Journal of Arid Land

Volume 2 | Issue 4 Article 1

12-7-2010

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Recommended Citation

LI, XiangYi; LIN, LiSha; ZHAO, Qiang; and ZHANG, XiMing (2010) "Influence of groundwater depth on speciescomposition and community structure inthe transition zone of Cele oasis," *Journal of Arid Land*: Vol. 2 : Iss. 4 , Article 1.
DOI: 10.3724/SP.J.1227.2010.00235
Available at: https://egijournals.researchcommons.org/journal-of-arid-land/vol2/iss4/1

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Cover Page Footnote

This research was funded by the National Basic Research Pro-gram of China (2009CB421303), the Key Project in Science & Technology Program of Xinjiang Uygur Autonomous Region (200933125) and the Science and Technology Ministry Program (2009BAC54B03).

JOURNAL OF ARID LAND, 2010, VOL. 2, NO. 4, 235–242

Influence of groundwater depth on species composition and community structure in the transition zone of Cele oasis

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Abstract: The paper analyzes the hypothesis that the distribution of dominant plant species and characteristics of plant communities are related to groundwater depth. The results showed that variations of groundwater depth impacted distributions and characteristics of dominant plant communities. However, besides groundwater depth, the community composition and species diversity were also influenced by physiognomy of the habitat. Based on the similarity coefficient, the differences between dominant plant communities were significant at different groundwater depths. Compared with other results relating to desert vegetation and groundwater depth, variations of community distribution were similar at the large spatial scale. However, in this extremely arid region, there were significant differences in community type and community succession when compared with other arid regions, especially in relationship to deep groundwater depth. With groundwater depth from deep to shallow, communities transformed with the sequence of *Alhagi* communities, *Tamarix* spp. communities, *Populus* communities, *Phragmites* communities, and *Sophora* communities. At groundwater depth of less than 6.0 m, the community type and composition changed, and the species diversity increased. Among these dominant species, *Tamarix* exhibited the biggest efficiency in resource utilization according to niche breadth, which means it possessed the best adaptability to environmental conditions at the oasis margins.

Keywords: groundwater depth; community characteristic; niche breadth; oases; Taklamakan desert

1 Introduction

Impacts of groundwater on vegetation are the focus of much research in arid and semi-arid regions since groundwater is an important water source for vegetation (Runge and Zhang, 2004; Zhao and Liu, 2006). At the extremely arid southern margin of the Taklamakan desert in Xinjiang, northwestern China, oases occur in the desert. Two opposite ecological processes, desertification and oasification, exist simultaneously in the transition zone between these oases and the desert. These two opposing processes in ecological change depend on the water condition of the environment, and the state of homeostasis in the relationship between groundwater, soil moisture and vegetation (Ma, 2000; Runge and Zhang, 2004).

In an extremely arid region (the annual precipitation is less than 50 mm and potential annual evaporation is more than 2,600 mm) (Zhou, 1993; Qong *et al*., 2002), the groundwater impacts intensively on the characteristics of indigenous vegetation because of the very low precipitation (Li *et al*., 2004; Zhao and Liu, 2006; Thomas *et al*., 2008). The transition zone of indigenous vegetation between oases and open desert is a valuable shelter belt for the oases to prevent sand drift and desertification, and to provide grazing, forage, construction materials and fuel (Gries *et al*., 2003; Runge and Zhang, 2004). With the rapid increase of oasis population, the indigenous vegetation plays a more important role in the ecological and agro-economic system of the oases (Li *et al*., 2002;

Received 2010-06-02; accepted 2010-08-25
doi: 10.3724/SP.J.1227.2010.00235
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Thomas *et al*., 2006).

In the southern margin of the Taklamakan desert, investigations have been mostly concerned with the ecological function of groundwater, such as the hydrological cycle, water resources and soil environment (moisture, salinity) (Ma *et al*., 2002). The effects of groundwater on plant water status, growth and distribution have been widely studied (Bruelheide *et al*., 2003; Gries *et al*., 2003; Li *et al*., 2004; Zeng *et al*., 2006; Thomas *et al*., 2008), however, little is known about the characteristics of vegetation populations and communities in relation to different groundwater depths in the transition zone between oases and the desert. Moreover, the relationship between groundwater and vegetation distribution is only partially described in some results (Ma *et al*., 2000; Bruelheide *et al*., 2003), and the characteristics of plant populations and communities has rarely been the main focus of studies. The impact of variation in groundwater depth on distributions and characteristics of plant populations and communities is still not well defined. Since groundwater is consumed by oasis agriculture, with the flooding rarely reaching the transition zone, the resulting changes in groundwater depth must play a key role in plant survival.

