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The distribution pattern of desert riparian forests and its relationship with soil moisture and soil properties in the low reaches of Heihe River Basin, China

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Abstract. Desert riparian forests are critical habitats that provide a variety of ecosystem services in arid environments. They are also endangered ecosystem types that are sensitive to disturbance and threatened by desertification. Despite of previous studies stressed on the interactions between desert riparian forests and water availability, the lack of comprehensive information on the forests distribution range and their relationship with soil properties constraints further conservation efforts of this community under a changing climate. In this study, vegetation community characteristics, soil moisture and soil properties were investigated within a 3000 m radius around the river channel in the low reaches of Heihe River Basin, northwest China to determine the distribution pattern of desert riparian forests and their relationship with environmental factors. We found that desert riparian forests mainly distributed within the range of 2500 m from the river channel and the first 1000 m was regarded as the optimum range. Five types of vegetation communities were identified based on Two-way Indicator Species Analysis (TWINSPAN) and they gradually shifted from the riparian tree-shrub-herb communities to riparian-desert shrubs with increasing distance from the river channel. Vegetation community coverage and diversity indices formed bimodal patterns while community height and density declined significantly as the distance from the river increased. Soil moisture, soil physical properties, and soil nutrition explained 53.6% of the variance in community characteristics and different environment variables influenced different community characteristics. Soil moisture, accounting for 62.7% of the total explanation, mainly influenced the community coverage and density. Soil physical properties (e.g., bulk density, soil particle composition) exerted influence on shrub layer, while soil nutrition mainly affected community richness. With surface (0-30 cm) and deep (100-200 cm) soil moisture, bulk density and total phosphorus regarded as major determining factors in the community structure and diversity, conservation measures that protect the soil structure and prevent soil moisture deficiency (e.g., artificial soil cover and water conveyance channel) were suggested to better protect the desert riparian forests under climate change and intensive human disturbance.

1 Introduction

Riparian zone is the linkage between terrestrial and aquatic ecosystem (Naiman and Décamps, 1997), which plays an important part in ecological processes and provides a variety of ecosystem services. (Naiman et al., 1993; Décamps et al., 2004). Desert riparian forests, also known as 'Tugai forests', are considered as the main body of riparian zone in the hyperarid areas and are mainly located in the floodplains of the major Central Asian rivers (Gärtner et al., 2014). They provide critical habitats for various species and functions as the "ecological shelter" against desertification in the hyperarid area (Thevs, 2008). However, due to the low diversity level and weak resilience, desert riparian forests are sensitive to the disturbance and likely to be threatened by desertification under changing environment (Li et al., 2013; Ling et al., 2015).

Desert riparian forests are the main communities in the low reaches of Heihe River, the second largest inland river of China (Feng et al., 2015). During the past century, human population increase and overexploitation of the water resources in the middle reaches led to significant degradation of desert riparian forests in the low reaches (Wang et al., 2014). Since 2000, ecological water conveyance project has been implemented with the aim of restoring the ecosystems of Heihe River basin (Yu et al., 2013). While the vegetation has been recovered in the low reaches (Wang et al., 2014; Lü et al., 2015), nearly 20% of the oasis area covered by desert riparian forests still underwent major degradation process in spite of the rising groundwater level and better water condition in the low reaches. (Zhang et al., 2011a; Lu et al., 2015). To conserve and restore this fragile ecosystem more effectively, studies that address the variation of desert riparian forests and their relationship with the environmental factors need to be conducted.

Previous studies have indicated that in the hyperarid zone, groundwater was a crucial water source for vegetation growth (Zheng et al., 2005; Hao et al., 2010). Species diversity would peak where groundwater depth was around 2-4 m, as opposed to the deficiency in soil moisture and degradation of vegetation once groundwater went below 4-4.5m (Zheng et al., 2005; Li et al., 2013). While this could be true for some hyperarid zones (e.g., Tarim river) where groundwater dropped rapidly away from the river bank to about 6 m deep at the distance of 1000 m from river channel (Aishan et al., 2013), in the low reaches of Heihe River Basin, the perennial groundwater table remained above 4 m at the distance of 3800 m from river channel (Wang et al., 2011; Fu et al., 2014). Yet, the vegetation community at lower Heihe riparian zones still shifted from multiple layers of trees to shrubs and some sites were not completely restored (He and Zhao, 2006; Zhang et al., 2011a), indicating that there could be other factors affecting the distribution of desert riparian forests.

