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Indicating appropriate groundwater tables for desert river-bank forest at the Tarim River, Xinjiang, China

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Abstract Based on data collected over 2 years of monitoring the lower reaches of the Tarim River, the groundwater table depth was divided into six classes; 0 to 2 m, 2 to 4 m, 4 to 6 m, 6 to 8 m, 8 to 10 m, >10 m. We investigated the vegetation in this area to measure the influence of groundwater table depth on plant diversity and species ecological niche. The results indicated that plant diversity was highest at the 2 to 4 m groundwater table depth, followed by that at 4 to 6 m, and then that at 0 to 2 m. When the groundwater depth dropped to below 6 m, species diversity decreased dramatically, and the slope of Hill's index tended to level off. The ecological niche of the major species in this area initially expanded as the groundwater level dropped. The widest niche appeared at the 4 to 6 m groundwater table depth and gradually narrowed with deepening groundwater. Ecological niche analysis also revealed that the 4 to 6 m groundwater table depth was associated with the lowest degree of niche overlap and the richest variety of species. Our findings indicate that in the lower reaches of the Tarim River, the groundwater table depth must be a minimum of 6 m for vegetation restoration; it should be maintained at 2 to 4 m in the vicinity of the water path, and at 4 to 6 m for the rest of this arid area.

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Introduction

In arid regions, inland river flow influences the local ecosystem stability and thereby controls the associated ecological changes (Hughes et al. 1990; Shafroth et al. 2002). In this ecosystem, natural vegetation is the major producer of organic matter. Because natural vegetation is the major biological component, its status largely determines the desertification process and environmental conditions (Lammerts et al. 2001; Wang et al. 2002). However, plant survival, growth, and development rely on surface water and groundwater (Horton and Clark 2001; Hipondoka et al. 2003; Gries et al. 2003; Lamontagne et al. 2005). Consequently, changes in the groundwater table became one of the key ecological factors by directly affecting plant survival and the resultant changes in the plant community (Mahoney and Rood 1992;

Robbins and Bell 2000; Munoz-Reinoso 2001; Riis and Hawes 2002).

Particularly in arid areas, the relationship between the groundwater table and vegetation is complex; therefore, determination of the appropriate ecological water level must consider the dynamics and balance in the interaction of groundwater, soil, and vegetation (Gries et al. 2003; Chen et al. 2004). Relevant studies of the Tarim River have focused on the following two areas: (1) evaluation of quantitative vegetation traits (coverage, biomass production, diversity) in response to dynamic changes in the groundwater table after ecological water recharge (Chen et al. 2006) and (2) the adaptive process and physiological mechanism associated with water availability (Zhuang and Chen 2006).

Ecological theory suggests that species numbers should be highest at intermediate levels of both disturbance and environmental stress, and environmental variability can promote coexistence (Lite et al. 2005; Reineking et al. 2006). Studies on species diversity have been focused mostly on changes in species quantity and degree of biodiversity, including pattern, formation, and regulations of small- and large-scale temporal and spatial changes in species richness, abundance, and distribution (Zhou et al. 2000). Information on species diversity is crucial for understanding the composition, changes, and development of plant communities, as well as for understanding the structural and functional stability of ecosystems. Many studies have found changes of species diversity with water availability (Brockway 1998; Riis and Hawes 2002; Lite et al. 2005). However, information on the relationship between groundwater and species diversity and ecological niches is still lacking, especially for arid regions.

This study evaluated species diversity and ecological niches of a desert river-bank community at different groundwater table levels, in combination with groundwater monitoring data. Through an integrated analysis of the relationship among ecological niches of plant community, plant diversity, and groundwater table depth, we attempt to determine the appropriate water table for the forest vegetation in the desert bank in the lower reaches of the Tarim River. Understanding the effect of ecological water recharge on groundwater status and restoration of vegetation will provide a scientific basis for restoration of the damaged ecosystem in this area. Also, we expect that this analysis will provide a case study for analyzing the relationship between vegetation and groundwater table in other arid inland river regions.