We hypothesize that distribution of dominant plant species and characteristics of their communities relate to variation in groundwater depth. In order to test our hypothesis, we established ten plant transects over areas where groundwater depth varied from 1 m to 16 m, and studied the distributions and characteristics of dominant plant populations and communities in the transition zone (also referred to as 'foreland') of the Cele (also known as Qira) oasis. The results will be important to indicate the impact of variations of groundwater depth on distributions and compositions of natural vegetation, and inform projects aiming to restore and re-establish vegetation in the transition zone between oases and desert.

2 Materials and methods

2.1 Study area

The study was conducted in 2004 in the transition zone between the Cele oasis and the desert (37°01′N, 80°48′E; 1,365 m a.s.l.). Cele oasis is located in Cele County at the southern fringe of the Taklamakan desert in Xinjiang Uygur Autonomous Region, northwest China. The climate in this southern fringe of the Taklamakan desert is extremely arid. The mean annual potential evaporation is 2,600 mm and the annual mean precipitation is 35.1 mm. Based on groundwater depth, ten transects were established from west to east in the transition zone in the foreland of the oasis (37°01′–37°06′N, 80°39′–80°50′E). In the northwest transect, the groundwater depth was more than 15.0 m, while in the northeast transect, the groundwater depth was less than 2.0 m due to proximity to the overflow zone of oasis irrigation.

Indigenous vegetation, in locations of different groundwater depths, was composed of different plant species, primarily *Alhagi sparsifolia* Shap., *Karelinia caspica* (Pall.) Less., *Scorzonera divaricata* Turcz., *Tamarix* spp., *Populus euphratica* Oliv., *Phragmites australis* (Cav.) Steudel and *Sophora alopecroides* L. (Table 1). Soil water content, salt content and soil types varied as well as groundwater depth in different transects. In the area of groundwater depth from 15 m to 6 m, the soil types were mainly sandy soil and brown desert soil, however, in areas of shallow groundwater depth, the soil type was mainly saline soil. In all transects soil lacked organic matter, with an average content around 1.02%. In each transect, groundwater depths, plant community types, topographic features, soil types, and primary plant species were recorded (Table 1).

2.2 Groundwater depths

Observation wells were established on each transect near communities of dominant species to monitor groundwater depth. The groundwater depth was measured at each well once a month between May and October. The characteristics of plant communities were investigated near the observation wells.

2.3 Plant community characteristics

Study plots were chosen according to (1) recommendations by Cain and Castro (1959) on subplot area for different plant life forms in the temperate zone, and (2) the principle of species-area curve (Dong, 1996). Three or four study plots were established in the dominant plant community near the observation well on each transects. We selected 10 m × 10 m plots to study community characteristics for perennial herbs and shrubs, with 20 m × 20 m plots for *Populus*

Table 1 General characteristics of vegetation-plots at different groundwater depths in the foreland of Cele oasis

Groundwater depth (m)	Coordinates	Community type	Topographical feature	Soil type	Plant species
15.7	37°01'31"N 80°43'59"E	*Al* dominant community	Flat and semi-fixed sand ground	Aeolian sandy soil	*Al*, *Ka*, *Ph*, *Sc*
11.7	37°01'37"N 80°42'52"E	*Al–Ta–Ka* community	Big sand dunes and semi-moved sand	Aeolian sandy soil	*Al*, *Ka*, *Sc*, *Ta*
8.8	37°02'36"N 80°40'33"E	Single *Ta* community	Flat and wind erosion with *Ta* cones	Aeolian sandy soil	*Ta*
6.3	37°04'28"N 80°44'29"E	*Ta* dominant community	Flat and fixed sand with big and lower *Ta* cones	Aeolian sandy soil	*Al*, *Ka*, *Ph*, *Sc*, *Ta*
6.0	37°04'53"N 80°44'42"E	Single *Po* community	Flat erosion sand ground around large sand dunes	Aeolian sandy soil	*Po*
4.7	37°04'36"N 80°44'49"E	Po dominant community	Flat and fixed sand ground	Brown desert soil	*Ka*, *Po*, *Ta*
3.3	37°02'33"N 80°40'34"E	*Ta–Ph* community	Floodplain of riverbank	Brown desert soil	*Ha*, *Ph*, *Po*, *Sc*, *Ta*
2.1	37°04'52"N 80°49'06"E	*Ph–Ta* community	Flat, salinization and meadow zone	Saline soil	*Al*, *Ly*, *Ph*, *So, Ta*
1.2	37°02'34"N 80°40'33"E	*Ta–Ph* community	Alluvial river terraces	Saline soil	*Cy*, *Ha*, *Ly*, *Ph*, *Po*, *Sc*, *Ta*
0.9	37°04'54"N 80°48'56"E	*So–Ph* community	Salinization and meadow near overflow zone	Saline soil	*Ph*, *So*, *Ta*