The distribution pattern of desert riparian forests is the result of combined effects of many environmental factors, particularly water availability (Goebel et al., 2012; Li et al., 2013). With river acting as the main supply of water in hyperarid zone, the distance from river channel would be regarded as a proxy to water availability which declined with the weakening of river influence (Hao et al., 2010; Chen et al., 2014). Soil moisture, influenced by precipitation and groundwater, is the direct water source for the desert riparian forests (Wang et al., 2012). The shallow soil moisture layer recharged by the river flooding, mainly affected the richness of herbaceous plant and the regeneration of trees, while the deep layer soil moisture recharged by the groundwater, mainly affected the abundance of shrubs and trees (Li et al., 2008). With different depth of soil moisture exerted different impacts on vegetation (D'Odorico et al., 2007), the decline of soil moisture would reduce the abundance of tree and herb species, resulting in the community shift to drought-tolerant vegetation types along the distance from river channel (Zhu et al., 2014).

Since soil moisture is greatly influenced by soil properties, the distance from the river channel is therefore a synthesis, not only of water availability but also soil properties (e.g., bulk density, soil particle size, and soil nutrition) (Zhang and Zhao, 2015). Rosenthal et al. (2005) suggested that water was more tightly bound to clay than to sand particles and soils with higher clay content had greater resistance to water movement than soils with higher sand content. Similarly, soil nutrition (e.g., soil organic matter and total nitrogen) is the basic substance that sustains vegetation growth of desert riparian forests (Yarwood et al., 2015), as opposed to salt content which mainly halts the restoration of vegetation (Kong et al., 2010; Chen et al., 2014). These interactions between water availability and soil properties mainly resulted in the heterogeneity environment and are likely to become important selective forces in shaping plant adaptation strategies and vegetation distribution pattern (Rosenthal et al., 2005). Although the variation of floristic composition and community structure (e.g. height, density, coverage) generally showed clear pattern along the distance from river channel (i.e., exponential decrease or unimodal variation) (Li, 2006; Hao et al., 2010; Li et al., 2013), interactions between communities and extreme environmental stress may cause non-unimodal responses in the hyperarid zone (Oksanen and Minchin, 2002). Previous study by Zhu et al. (2013) for example showed that

Patrick's richness index and Shannon–Wiener's index formed a bimodal pattern along groundwater depth in the low reaches of Heihe River Basin. Study on the impacts of soil moisture and soil properties on desert riparian forests can therefore contribute to the comprehensive understanding of vegetation community variation and act as scientific basis for more advanced ecological restoration under changing circumstances.

Currently, studies on desert riparian forests distribution pattern have indicated floristic composition and community structure form different patterns along the distance gradient. While vegetation community variation along the distance from river channel could help defining the distribution range of desert riparian forests, it has not been clarified in the previous studies due to the heterogeneity of landforms, communities, and environments variability in different geomorphic and hydrologic patterns (Lü et al., 2003; Décamps et al., 2004). Similarly, the influence of soil moisture and soil properties on the desert riparian forests community characteristics were rarely discussed in comparison to the effects of groundwater in hyperarid zone. In this research, we therefore investigated variability in desert riparian forests sites that differently located along the distance from river channel. Changes of floristic composition, community structure and diversity were used to depict community distribution pattern, while different depth of soil moisture, soil physical properties and soil nutrition were used to explain the vegetation community variance. The objectives of this study were to: (1) explore the variation pattern of floristic composition and community characteristics along the distance from river channel, (2) analyze the effect of soil moisture and soil prosperities on the community characteristics of desert riparian forests, and (3) suggest advanced restoration and protection measures for desert riparian forests under changing environment.

2 Data and methods

2.1 Study area

The study was conducted in the lower reaches of Heihe River (40°20′–42°30′N; 99°30′–102°00′E), in the Ejina Oasis, Inner Mongolia, Northwest China. The oasis covers an area of 3×10^4 km^2, with declining surface elevation from the southwest to the northeast in the range of 1127 to 820 meters above sea level (Qin et al., 2012). This region has a typical continental arid climate with mean annual temperature of 8.77 °C. Its maximum and minimum temperatures usually occur in July (41°C) and

January (−36 °C) (Wen et al., 2005). The mean annual precipitation is <39 mm, 84% of which occurs during the growing season (May to September), while the mean annual potential evaporation is >3,390 mm (Chen et al., 2014). Prevailing wind direction is northwest, mean annual wind velocity is 2.9-5 m·s^{-1}, and annual number of gale (>8 m·s^{-1}) days is 70 d or so (Chen et al., 2014).

