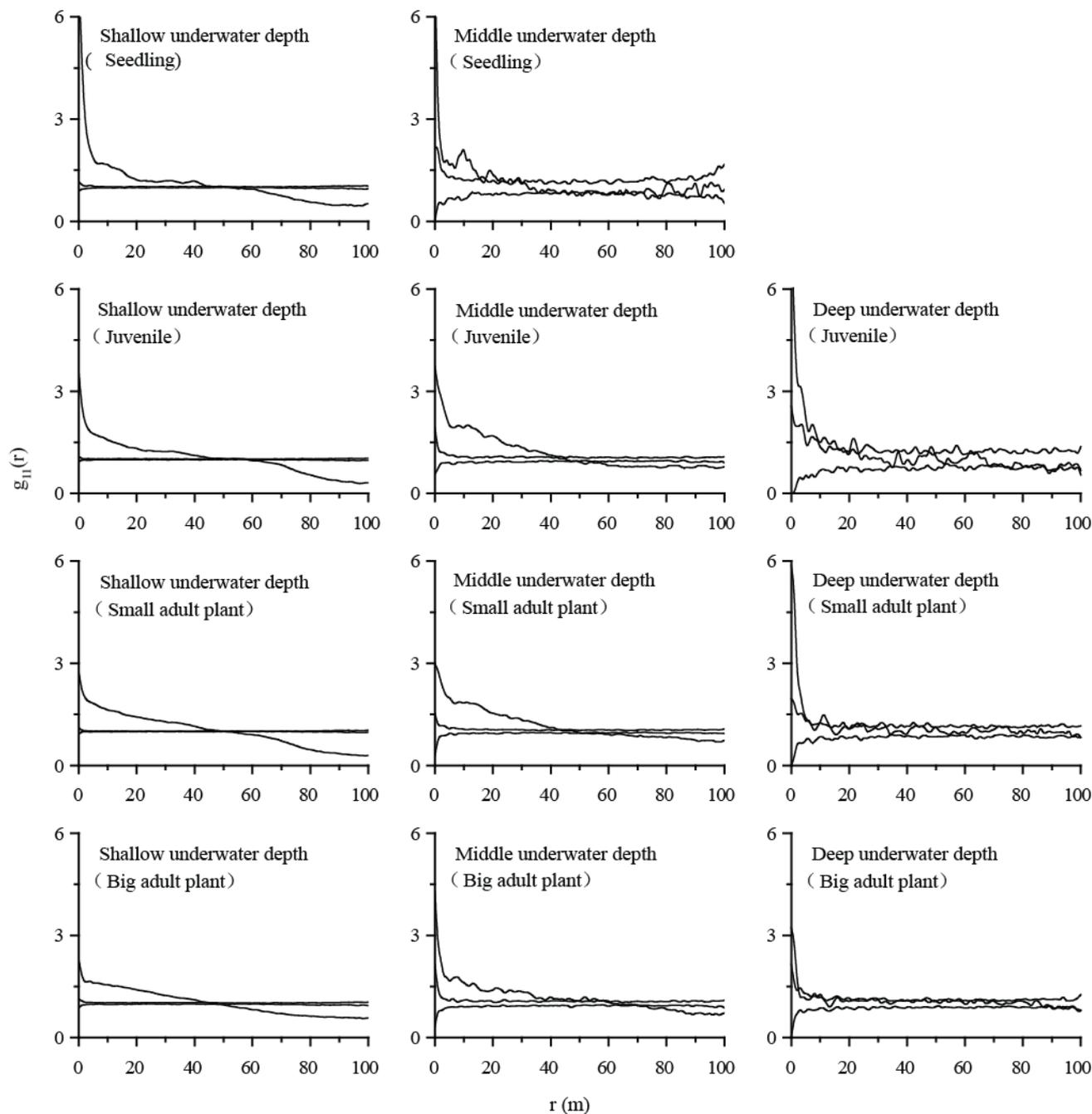| Underground water depth (plot)	Coverage (%)	Seedling density/ (individual·hm-2)	Juvenile density/ (individual·hm-2)	Small adult plant density/ (individual·hm-2)	Big adult plant density/ (individual·hm-2)	Dead standing plant density/ (individual·hm-2)
Shallow	25.62	1 997	2 942	3 171	1 925	1 015
Middle	6.83	277	1 098	1 372	910	5 396
Deep	2.63	24	230	373	504	6 873

Fig. 1. Spatial patterns of different growth stages of the *H. caspica* population in all three areas.