Note: Mean values of groundwater depths were recorded during the growing season. Coordinates are the sites of groundwater observation wells. *Al*, *Alhagi sparsifolia*; *Cy*, *Cynanchum chinense* R. Br.; *Ha*, *Halogeton glomeratus* (Bieb.) C. A. Mey.; *Ka*, *Karelinia caspica*; *Ly*, *Lycium ruthenicum* Murr.; *Ph*, *Phragmites communis*; *Po*, *Populus euphratica*; *Sc*, *Scorzonera divaricata*; *So*, *Sophora alopecroides*; *Ta*, *Tamarix* spp.

euphratica. A total of 36 plots were established to study plant species, quantity, height, density, coverage and other indices of plant communities in the areas of different groundwater depths. Characteristics of plant communities, such as composition, quantity, density and coverage, were investigated according to standard methods for subplots described by Dong (1996) and Song (2001).

2.4 Data analysis

In the presentation of the results, mean values and standard errors are given. Correlation coefficients for different plant communities were calculated using SPSS 13.0.1. For each research plot density (D), frequency (F), relative frequency (RFE), relative density (RDE), importance value (IV) and niche breadth of plant species were calculated using Excel.

Importance value (IV) was calculated using the equation:

$$IV_a=RDE+RDO+RFE, \qquad (1)$$

where *RDO* is relative dominance (Dong, 1996).

Niche breadth was calculated using the equation:

$$H_i' = -\sum_{j=1}^{R} P_{ij} \log P_{ij}, \qquad (2)$$

where H_i' is niche breadth of species. P_{ij} is the proportion of resource *i* used; and *R* is the total number of resource states (Levins, 1968; Smith, 1982).

The correlation coefficients of plant communities were calculated according to the Jaccard coefficient of community:

$$S_b=a/(a+b+c), \qquad (3)$$

where *a* is the species in both communities A and B; *b* is the species in community B that do not occur in community A; and *c* is the species in community A that do not occur in Community B. Clustering was analyzed according to correlation coefficients (Jie *et al*., 2009; Yang *et al*., 2009) to assess the similarities and differences within and between communities in terms of composition, type and structure over different groundwater depths. We used multi-level coverage to assess the soil coverage of communities (Song, 2001). The other parameters were calculated according to methods described by Dong (1996) and Song (2001).

3 Results

3.1 Characteristics of plant communities associated with different groundwater depths

In the transition zone of Cele oasis, plant distribution and community characteristics were very different in areas of different groundwater depths (Table 1 and Table 2). According to the results of plant community investigations, such as density, coverage and frequency, *Alhagi sparsifolia* possessed absolute dominance in the community with a groundwater depth of 15.7 m, and exhibited a uniform distribution (Table 2). At the groundwater depth of 11.7 m, the importance values of *Tamarix* spp. and *Karelinia caspica* increased in their communities. The density of *Tamarix* was greater than that of *Alhagi sparsifolia*, however, the important value, coverage and frequency indicated that *Alhagi sparsifolia* was still a dominant species (Table 2 and Fig. 1). A community composed entirely of a single *Tamarix* species occurred in an area where the groundwater depth was 8.8 m, however, the frequency, relative abundance and coverage values of *Tamarix* in this community were very low and there were large areas of open ground in the community.

At 6.3 m groundwater depth, *Tamarix* was still the dominant species in the community. Here, the coverage and biodiversity of the community increased significantly. In addition, the quantitative index of the community indicated that *Tamarix* occupied the absolute first position in the community although the distribution of *Tamarix* was not uniform. At the sites of 6.0 m and 4.7 m groundwater depths, *Populus euphratica* was the dominant species in the community; *Populus euphratica* was the only perennial species found at the site of 6.0 m groundwater depth. In the community of 4.7 m groundwater depth, the coverage increased and the composition expanded. Here the density of *Tamarix* was even more than that of *Populus*, however, *Populus euphratica* was still the absolute dominant species in the community (Table 2 and Fig. 1). At 3.3 m groundwater depth, although *Tamarix* was still an important species in the community, especially in the structure of the community, its density decreased significantly. At the same time, the importance value and density of *Phragmites communis* significantly increased and gradually replaced *Tamarix* as the dominant species.