The Heihe River originates from rainfall and snow melt in the Qilian Mountains. It branches into the Donghe River and the Xihe River at Langxinshan Mountain and ultimately flow into the East Juyan Lake and the West Juyan Lake in Ejina. Due to sparse precipitation and hyper arid environment, no perennial runoff is originated from in this area. Heihe River is therefore the only runoff flow through the area and the main source of recharge for the groundwater system in Ejina Oasis (He and Zhao, 2006). As the distance from river channel increasing, water availability declines and the vegetation shifts from desert riparian forests to desert scrub. The desert riparian forests are the main components of Ejina oasis. It mainly grows along the river banks and distributed in the fluvial plain, with the dominant vegetation including *Populus euphratica*, *Tamarix ramosissima*, *Lyceum ruthenicum*, *Sophara alopecuriodes*, *Karilinia caspica*, and *Peganum harmala*(Zhao et al., 2016). The sparse and drought tolerant desert species such as *Reaumuria soongorica*, *Zygophyllum xanthoxylon* and *Calligonum mongolicunl* are mainly distributed in low mountainous area and the Gobi desert. The main soil types in the area are grey desert soils and grey–brown desert soils. Saline-alkaline soils and swamp soils also exist in the lake basins and lowlands (Chen et al., 2014).

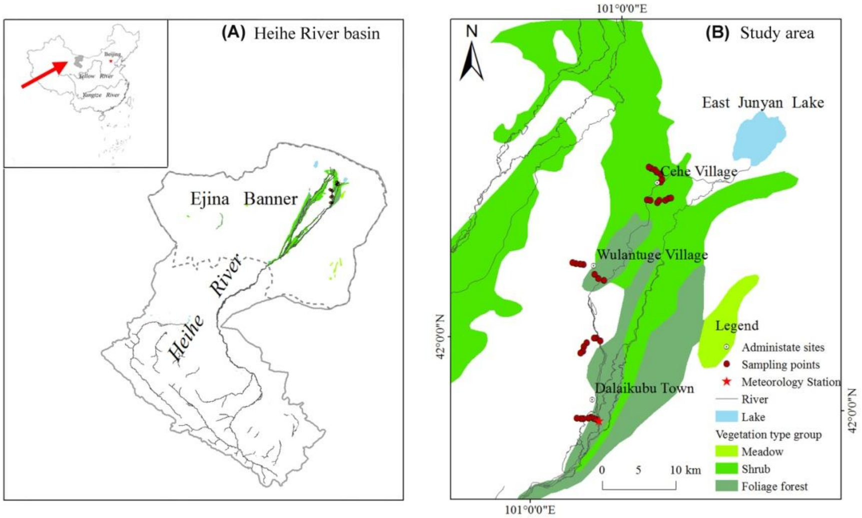


Figure 1. The low reaches of Heihe River basin in China (A) and the location of sampling points in

the study area (B).

2.2 Field sampling

Riparian zone is defined as the area that spread from both sides of the land-water ecotone, up to the point where the effects of river disappeared. Some studies, for examples, showed that the range of river influence was around 0-2000 m from the river channel in the low reaches of Heihe (Si et al., 2005;Guo et al., 2009). The spatial extent of the riparian zone, however, is difficult to be precisely delineated due to the heterogeneity of mosaics of landforms, communities, and environments varied in different geomorphic and hydrologic pattern (Décamps et al., 2004). We therefore conducted our research in the range of 0-3000 m distance from the river channel to fully cover the distribution pattern of desert riparian forests.

The field survey was conducted in July 2015, after the ecological water conveyance delivered to low reaches. To minimize the impact of human disturbance and other water resources, we chose sites that were far from farmlands, roads, irrigated channels and reservoirs. Sampling was conducted perpendicular to the river channel and the distance from river channel was stratified into six gradients: 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m. Five sites were selected randomly as replicates in each distance from river channel gradient under the premise of consistence in soil type and micro-topography. A total of 35 sites were sampled in the low reaches of Heihe River Basin.

Three tree quadrats (30 × 30 m) and shrub quadrats (10 × 10 m) were established in each site. The number of each species (tree and shrub), plant height, coverage and diameter at breast height (DBH) of the trees ($\geq$ 2 m) were recorded individually. Four (2 × 2 m) herb quadrats were established at each corner of the tree or shrub quadrat to collect data on the number of plants, vegetation cover and height.