Similar to shallow groundwater depths, the seedling, juvenile, small adult, and big adult plants at middle groundwater depth were significantly aggregated at 0–28 m, 0–43 m, 0–45 m and 0–62 m, respectively, and tended to regular spatial distribution at > 29 m, > 57 m, > 52 m, and > 72 m respectively, while plants tended to random spatial distribution at other scales, respectively (Fig. 1).

Seedlings at deep groundwater depth could not form inherent spatial patterns, because their quantity was extremely low, while juvenile, small adult, and big adult plants in deep groundwater depth were significantly aggregated at 0–25 m, 0–15 m, and 0–4 m respectively, and tended to random spatial distribution at other scales (Fig. 1).

Spatial associations: Each growth stage of the *H. caspica* population had a positive association with the other stages at 0–50 m in the shallow groundwater depth area, and either a negative association or no association at other scales. In the middle groundwater depth area, seedlings and juveniles showed a positive association at 0–33 m, and a negative association at other scales. Seedlings and small adult plants showed a positive association at 0–40 m, and a negative association at other scales. Seedling and big adult plants showed a positive association at 0–34 m, and a negative association at other scales except for the individual scale. Seedlings and small adult plants showed a positive association at 0–45 m, and either a negative association or no association at other scales. Juveniles and

big adults plant showed a positive association at 0–41 m, no association at 42–69 m, and a negative association at other scales. Small and big adult plants showed a positive association at 0–42 m, no association at 43–68 m, and a negative association at other scales (Fig. 2).

In the deep area, associations at different scales tended to show no association between seedlings and juvenile plants, as well as between seedlings and small adult plants. Juvenile and small adult plants showed a positive association at 0–15 m, but no association at other scales. Juvenile and big adult plants showed a positive association at 0–9 m, but no association at other scales. Small and big adult plants showed a positive association at 0–9 m, but no association at other scales (Fig. 2).
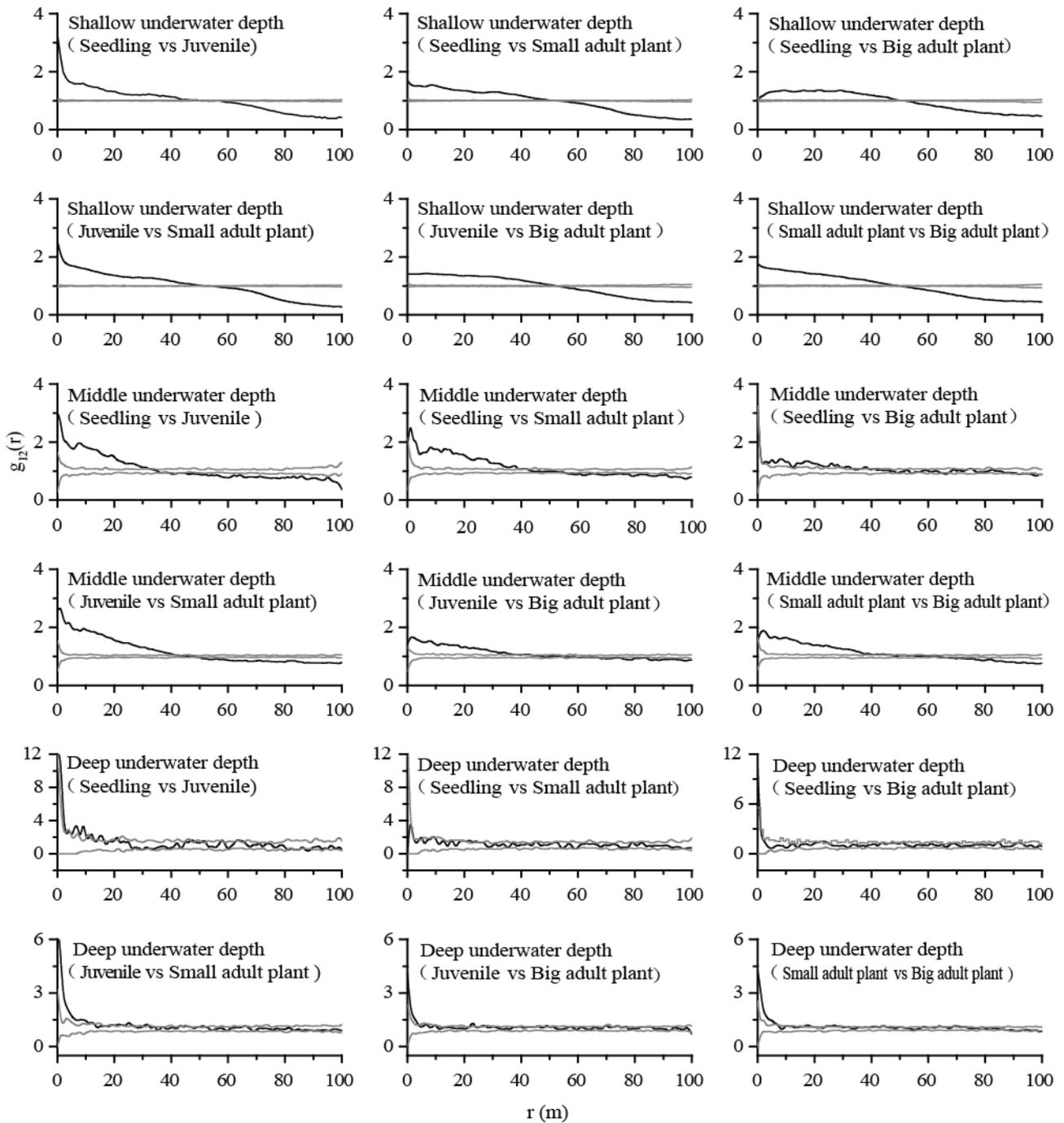