Study area

The Tarim River is located on the northern border of the Taklimakan Desert of Xinjiang, China. The lower reaches of the Tarim River are situated in the temperate continental zone. This area has a desert climate, with weather that is predominantly dry and windy; the ecological environment is vulnerable, with an annual precipitation of 17.4–42.0 mm. Several halophyte species can be seen in some areas along the river bank of the lower reaches of the Tarim River. Generally, the vegetation structure is simple, with only a few plant species (Song and Fan 2000).

In the past 50 years, intense local economical and social development has tremendously expanded the consumption of water resources in the Tarim River, which has had a large effect on the ecological conditions in the river basin (Liu et al. 2007). Since 1970, the stream flow at the lower reach of 321 km has ceased, and the trail lakes, Luobupo and Taitima, dried up in 1970 and 1972, respectively. Consequently, the groundwater table has dropped significantly, which has led to a serious decline of the natural vegetation in the affected area. Large patches of herbaceous plants, such as *Phragmites communis Trirn*, *Apocynum venetum* L., and *Alhagi sparsifolia* (B. Keller et Shap.) Shap, have died out. The *Populus euphratica Olivier* and *Tamarix* plant communities have also degenerated in a large expanse. As a result, wind erosion and desertification have become intense (Liu et al. 2007).

To preserve the endangered desert river bank forest vegetation and restore the damaged ecological system, an Ecological Water Conveyance Project, which spans from Bosten Lake through the Kunque River to recharge water into the lower reaches of the Tarim River, was initiated in 2000 (Fig. 1). Carrying out this project has raised the groundwater table noticeably; however, its effect decreases as it gets farther away from the feeding water resources. Horizontally, the area with improved groundwater expands after several long processes of water recharging. Data collected from a case study along the Yengisu transect indicated that the width of groundwater spans around 1000 m

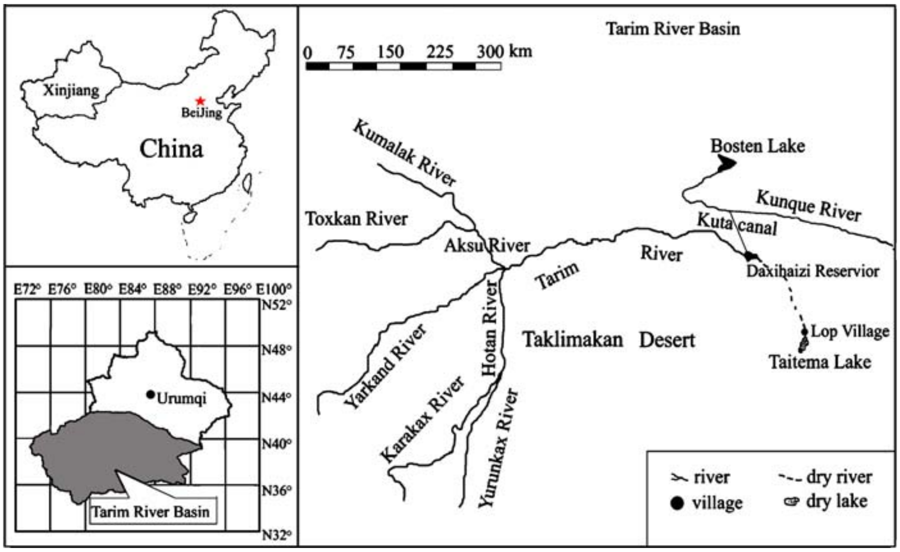


Fig. 1 The Tarim River Basin, Xinjiang, China

(Hou et al. 2007). The elevated groundwater table from water recharging has prevented further degeneration of the vegetation and partially restored the ecological system (Chen et al. 2006; Xu et al. 2007).

Data and methods

Data collection

A 50-m-wide transect for monitoring groundwater table depth was established at intervals of approximately 30 km along the channel between the Daxihaizi Reservoir and Taitema Lake. These transects are named Akdun, Yahopmarhan, Yengsu, Abudali, Kardayi, Tugmailai, Aragan, Yikanbujima, and Korgan, and they are designated A, B, C, D, E, F, G, H, and I, respectively, for this study. All transects are perpendicular to the main channel. Three to six groundwater wells (depth, 8–17 m) were installed along the center line of each transect at distances of 100 or 200 m. A total of 44 wells were installed (Fig. 2). We measured the groundwater depth in every well at a 5- or 10-day interval when water was being conveyed and a 15- or 30-day interval after each water transfer. Monitoring began in March 2005 and ended in December 2006.