At each site, soil samples and soil moisture samples were randomly collected in three replicates using auger (5 cm in diameter). Soil gravimetric water content (SWC) was collected at depths of 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180, 200 cm. At some sites where groundwater was less than 2 m (i.e., 21 sites), the SWC sampling was ended at the depth of groundwater table. To measure soil moisture content, samples were collected with aluminum boxes and weighed at the time of sampling as well as after oven drying at 105 °C for 48 hours. To measure bulk density (BD), the undisturbed soil cores at surface layer were collected using a stainless-steel cutting ring (100 cm^3 in volume) with three replicates each site and oven dried at 105 °C until they reached constant weight.

Disturbed 0-100 cm soil samples were collected at five depth increments (0-20, 20-40, 40-60, 60-80 and 80-100 cm) in each sites to determine soil composition and nutrients. Three samples at each layer were mixed evenly to form one composite sample and sealed in air-tight bags. After sorted for roots, air-dried and passed through a 2 mm sieve, surface soil samples (0-20cm) were subsequently analyzed in the laboratory for the silt (<0.02mm), clay (0.02-0.05 mm), sand (0.05-2 mm), and gravel (>2mm) contents by using Mastersizer 2000. Soil chemical properties including the concentrations of soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP) and total salt content (TS) at 0-20, 20-40, 40-60, 60-80 and 80-100 cm were also analyzed in the laboratory.

2.3 Statistical analysis

The IV (importance value) of each tree, shrub and herb in each plant site was calculated with the following formulas(Zhang and Dong, 2010):

$$\mathrm{IV}_{\mathrm{Tree}} = (RDen + RDom + RH)/3 \qquad (1)$$

$$\mathrm{IV}_{\mathrm{Shrub\ or\ Grass}} = (RDen + RDom + RC)/3 \qquad (2)$$

where *RDen* is the relative density, *RF* is the relative frequency, *RDom* is the relative dominance, *RH* is the relative coverage and *RC* is the relative coverage.

In our study, the total diversity index of community was deployed to depict the community diversity in each site. According to the characteristic of community vertical structure, the total diversity index of community is measured using the weight of indices in different growth types. The weight is the average of the relative coverage and the thickness of the leaf layer (Fan et al., 2006). We applied the following formula (Gao et al., 1997):

$$W_i = (C_i/C + h_i/h)/2 \qquad (3)$$

where C is the total coverage of community ($C = \sum C_i$); i = 1, tree layer; 2, shrub layer; 3, herb layer, and the meaning of i same below; h is the thickness of the leaf layer for various growth types ($h = \sum h_i$), W_i is the weighted parameter of diversity index of i^{th} growth type, C_i is the coverage of the i^{th} growth type and h_i is the average thickness of the leaf layer of the i^{th} growth type. Among them, the thickness of tree leaf layer is calculated at 33.3% the height of the tree layer, the shrub layer is at 50% and the herb layer is at 100%.

The total diversity index of the community was calculated according to the following formula:

$$D = \sum W_i D_i \qquad (4)$$

where *W* is the weighted parameters of the tree layer, shrub layer and herb layer. *D* is the diversity index of the tree layer, shrub layer and herb layer.

The diversity index of different layers can be calculated using the formulae listed below.

Species diversity indices were determined (Liu et al., 1997) as Shannon–Wiener's index of diversity

$$H = -\sum_{i=1}^{s}(P_i \ln P_i) \qquad (5)$$

and Simpson's index of dominance was calculated as

$$D = 1 - \sum_{i=1}^{s} P_i^2 \qquad (6)$$

and Pielou's index of evenness was calculated as

$$J_{sw} = H/(\ln(S)) \qquad (7)$$

Finally, Patrick's index of richness was calculated as

$$R = S \qquad (8)$$

where P_i is the relative important value of species *i*, and *S* is the total number of species in the *i*th site.

Within each gradient, community, data of soil moisture and soil properties of the 5 sites at each distance range were calculated as mean ± standard error (SE) of mean. To depict the vertical structure of soil moisture, soil water content was divided into three layers: 0-30 cm soil moisture (SWC1), 30-100 cm soil moisture (SWC2), and 100-200 cm soil moisture (SWC3) in accordance to the fine roots distribution of herbs, trees and shrubs in this area (Fu et al., 2014). We averaged the soil moisture at each corresponding finer increment to obtain the value of SWC1, SWC2 and SWC3. Similarly, the SOM, TN, TP, TS at 0-100 cm were the average value of each property at 0-20, 20-40, 40-60, 60-80 and 80-100 cm.