Fig. 2. Spatial associations among different growth stages of the *H. caspica* population in all three areas.

Discussion

Spatial patterns of the *H. caspica* population: The spatial distribution pattern of the *H. caspica* population has apparent differences in different groundwater depth gradients. No inherent distribution pattern was found in the deep groundwater depth area, because the quantity of seedlings was extremely low. However, the aggregation intensity of other growth stages declined quickly at small scale, and fluctuated around specific scale at middle scales, finally tending to random distribution. In the middle underwater depth area, the aggregation intensity of the *H. caspica* population was higher, while the aggregation scale was less for shallow areas due to a severe self-thinning mechanism that is affected by the underground water level. Spatial distribution patterns in the shallow and middle areas were similar, while the aggregation intensity always declined with increasing scales. This suggests that the *H. caspica* population in the middle areas has severely degraded, but still retains an inherent distribution pattern and temporary steady. Due to long-term drought and deepening of the underground water level, the distribution heterogeneity of soil resources (such as salinity) has changed; therefore, the amount of *H. caspica* individuals decreased, and the distribution is more scattered. As a result, the local aggregation and random distribution at large scale tended to become more obvious for the *H. caspica* population. In addition, due to declining underground water levels, the use of groundwater has become difficult for *H. caspica* and the salt of the ground surface has been intensely accumulated. Furthermore, seeds of *H. caspica* face reproduction difficultly in the deep groundwater depth area and consequently, the population cannot effectively update and supplement itself, and each growth stage ultimately tended to random distribution.

In the three groundwater depth areas, the aggregation intensity was always declining with increasing scales for the *H. caspica* population. In the arid region, the aggregation of shrub population patterns at small scales has many causes, in which seed spread and habitat heterogeneity are very important (Chu *et al.*, 2014; Li *et al.*, 2013). The seed spread can lead to intraspecific aggregation due to space limitations (Nathan & Mullerlandau, 2000; Schleicher *et al.*, 2011), while the heterogeneity of plant growth space (such as patches or depressions) is advantageous to improve the survival rate of seedlings (Holmgren *et al.*, 1997; Wang *et al.*, 2013). The seed of *H. caspica* is small and light in weight; therefore, it is apt to long distance spread by stronger wind, and can gather in microhabitats (such as depressions and gullies), which are suitable for germination and settlement, benefiting from the snowmelt mechanism. Therefore, seed spread and microhabitat may be the two principal factors leading to spatial aggregation of the *H. caspica* population. In addition, different groundwater depth can affect spatial distribution patterns and population structures by changing the utilization degree of both ground and capillary water.