Each year, we examined on a seasonal basis the natural vegetation occurring around each well. Along the nine groundwater monitoring transects, 44 plant sampling sites were chosen in Akdun (A, three sites), Yahopmarhan (B, four sites), Yengsu (C, six sites), Abudali (D, five sites), Kardayi (E, six sites), Tugmailai (F, five sites), Aragan (G, five sites), Yikanbujima (H, five sites), and Korgan (I, five sites). The size of each site was 50×50 m, and each site was further split into four tree and shrub sampling spots of 250×25 m. We recorded the number of each species (tree and shrub), coverage, and plant height. Alternatively, each shrub sampling spot (25×25 m) was divided into four herbaceous sampling plots of 5×5 m to collect data on the number of plants, coverage, height, and frequency. All sampling sites, spots, and plots were localized with GPS, and we recorded depth of groundwater table. We performed these investigations during 2005–2006.

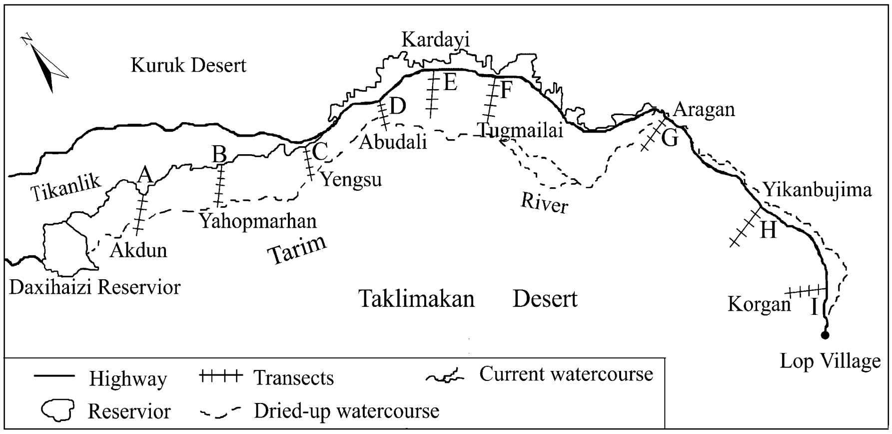
According to the collected data, 19 species of higher plants inhabited the study area, of which two were trees, six were shrubs, and 11 were herbs (Table 1). We have divided the groundwater table depth into six classes of 0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, and >10 m on the basis of the annual average value from the 44 monitoring wells. We analyzed the plant diversity and niche at each groundwater depth class to establish the relationship between vegetation and groundwater table depth.

Methods

Measurement of species diversity

To evaluate changes in species diversity, we calculated the following indices: the Margalef index (Margalef 1958), which reflects richness of species; the Alatalo index (Alatalo 1981), which represents evenness of species; the Shannon–Wiener index (Shannon and

Fig. 2 The study area in the lower reaches of the Tarim River



Weiner 1949), which represents diversity; and the modified Simpson index, which reflects comprehensive species richness and evenness (Romme 1982). The Hill diversity index (Hill 1973) can also be used to help explain the ecological significance of the scale of vegetation diversity. The indices are calculated using the following equations:

$$\text{Marganel richness index}: D = (\mathrm{S}-1)/\ln N \qquad (1)$$

Alatalo eveness index :

$$E = \left(1\Big/\sum_{\mathrm{i}=1}^{\mathrm{S}}\left(\frac{Ni}{N}\right)^2 - 1\right)\Big/\left(\exp\left(-\sum_{i=1}^{S}\frac{Ni}{N}\ln\frac{Ni}{N}\right) - 1\right) \qquad (2)$$

$$\text{Shannon} - \text{Wiener index}: H = -\sum_{i=1}^{S}(Pi\ln Pi) \qquad (3)$$

$$\text{Modified Simpson index}: D = -\ln\left[\sum_{i=1}^{S}\left(\frac{Ni}{N}\right)^2\right] \qquad (4)$$

$$\text{Hill diversity index}: N_\alpha = \left(\sum_{i=1}^{S} Pi^\alpha\right)^{1/1-\alpha} \qquad (5)$$

where Pi is the richness ratio for species i;Ni is the individual number of species i; N is the total number of individuals in each sampling plot; and S is the number of species in the sampling plot. In Eq. 5, when α=1, $N\alpha = e^H$, H is the Shannon–Wiener information index; when α=0, $N\alpha = \mathrm{S}$; when α=2, $N\alpha = 1/\mathrm{D}$, and D is the Simpson diversity index.