Regression analysis was used to examine variation tendency of the height, density and cover with distance from river channel. Exponential and polynomial regressions were fit to the data to best explain the statistical relationship. Pearson correlation was used to determine the strength of possible relationship between community characteristics and environmental factors. Significant differences were evaluated at the 0.05 and 0.01 level. Statistical analysis was performed using SPSS (ver. 18.0).

To depict the variation of desert riparian forests composition, we used Two-way Indicator Species Analysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of hierarchical classification (Hill, 1979), to classify the possible desert riparian forests community types. The presence/absence data for all plant species, obtained from the vegetation survey were used in this analysis and the cutoff levels were set as: 0, 0.1, 0.2, 0.4, 0.6 and 0.9 under the consideration of important value frequency. To further separating the key influencing factors of the 12 environment variables, marginal and conditional effects of various variables were calculated through the Monte Carlo test in the process of forward selection. Marginal effects reflected the effects of the environmental variable on the community characteristics, while conditional effects reflected the effects of the environmental variables on the community characteristics after the anterior variable was eliminated by the forward selection method. Since the redundant variables were eliminated and a group of key environmental factors was determined through the forward selection, this method allowed key variables to be determined through the strength of their effects and significance. Variation of community characteristics explained by the key environmental factors was analyzed using variation partitioning analysis. The significance of the resulting ordination was evaluated by 499 Monte Carlo permutations (Zhang and Dong, 2010). The Monte Carlo test and variation partitioning analysis was performed by the software program CANOCO (ver. 5.0) (Microcomputer Power, USA) (Braak et al., 2012).

3 Results

3.1 Vegetation community types

We found that vegetation community diversity was relatively low in the low reaches of Heihe. Only 19 plant species (frequency ≥2) were recorded in 35 sites. Out of these 35 sites, the tree layer only appeared in 7 sites, while the shrub and herb layer appeared in 32 and 29 sites, respectively. The species composition at each site in the low reaches of Heihe is shown in Table S1 and the following five plant community types distributed along the distance of 0-3000 m from river channel were obtained based on TWINSPAN classification (Fig. 2).

Community I was Ass. *Populus euphratica–Tamarix ramosissima* +herbs, found at sites 1, 2, 3, 4, 6, 7, 15 and 21. Although this community was typical desert riparian forests type with multiple layers of tree-shrub-herb, its coverage was relatively low (38.05%). The community was dominated by tree species *Populus euphratica* with sparse understory vegetation. *Tamarix ramosissima* was the only species of shrub layer and the herb layer was dominated by *Sophora alopecuroides*. This community was distributed near the river bank, mostly within 500 m from river channel.

Community II was Ass. *Tamarix ramosissima–Lycium ruthenicum* + herbs, found at sites 5, 10 and 26. This community was constituted of shrub and herb layers with high community coverage of 81.43%. *Tamarix ramosissima* was the dominant species of the shrub layer with the importance value of 0.84-1. The herb layer contains both hygrophyte and xerophyte species, such as *Kochia scoparia* and *Peganum harmala*. This community was mainly distributed near the river bank, distanced about 1000 m from the river channel.

Community III was *Tamarix ramosissima*, found at sites 8, 9, 20, 23 and 25. This community was mainly constituted of shrub layers, except that sparsely grown herbs existed at site 8. The community was dominated by *Tamarix ramosissima* with average community coverage of 75.93% and mainly distributed at the distance of 1000-2000 m from the river channel.

Community IV was Ass. *Lycium ruthenicum–Tamarix ramosissima* + xerophytes herbs, found at sites 12, 13, 14, 17, 18, 22, 24, 27, 32 and 34. This community mainly composed of shrub and herb layers with average community coverage at 68.86%. *Lycium ruthenicum* was the dominant species of the shrub layer (importance value = 0.42-0.77), while the dominant xerophytic herb species were *Sophora alopecuroides* and *Suaeda salsa*. It mainly distributed at the distance of 1500-2500 m from the river channel.

Community V was Ass. *Tamarix ramosissima–Lycium ruthenicum–Reaumuria songarica*, found at sites 11, 16, 19, 28, 29, 30, 31, 33 and 35. This community was the transition community from desert riparian shrub forests to desert shrub community, indicated by the presence of *Reaumuria songarica*, a typical desert shrub. *Tamarix ramosissima* was the dominant species of the shrub layer and mainly exist in the form of shrub dune, with the importance value of 0.38-0.93. The *Karilinia caspica and Phragmites communis* herbs were distributed sparsely and only existed in one sampling site. This community was mainly distributed at the distance of 2500-3000 m from the river channel, with a relatively low community coverage (54.40%).