The aggregation intensity of the *H. caspica* population is closely related to plant sizes in the different groundwater depth gradient. Since smaller size plants are interdependent in an arid condition, the possibility for intraspecific competition is very small. A further reason is that desert plants reproduce through seeds, and the density restriction among smaller sized plants has not yet happened in the relatively short period. Therefore, seedlings were apt to form aggregation patterns. However, the larger size plants tend to regular distribution due to intraspecific competition (Li *et al.*, 2003; Sun *et al.*, 1998). In the middle and deep underwater depth areas, intraspecific competition hardly ever happens, because the *H. caspica* population is widely spaced due to drought and salt stress, where a large number of dead standing plants exist and only local and small plants survive. The surviving larger sized plants require ample of resources and are sparsely distributed due to stronger intraspecific competition; therefore, their aggregation intensity is apparently lower than that of smaller sized plants. Consequently, the aggregation intensity of adult plants is weak in the deep underwater depth area, and tends to have a random distribution.

Intraspecific associations of the *H. caspica* population: Each growth stage of the *H. caspica* population had positive associations with the other stages at smaller scales in the shallow and middle groundwater depth areas, suggesting that plants at different growth stages share resources, have little contention, and show a consistent adaptability to the environment; consequently, they could form common patches to gradually spread outward and keep stable, finally forming positive associations and dominating each other. However, positive associations happen only at the smaller scale range, suggesting that the intraspecific relationship has strong dependence on a spatial scale. The intraspecific relationship at a smaller scale is related to reproduction, because behavior such as seed spread, nutrition reproduction, and maternal plant refuge can only occur at a smaller scale range (Schenk *et al.*, 2003; Wu & Yang, 2013). However, the seeds of *H. caspica* are tiny, and the mobility is relatively poor after falling into soil. Plenty of seeds end up near to adult plants, and seedlings thrive through a dependence on adult plants. Hence, the smaller size plant of the *H. caspica* population is moderately based on larger plants with their bigger canopy, enabling higher seedling survival rates.

At large scales, the *H. caspica* population has a substantial negative association with groundwater in shallow underwater depth areas, no association or weak negative association in middle underwater depth area, and consequently tends to a lack of association in deep underwater depth area for all scales. Therefore, the association between each stage would have changed due to different population degradation degree that has been caused by groundwater depth. In the middle underwater depth area, adult individuals have a higher probability to generate new plants via different modes of reproduction, so that the new plants can maintain a specific population number and the population would have an increased chance of extending space in a year with rising groundwater level. However, seedling recruitment is lower, and the survival rate is small due to harsh environmental conditions in the deep underwater depth area; therefore, dependence among different growth stages would decrease and natural regeneration would hardly be possible.

Implications for *H. caspica* population management: In recent years, the halophyte population degenerated severely because groundwater levels have been declining, caused by oil exploitation and a long-term duration of agricultural development. Currently, the halophyte population number has plummeted and only a small amount of annual halophytes survived, turning climax vegetation into bare land in most areas; therefore, it is urgent to recover and protect the woody halophyte (Sun *et al.*, 1998). As a dominant species on saline-alkali land, *H. caspica* has both salt and drought tolerant characteristics and tends to an aggregated distribution pattern (Tao, 2007). In the present study area, the *H. caspica* population has shown different degrees of aggregated distribution patterns, which is caused by unevenly distributed soil salinity and connected with their reproduction strategy. The study results also indicate that aggregated distribution has only developed at small scales, and habitat fragmentation has led to the formation of patches of population distribution. The surviving plaques will become the primary origin of natural regeneration and recovery on saline-alkali land. To increase *H. caspica* plant survival rate, the micro-topography should be transformed to collect natural rainfall or snowmelt, and artificial seeding or afforestation in promising habitat condition areas should be adopted.

Conclusions

At small scales, intense positive associations occurred in the shallow and middle groundwater depth areas, while a negative association was found for deep areas among different growth stages. The groundwater depth was found to have an important effect on the spatial pattern and intraspecific association of the *H. caspica* population of the South Junggar Basin. In particular, it has restricted the formation of the population spatial distribution pattern.

Acknowledgements

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