Table 1 List of 19 species in the lower reaches of Tarim River

Code number	Species	Code number	Species
1	*Tamarix ramosissima* Ledeb	11	*Salsola* sp.
2	*Glycyrrhiza inflata* Batalin	12	*Nitraria sibirica* Pall
3	*T. hispida* Willd	13	*Salsola ruthenica* Iljin
4	*Lycium ruthenicum* Murray	14	*Calamagrostis pseudophragmites* (Linn.) Roth
5	*Populus euphratica* Olivier	15	*Hexinia polydichotoma* (Ostent.) H. L.Yang
6	*Karelinia caspia* (Pall.) Less	16	*Inula salsoloides* (Turcz.) Ostenf
7	*Halimodendron halodendron* (Pall.) Voss	17	*Cynanchum sibiricum* Willd
8	*Phragmites communis* Trin.	18	*Elaeaanus angustifolia L.*
9	*Apocynum venetum* L.	19	*Aeluropus pungens* M. Bieb.) C. Koch
10	*Alhagi sparsifolia* (B. Keller et Shap.) Shap		

Determination of the niche

Ecological niche evaluation consists of breadth and overlap of the niches. These two parameters measure the distribution of a species community versus the states of a series of resources, such as water and nutrient gradient. Ecological breadth measures the requirements of the natural resources for each species; it also reflects the adaptability of the species into the microenvironment. In general, wider breadth of ecological niche represents better adaptability. To facilitate the evaluation of the usage efficiency for the limited water resources by the vegetation along the river bank after the water recharging project, we first classified the groundwater table depth into six classes: 0–2 m, 2–4 m, 4–6 m, 6–8 m, 8–10 m, and >10 m, and we calculated the ecological niche breadth for the selected species. The niche breadth was estimated with the Levins index (Levins 1968) and was calculated using the following equation:

$$\mathrm{B}i = 1 \bigg/ \sum_{j=1}^{r} \left(P_{ij}\right)^2 \tag{6}$$

where Bi is the ecological niche breadth for species i, $P_{ij} = n_{ij}/N_i$; it represents the ratio of species i in using the j grade resources compared with the total resource. In $N_i = \sum n_{ij}$, n_{ij} is the quantitative trait value for species i in j grade resources (such as coverage, important value, density). In this report, it is the important value for species i in j sampling plot. r is the resources grade level; in this report, it is the plot number.

We used the Schoener overlap index (Schoener 1974) to estimate the ecological niche overlap among species. This index was calculated as a percentage by using the equation

$$O_{ik} = 1 - \frac{1}{2} \sum_{j=1}^{r} \left|P_{ij} - P_{kj}\right| \tag{7}$$

When species i and k have the same distribution under all kinds of resource states, the value of Oik is the largest, and equals 1, which indicates that these two species are ecologically completely overlapped. In the opposite, when two species not sharing resources, their ecological niches have no overlap and Oik=0.

Results

Relationship between species diversity and groundwater status

We used the average of species diversity indices from all plots to represent vegetation diversity at each groundwater table depth class. The data analysis revealed that all the values increased gradually, reached the maximum value at the 2–4 m groundwater table depth, and then began to decrease as the groundwater level dropped (Fig. 3). Simpson, Shannon–Wiener, and Alatalo index values were higher for groundwater table depth of 4–6 m than of 0–2 m. The Shannon–Wiener index had the most significant fluctuation in a range of 0.21–1.47 in response to decline of the groundwater level. The Alatalo index changed between 0.49 and 0.78 as the most stable parameter. This trend of the different indices reflects that plant species diversity, richness, and evenness have all undergone trends of decline in response to the drop of groundwater table in the lower reaches of the Tarim River.