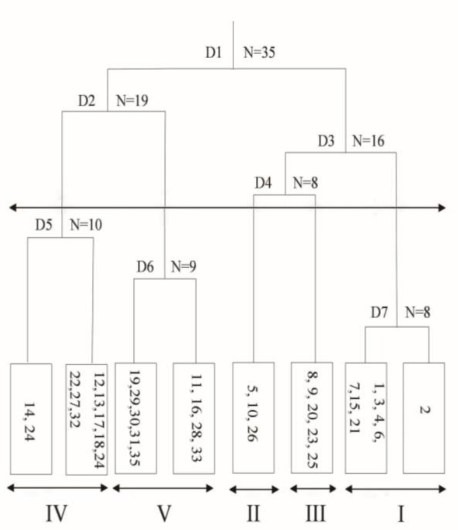


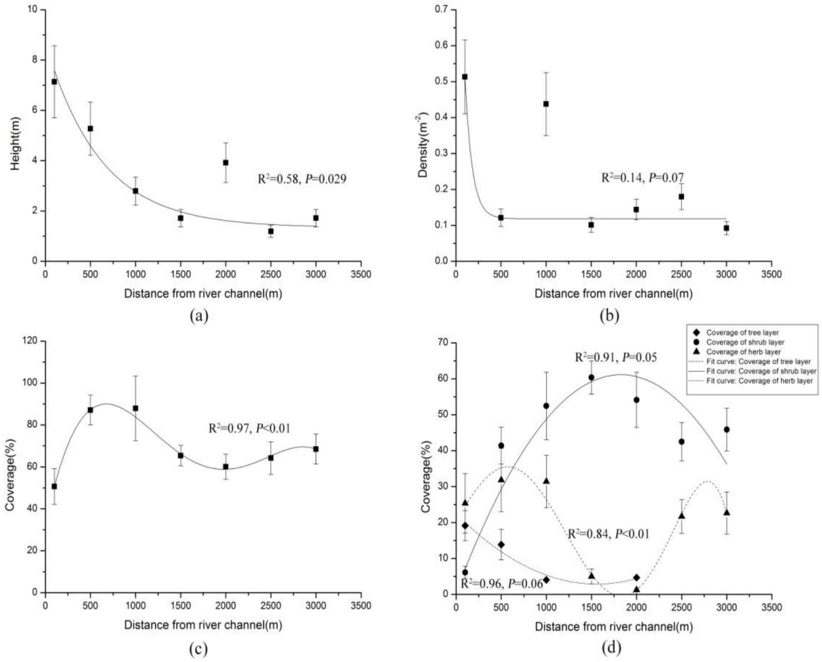
Figure 2. The dendrogram of sampling sites based on the TWINSPAN classification

Note: Number 1-35 represents the site number of the sampling sites. D is for the classification levels and N is for the numbers of sampling sites for the classification. I to V represent community I to V. Arrows depicted all the sites were divided into five major groups after the fourth classification.

3.2 Variation of vegetation community structure and diversity along the distance from the river channel

Vegetation community height and density dropped rapidly along the distance from the river channel (Fig. 3a, b). Community coverage experienced a bimodal pattern, peaked at the distance of 500-1000 m and 3000 m with the coverage of 88% and 70%, respectively (Fig. 3c). The variation of vertical structure was depicted by the following hierarchy coverage (Fig. 3d). The tree layer mainly existed within 1000m from river channel, while the coverage of shrub formed a unimodal pattern, peaking at the distance of 1500-2000 m. The coverage of herb fluctuated along the distance gradient, peaking at 500 m and 2500-3000 m from the river channel.