When groundwater depth decreased to 2.1 m, *Phragmites communis* became a major component in the plant community. Although *Tamarix* and *Alhagi sparsifolia* were still present, they were no longer important species. In addition, as an indicator plant of salinity and alkalinity, *Lycium ruthenicum* occurred in the community, indicating a tendency towards salinization in the habitat of this community. In the area with very shallow groundwater depth (< 1.0 m), the dominant herb species, *Sophora alopecroides* was responsible for 75%–80% of community composition and community soil cover. The site of 1.2 m groundwater depth is on a floodplain where the community was composed of germinated seedlings. Seedlings of *Tamarix* dominated this community with far more seedlings than those of all the other species combined. *Phragmites communis* was the second dominant species in this community (Table 2 and Fig. 1).

Table 2 Characteristics of plant communities associated with different groundwater depths

Groundwater depth (m)	Community type	Amount of species	Dominant species	Density (m^2)	Frequency (%)	Relative abundance (%)	Multi-level coverage
15.7	*Al*	4	*Al*	1.32±0.28	98.2±5.1	84.5±10.5	2
11.7	*Al*	4	*Al*	0.59±0.29	57.8±18.6	48.8±29.7	2
8.8	*Ta*	1	*Ta*	0.80±0.74	18.3±15.8	66.7±49.2	1
6.3	*Ta*	5	*Ta*	12.10±8.10	66.7±26.5	87.2±19.2	2–3
6.0	*Po*	1	*Po*	0.41±0.38	53.3±24.2	100.0±49.2	3
4.7	*Po*	3	*Po*	0.35±0.11	50.0±10.9	65.3±39.3	3–4
3.3	*Ta*	5	*Ta*	4.51±5.17	97.5±7.1	62.1±12.6	2
2.1	*Ph*	5	*Ph*	11.20±9.24	100.0±0.0	78.9±15.1	1
1.2	*Ta*	12	*Ta*	26.30±8.30	96.0±8.9	60.6±9.2	1
0.9	*So*	3	*So*	46.20±3.33	100.0±0.0	63.9±4.3	4

Note: Density is the densities of dominant species. *Al*, *Alhagi sparsifolia*; *Ph*, *Phragmites communis*; *Po*, *Populus euphratica*; *So*, *Sophora alopecroides*; *Ta*, *Tamarix* spp.

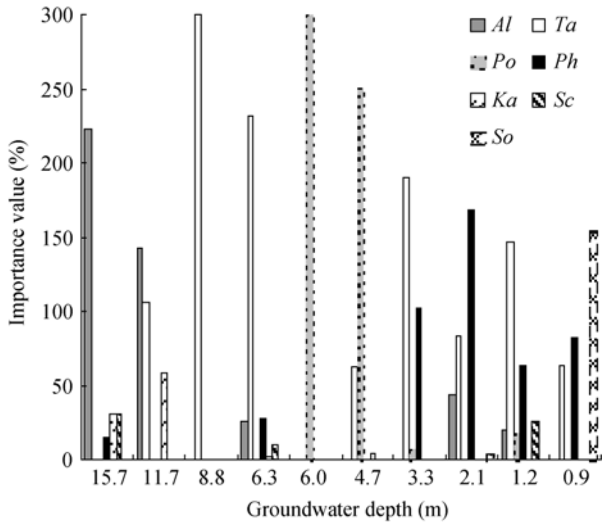

Fig.1 Importance values of plant species in communities related to different groundwater depths

Al, *Alhagi sparsifolia*; *Ka*, *Karelinia caspica*; *Ph*, *Phragmites communis*; *Po*, *Populus euphratica*; *Sc*, *Scorzonera divaricata*; *So*, *Sophora alopecroides*; *Ta*, *Tamarix* spp.

3.2 Relationship of communities associated with different groundwater depths

Cluster trees and correlation coefficients were used to compare similarities, differences and correlations of plant distribution and composition between communities associated with different groundwater depths (Fig. 2 and Table 3). As the groundwater depth varied, the plant communities above the ground surface changed greatly. The results showed that the plant communities at the study sites with 10 different groundwater depths exhibited comparatively large differences in terms of species composition and community structure. The variation of groundwater depth changed water conditions in the habitat that impacted on plant distribution and community characteristics significantly. However, characteristics of some communities under different groundwater depths were very similar. Correlation coefficients exhibited by communities associated with 6.3 m, 15.7 m and 11.7 m groundwater depths showed a strong relationship; communities associated with 2.1 m and 0.9 m groundwater depths did also.