Hill diversity index analysis revealed that the species diversity showed a decreasing order corresponding to the groundwater depths of 2–4 m, 4–6 m, 0–2 m, 6–8 m, 8–10 m, and >10 m (Fig. 4). Changes in the Hill diversity index were positively correlated with all other indices tested.

Hill diversity index analysis also indicated that the change trends of diversity can be separated into three phases. The first phase is at the groundwater table depth of 0–6 m. Within this range, all slopes of the Hill index appeared similarly for the three classes of groundwater table depth (0–2 m, 2–4 m, and 4–6 m).

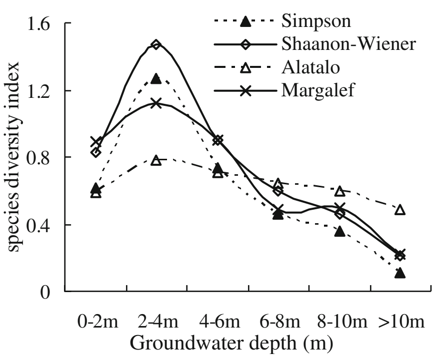


Fig. 3 The changes of different species diversity indices along the groundwater classes

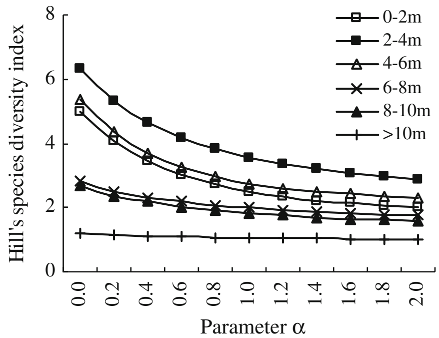


Fig. 4 The change trend of Hill diversity index along groundwater classes

The Hill index changed significantly with the modifying factor α, which causes a sensitive response from the slopes. The second phase is represented by groundwater table depth between 6 and 10 m. The diversity slope basically leveled off and became insensitive because the diversity index could not respond to the modifying factor α. The third phase includes the groundwater table depth below 10 m. At this stage, the vegetation degenerated, consisting solely of the *Tamarix* L. population. Because of serious water shortage, *T. ramosissima* was the dominating species and spread together with *T. hispida*. The diversity slope became almost linear. The correlation between groundwater depth and plant diversity clearly indicates that species diversity will significantly degenerate when the groundwater depth drops below 6 m in the lower reaches of the Tarim River. As the groundwater level becomes deeper than what is a suitable water table level for herbaceous plants, these species will die out, which will lead to sharp decrease in the species composition of the vegetation.

Effect of groundwater table depth on species ecological niche

Results of the analysis revealed that herbaceous plants appeared mostly in the sampling plots with a 0–6 m groundwater table depth and that the trees were distributed in a much wider range (Table 2). Generally, the species ecological niche expanded at lower groundwater levels. The widest ecological niche was realized at groundwater depth between 4 and 6 m and then narrowed as the water table got deeper. Among the 19 plant species identified in the lower reaches of the Tarim River, the total ecological niche breadths were the highest at 27.67, 19.21, and 18.83 for *T. ramosissima*, *P. euphratica*, and *T. hispida*, respectively.

This study compared 11 major species for their niche overlap. The highest values of niche overlap

Table 2 Coefficients of niche breadth along different groundwater table depth in the lower reaches of the Tarim River

Species	ID number	Ecological niche width					
		0–2	2–4 m	4–6 m	6–8 m	8–10 m	>10 m
T. ramosissima	1	1.00	5.96	22.50	11.66	8.22	4.35
G. inflata	2	1.82	10.95	6.74		2.00	
T. hispida	3		3.46	17.54	5.73	1.00	1.00
L. ruthenicum	4	1.00		10.56	4.44	1.99	
P. euphratica	5	1.00	9.74	14.58	6.79	3.77	
K. caspica	6		3.42	3.37		2.00	
H. halodendron	7		2.99	9.71	2.00		
P. communis	8	1.23	3.91	7.60			
A. venetum	9	1.00	5.28	7.59	2.00	1.00	
A. sparsifolia	10	0.63	1.88	2.41		1.37	
S. *sp.*	11		1.87	1.95	1.99		
N. sibirica	12		1.00	1.93			
S. ruthenica	13		1.90				
C. pseudophragmites	14		1.00				
H. polydichotoma	15		3.46	1.00		2.70	
I. salsoloides	16		1.99				
C. sibiricum	17		1.00	1.00			
E. angustifo	18		2.46				
A. pungens	19		2.90				