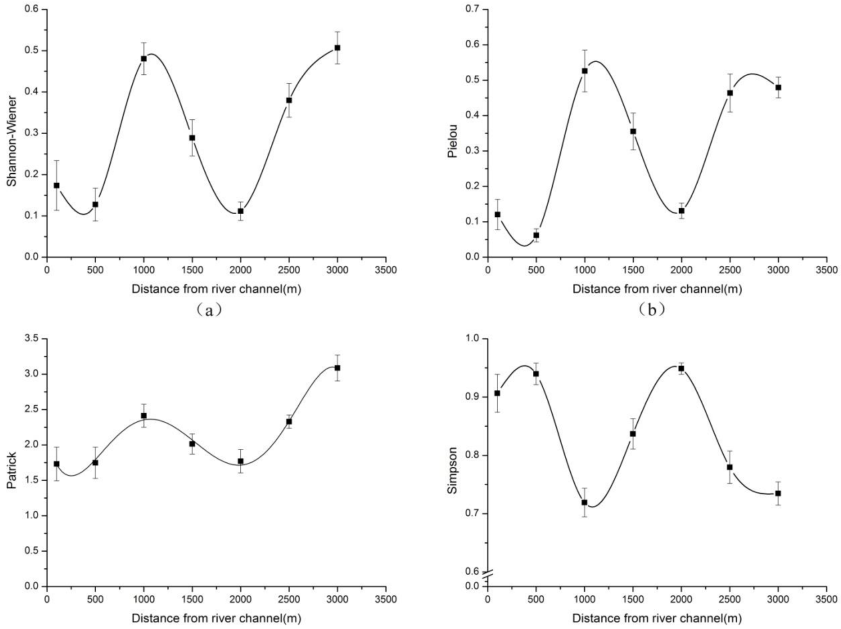
Community diversity was low along the whole gradient and all diversity indices showed a bimodal pattern along the distance from river channel (Fig. 4). The Shannon-Wiener diversity index, Pielou evenness index and Patrick richness index peaked at the distance of 1000m and 3000m (Fig. 4a-c). The Simpson dominance index, however, formed an opposing trend to the other three diversity indices, by peaking at the distance of 500m and 2000m where the other indices were at their low level (Fig. 4d).



(a) (b)

(c) (d)

Figure 3. The variation of community structure along the distance from the river channel.



（a） （b）

（c） （d）

Figure 4. The variation of community diversity along the distance from the river channel.

3.3 Variation of water availability and soil properties along the distance from the river channel

Our results indicated that SWC1 and SWC2 peaked at the distance of 500-1000 m and 2500 m, following the same pattern with vegetation community coverage, diversity, evenness, and richness indices along the gradient from river channel (Fig. 5a). SWC3, however, showed a different pattern by peaking at the distance of 1000 m from river channel and dropped rapidly after the distance of 2500 m.

The proportion of silt and clay peaked at the distance of 1000 m from the river channel (Fig. 5c), while bulk density reached its lowest point (1.07 g·cm^{-3}) (Fig. 5b). After peaking at 1500 m, sand proportion decreased gradually and the soil composition consisted of 43.4% silt and 4.5% clay at the distance of 2500 m from river channel. At the end of gradient, the proportion of sand and gravel reached 58.9% and 4.5%, respectively, with the highest bulk density (1.35 g·cm^{-3}). The variation of SOM, TN, TP showed the similar pattern with vegetation diversity along the ecological gradient (Fig. 5d-g). They generally decreased along the distance from river channel and reached a relatively high content at the distance of 500 m and 2000-2500 m. The total salt content peaked at the distance of 1000 m (2.57%) and dropped gradually until the end of the gradient.