Cluster analysis showed that communities associated with 8.8 m and 6.0 m groundwater depths were of very similar type, which proved that with the changes in groundwater depth, communities indicated obvious discontinuity in their spatial distribution, but at the same time also indicated characteristics of continuity, transitivity and similarity. Besides variation in groundwater depths, the complex and diverse topographical features impacted on correlations between community characteristics at different groundwater depths. The high or low differentiation of communities correlated with topographical features of the habitat in different environments, as seen in the communities associated with 8.8 m and 6.0 m groundwater depths.

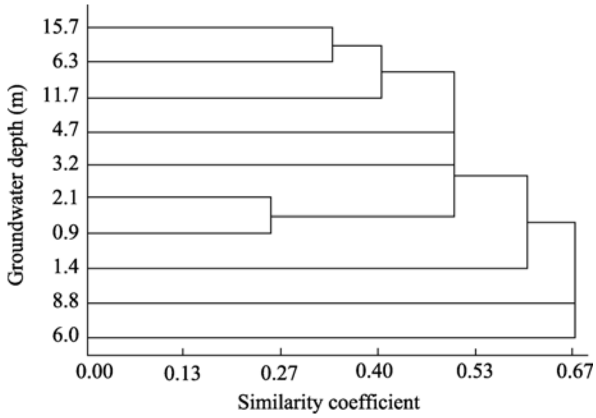

Fig. 2 Cluster tree of communities associated with different groundwater depths

3.3 Niche of dominant plant species associated with different groundwater depths

Niche is an important index to reveal relationships, diversity of species and formation, and structure of communities (Leibold, 1995; Lv *et al*., 2007; Wang *et al*., 2009), and is a good index to assess species adaptation to environmental conditions associated with different groundwater depths in the transition zone of oases. In the transition zone of Cele oasis, the results showed that no two species had identical niche breadths in a community associated with the same groundwater depth. That means plant populations showed discrepancies in their utilization of environmental resources (Table 4). But for communities in the same habitat, the same type of plant species possessed similar niche breadths. For example, *Alhagi sparsifolia*, *Karelinia caspica* and *Scorzonera divaricata* are all perennial herbs of similar type with deep roots. In the environment with 15.7 m groundwater depth, they had very similar niche breadths, whereas their niche breadths were very different to that of *Phragmites communis*, another type of species. This would indicate that the same type of species possessed a relatively similar adaptive strategy to utilize the environmental resources.

Table 3 Correlation coefficients of communities associated with different groundwater depths

	15.7	11.7	8.8	6.3	6.0	4.7	3.2	2.1	1.4	0.9
15.7	1.000									
11.7	0.3333	1.0000								
8.8	1.67E-09	0.3333	1.0000							
6.3	0.6667	0.6000	0.2000	1.0000						
6.0	1.67E-09	2.5E-09	5E-09	1.67E-09	1.0000					
4.7	0.1429	0.5000	0.3333	0.3333	0.3333	1.0000				
3.3	0.1429	0.2000	0.3333	0.3333	0.3333	0.5000	1.0000			
2.1	0.5000	0.4000	0.2500	0.5000	2E-09	0.1667	0.4000	1.0000		
1.2	0.2727	0.2000	0.1111	0.4000	0.1111	0.2000	0.3333	0.3000	1.0000	
0.9	0.3333	0.2000	0.3333	0.3333	2.5E-09	0.2000	0.5000	0.7500	0.2000	1.0000

Table 4 Niche breadths of dominant plant species associated with different groundwater depths

Species	Groundwater depth (m)									
	15.7	11.7	8.8	6.3	6.0	4.7	3.3	2.1	1.2	0.9
	Niche breadth									
Alhagi sparsifolia	0.152	0.158		0.071				0.098	0.059	
Tamarix spp		0.094	0.151	0.139		0.067	0.092	0.081	0.112	0.068
Populus euphratica					0.147	0.157	0.023		0.045	
Phragmites communis	0.049			0.074			0.145	0.161	0.119	0.134
Karelinia caspica	0.159	0.125		0.044						
Scorzonera divaricata	0.156			0.128					0.161	
Sophora alopecroides								0.044		0.148