index were reached at water tables between 0 and 2 m (Table 3). The overlap index became smaller at groundwater table depth between 4–6 m and 6–8 m, which indicated that each species has sufficient resources and that different species have established a coordinated and balanced relationship by mutual adaption. The vegetation structure maintains a relatively stable state. At this stage, many species have an ecological niche overlap index at 0, indicative of no sharing of natural resources. However, when the groundwater table depth dropped to 8–10 m, competition among species became intense again, an effect

Table 3 The coefficient of niche overlap along different groundwater table depth in the lower reach of Tarim River

ID Number	0–2 m						2–4 m								
	2	4	5	8	9	10	2	3	5	6	7	8	9	10	11
1	0.34	0.61	0.82	0.11	0.00	0.67	0.46	0.63	0.57	0.19	0.08	0.06	0.30	0.30	0.12
2		0.73	0.52	0.77	0.66	0.67		0.31	0.70	0.16	0.33	0.35	0.19	0.35	0.05
3									0.31	0.00	0.00	0.03	0.14	0.22	0.00
4			0.80	0.49	0.39	0.94									
5				0.29	0.18	0.85				0.32	0.37	0.12	0.32	0.26	0.16
6											0.00	0.20	0.50	0.39	0.47
7												0.00	0.00	0.00	0.00
8					0.89	0.44							0.36	0.46	0.02
9						0.33								0.61	0.24
10															0.23

ID Number	4–6 m					4–6 m					
	2	3	4	5	6	6	7	8	9	10	11
1	0.14	0.45	0.28	0.34	0.19	0.19	0.30	0.19	0.19	0.30	0.06
2		0.27	0.13	0.12	0.00	0.00	0.12	0.44	0.35	0.49	0.00
3			0.35	0.19	0.14	0.14	0.28	0.15	0.38	0.32	0.00
4				0.05	0.00	0.00	0.68	0.24	0.25	0.29	0.00
5					0.10	0.10	0.06	0.14	0.07	0.15	0.09
6							0.08	0.25	0.23	0.12	0.00
7								0.14	0.33	0.27	0.00
8									0.00	0.44	0.00
9										0.22	0.00
10											0.04

ID Number	6–8 m						8–10 m							>10 m
	3	4	5	7	9	11	2	3	4	5	6	9	10	3
1	0.31	0.42	0.30	0.04	0.17	0.10	0.20	0.07	0.33	0.39	0.20	0.13	0.44	0.05
2		0.37	0.21	0.34	0.00	0.37		0.10	0.81	0.33	0.20	0.98	0.10	
3			0.12	0.12	0.10	0.06			0.06	0.33	0.10	0.00	0.10	
4										0.15	0.20	0.10	0.10	
5				0.21	0.00	0.00					0.20	0.10	0.20	
6												0.10	0.54	
7					0.00	0.00								
8														
9						0.00							0.10	
10														

The species is numbered the same as in Tables 1 and Table 2; Those discontinuous (without number) under groundwater table (horizontally) indicate the corresponding species disappear that manifests mainly in some herbaceous plants and shrubs. The ecological niche overlap index between *G. inflata* and *A. venetum* reached 0.981.

Corresponding to groundwater table depth of 0–2 m, 2–4 m, 4–6 m, 6–8 m, and 8–10 m, the percentages of species with ecological niche overlap index higher than 0.5 were 57.1%, 11.1%, 1.8%, 0%, and 10.7%, respectively. The respective percentages were 81%, 40%, 21.8%, 28.6%, and 28.6% for those with an ecological niche overlap index of 0.3. However, when the groundwater depth dropped below 10 m, the vegetation degenerated into single species *Tamarix* L., and the ecological niche overlap index for *T. ramosissima* and *T. hispida* was 0.046. We can definitively conclude that, as the groundwater table drops, the degree of species ecological niche overlap will be significantly reduced initially and then slightly increased. That is, the separation scale of ecological niches among different species basically decreases first and then increases slightly as the groundwater table depth becomes lower.

Discussion

The decline in species diversity in the lower reaches of the Tarim River is caused mainly by the disappearance of herbaceous plants and serious degeneration of semishrubs and shrubs (Liu et al. 2005). In this study, the maximum value of diversity index appeared at a groundwater table depth of 2–4 m, followed by 4–6 m. Vegetation had the lowest species diversity index when the groundwater table depth was lower than 6 m. These results suggest that to increase the species diversity, the groundwater table depth needs to maintain at a threshold level, probably higher than 6 m for this area. All these indices, including the Margale index, Alatalo index, Shannon–Wiener index, and modified Simpson index, have fixed values. When values and samples are collected from defined areas, one index can be calculated for each sampling plot. However, the ecological relationship is relatively more complex in the natural habitat; none of these fixed-value parameters can represent characteristics of species diversity (Patil and Tailie 1982). Therefore, we used the Hill index as a measure of diversity ordering to determine species diversity at different spatial dimensions and under the influence of environmental changes. Hill diversity index analysis concluded that species diversity can be divided into three phases, using 6 and 10 m as the cutoff threshold endpoint values for the groundwater table depth. When the groundwater table depth was below 6 m, species diversity decreased significantly, as shown by the slope of the Hill index eventually leveling off. By then the groundwater had little effect on species diversity. Six meters could be used as the threshold for this area. Therefore, the groundwater table depth needs to be raised to above 6 m to maintain the growth of tree, shrub, and herbaceous vegetation in this region. The environmental water requirements of plants can be a complex function of several attributes of groundwater systems (including attributes related to the quantity and quality of groundwater). Each species may have a physiological limit to the depth and rate of groundwater extraction (Zencich et al. 2002) or a maximum salinity level above which groundwater cannot be used (Lamontagne et al. 2005). Relevant studies on degeneration process, stress plant physiology, and the water quality requirements of the vegetation in the same area (Chen et al. 2004; Zhuang and Chen 2006; Ruan et al. 2007; Chen et al. 2007) also indicate that a 6-m groundwater table depth is the cutoff criterion for plants to start experiencing stresses.

Ecological niche analysis showed that *T. ramosissima*, *P. euphratica*, and *T. hispida* had the highest ecological niche breadth at 4–6 m groundwater table level. This phenomenon suggests that these three dominant species are relatively better adapted to the environment; they intend to become generalization species, which have higher coverage, abundance, and frequency than other species under all water conditions. *K. caspia*, *G. inflata*, *A. venetum*, *H. halodendron*, *A. sparsifolia*, and *L. ruthenicum* were the main accompanying species. They occupied wider niche breadth in the same habitat as *Tamarix* L. and *P. euphratica*. *C. pseudophragmites*, *E. angustifolia*, *H. polydichotoma*, *C. sibiricum*, and *I. salsoloides*.

In the study area, the ecological niche overlap was phenomenal at high-groundwater table depth (0–4 m), especially between 0–2 m, which indicated that the trees, shrub, and grass, as well as different herbaceous species, compete furiously. This finding also indicated that the competitive repelling relationship was intense among herbaceous plants and among grass, trees, and shrubs. As the groundwater table depth got deeper (6–10 m), ecological overlap became less obvious. When the water table dropped to >10 m, only *Tamarix* L. could grow because of lack of water resources. With the water table at 4–6 m, ecological overlap among various species was moderate, competition among species was not so intense, and they were able to accommodate each other. On the basis of these findings that when the groundwater table depth is 4–6 m in the lower reaches of the Tarim River, plant species ecological niches separate obviously, different species occupy their own spaces of resources, and no obvious overlap exists. Furthermore, in addition to ecological separation in resource usage, coexistence of different species can be regulated by the life forms and their phenology (Lusk and Smith 1998). Therefore, even if most of the species appear in the 4–6 m groundwater class, these species can still adapt to and synchronize with each other because of the difference in life forms and their phenology of each species.