4 Discussion and conclusions

In the interrelationship between vegetation and environment, environment influences the composition, structure, function, formation and distribution of plant communities (Song, 2001). In the transition zone between Cele oasis and the open desert, with the change of groundwater depths, the indigenous species exhibited a certain distribution characteristics. In the area with the deepest groundwater depth of more than 15.0 m, there was a plant community dominated by *Alhagi sparsifolia*. As the groundwater depth became shallower, *Tamarix* gradually became the dominant species and developed predominant communities. While the groundwater depths rose further, in the area with middle groundwater depth of less than 6.0 m, *Populus euphratica* dominated communities. In sites where the groundwater depth was less than 3.0 m, *Phragmites communis* and *Sophora alopecroides* dominated their respective communities. Community characteristics changed as groundwater became shallower in the following order: perennial herb communities, shrub communities, arbor communities, shrub-herb communities and herb communities. Characteristics of vegetation types varying with the groundwater depth are similar to the forest vegetation types which change with variation in altitude and precipitation in mountains in temperate arid regions (Wang and Pen, 1997). In the transition zone of Cele oasis, variation in groundwater depth (shallower to deeper) impacted the succession of plant communities, which occurred in the order: herb communities, tree communities, and shrub communities. This succession order was similar to that observed in the arid regions of the Ejina Plain and Tarim River (Zhang *et al*., 2000; Liu *et al*., 2004). In extremely arid regions the structure and species composition of plant communities tends to be simple. In the area with the deepest groundwater depth, the plant communities were composed of phreatophytes rather than xerophils such as *Haloxylon ammondendron* or *Reaumuria soongorica* (Li *et al*., 2004). This was a marked difference between the Cele oasis and other arid regions, such as the Ejina Plain (Zhang *et al*., 2000). Moreover, in the foreland area of Cele oasis, the succession climax community with the decrease of groundwater was perennial herb communities, but not shrubs or micro-shrub communities.

The results of correlation coefficients and cluster analysis showed that plant communities in the foreland of oases exhibited high discrepancy and discontinuity in spatial distribution. This result was very different from communities in riparian forests where plant communities had high correlation coefficients (Ji *et al*., 2009). In the foreland of Cele oasis, in areas of different groundwater depths, the change of plant communities' distribution indicated that plant distribution and community characteristics were affected by the variations of groundwater depths. However, the change of some communities associated with different groundwater depths presented similarities. The variations of plant community in spatial patterns could be substituted or reflected as succession of the community in a time series. The correlations between communities in spatial patterns could be considered the succession steps of plant communities corresponding to environmental conditions (Zhao *et al*., 2004). Thus, our results provide a useful reference to study the relationships between distribution and succession of vegetation and variation in groundwater depths in the foreland of oases. Except for the groundwater depth, community differentiation and composition are also influenced by topographical features. For example, the biodiversity in *Tamarix* and *Populus euphratica* communities where the groundwater depths were 11.7 m and 6.3 m, respectively significant decreased compared with the similar communities associate with the groundwater depths of 8.8 m and 6.0 m. The reason for the phenomenon is thought to be aeolian erosion, fluidity of the ground surface in the habitat and the proximity of sand dunes. In addition, salinization of habitat caused by shallow groundwater impacted the composition of plant communities.

Plant niche or niche breadth reflects resource utilization and adaptation of plants to their environment (Yang and Ma, 1992; Li *et al*., 2003). *Alhagi sparsifolia*, *Tamarix*, *Scorzonera divaricata* and *Phragmites communis* were distributed in the areas with varying groundwater depths from high to low, and were dominant species in their respective communities, but their niche breadths were very small. The niche of a species may be defined abstractly as a fitness measure in a multidimensional environmental space (Levins, 1968). More concretely, niches may be characterized as measures of resource utilization (Leibold, 1995). Our results from the foreland of Cele oasis showed that dominant species had low niche breadth. Perhaps water deficit in the environment restricted the species to utilize environmental resources. Based on niche breadth in areas of different groundwater depths, *Tamarix* exhibited the greatest resource utilization in the foreland of Cele oasis. This is consistent with the result that *Tamarix* had the largest distribution and coverage in the foreland of Cele oasis (Bruelheide *et al*., 2003).

Acknowledgements

This research was funded by the National Basic Research Program of China (2009CB421303), the Key Project in Science & Technology Program of Xinjiang Uygur Autonomous Region (200933125) and the Science and Technology Ministry Program (2009BAC54B03).

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