Species diversity reached the highest table at the 2–4 m groundwater table depth, whereas the ecological niche breadth was the largest at 4–6 m. As the groundwater gets deeper (4–6 m), some species cannot survive the water stress and begin to die. As fewer species are present in the vegetation, the diversity of the vegetation decreases. On the other hand, the surviving species should have strong ability to use limited water resources; and with less ecological niche overlap and interspecies competition, it is easily understandable that these species would have larger ecological niche breadth. This assertion should be postulated as an adaptive trait for the plant species to survive the harsh conditions in arid areas. The ecological significance is that a groundwater table depth of 2–4 m is probably the appropriate ecological water table level for the lower reaches of the Tarim River, and 6 m is the threshold for the local vegetation.

The relationship between ecological niche overlap and interspecies competition is still a controversial issue. Some studies (Colwell and Futuyma 1971; Silvertown and Law 1987; Mahdi et al. 1989) indicate that ecological niche overlap does not necessarily lead to interspecies competition, whereas the findings of other analyses (Pianka 1974; Abrams 1980; Chesson 1991) do not support this notion. A third hypothesis is postulated based on the results from this study, i.e., whether the ecological niche reflecting interspecies competition depends on the supply of resources. Clearly, the vegetation degeneration in the lower reaches of the Tarim River is caused by discontinuous water flow and dropping of the groundwater table. Currently, the groundwater table has been raised by the artificial water transportation system. However, water resources for the plants are still limited; therefore, the ecological niche overlap can indicate the interspecies competition under such circumstances.

In the 8–10 m class of groundwater table depth, herbaceous species, including *G. inflata* and *A. venetum* and others, can still grow. There is extraordinarily significant ecological niche overlap among these species, partly because of the ecological characteristics of these two species. *A. venetum* is a perennial root herbaceous plant. The root can grow up to 2–3 m in depth. *G. inflata* has a large root system; it can still grow when the groundwater drops below 6 m. Another plausible factor is the "hydro-lift" effect of the dry desert plant community. The hydro-lift effect means that the deep plant root absorbs water from deep soil (including groundwater) and transfers it to upper-level soil through the root system. Horton and Hart (1998) suggested that this effect can supply water to nearby plants and thus promote their growth. This process will eventually change the composition and distribution of the species in the vegetation. Consequently, the hydro-lift effect should also be considered when studying the effect of groundwater on vegetation in dry areas. When analyzing groundwater, one should also include the effect of soil moisture on the ecological processes of the vegetation.

Conclusion

Simpson, Shannon–Wiener, Margalef, Alatalo, and Hill diversity index analysis all indicate that species diversity reached the highest level when the groundwater table depth was at 2–4 m, followed by 4–6 m, and then 0–2 m. The Hill diversity index also indicates that, by using the 6- and 10-m groundwater table depth as the cutoff thresholds, one can distinguish the species diversity into three changing phases. Plant species diversity decreased sharply and then leveled off below the 6-m groundwater table depth. Therefore, the 6-m groundwater table depth can be considered the threshold for determining species diversity in the lower reaches of the Tarim River. The 2–4 m level is the most appropriate groundwater table depth for species diversity. Plant species ecological niche in the lower reaches of the Tarim River expanded gradually as the groundwater table level became lower, and the widest place appeared at the 4–6 m groundwater table depth and then started to narrow.

Ecological niche overlap was obvious under the high-groundwater table depth (0–4 m), suggesting that competition can be strong among the herbaceous species and among grass, shrubs, and trees. Ecological niche overlap was not pronounced at the deep water table (6–10 m). However, when the groundwater table depth was lower than 10 m, only the *Tamarix* trees survived. At groundwater table depths between 4 and 6 m, the ecological niche overlap among various species became the least obvious, indicating that interspecies competition also becomes less intense, and different species can accommodate each other.

After comparing the comprehensive ecological breadth and ecological niche overlap, we speculate that 4–6 m depth of groundwater plays an essential role for these two parameters. Its ecological significance is that this groundwater table depth is the threshold determining plant species' ecological niche in the lower reaches of the Tarim River. On the basis of the findings from our study, we recommend that the groundwater table depth be maintained at 6 m and above to ensure the restoration of the vegetation in this area.

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