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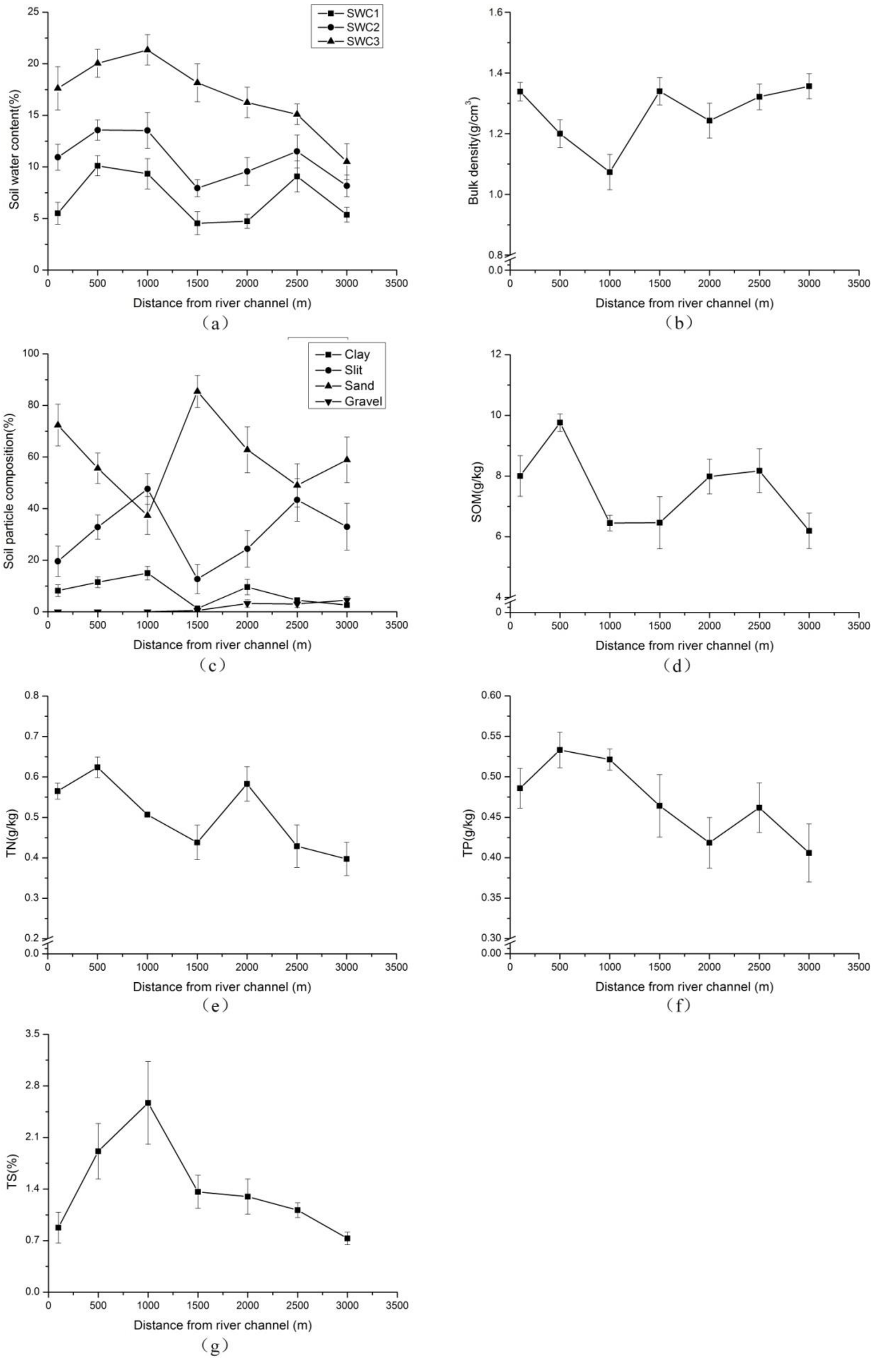

Figure 5. The variation of soil moisture (a), soil bulk density (b), soil particle composition (c), soil organic matter (d), total nitrogen (e), total phosphorus (f), total salinity (g) along the distance from river channel.

SWC1, 0-30cm soil moisture; SWC2, 30-100cm soil moisture; SWC3, 100-200cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content.

3.4 Pearson correlation between community characteristics and environmental factors

Pearson correlation analysis between community characteristics and environmental factors was shown in Table 1. The community density showed significant positive correlation with SWC2 ($r=0.382$, $P<0.05$), SWC3 ($r=0.362$, $P<0.05$), but negative correlations with BD ($r=-0.353$, $P<0.05$). Community coverage positively correlated with all the tree layers of soil moisture ($P<0.0.1$) but negatively correlated with BD ($r=-0.350$, $P<0.05$). Specifically, the coverage of shrub layer was negatively correlated with BD ($r=-0.465$, $P<0.01$), while the coverage of herb layer was positively correlated with SWC1 ($r=0.514$, $P<0.01$). The coverage of tree layer did not showed any significant relationship with any environmental factors. Among the diversity indices, the Patrick richness index was negatively correlated with SOM ($r=-0.398$, $P<0.05$), while Simpson domination index was positively correlated with sand ($r=0.354$, $P<0.05$) and negatively correlated with silt ($r=-0.344$, $P<0.05$).

Table 1. Pearson correlation between community characteristics and environmental factors

	H	C	R	J_{sw}	Height	Density	Cover-a	Cover-t	Cover-s	Cover-h
SWC1	0.26	-0.29	0.17	0.18	-0.09	0.25	**0.55**	-0.02	0.17	**0.51**
SWC2	0.05	-0.10	-0.07	0.07	-0.11	**0.38**	**0.44**	0.01	0.28	0.26
SWC3	0.14	-0.15	0.16	0.11	-0.24	**0.36**	**0.45**	-0.14	0.18	0.38
Clay	0.11	-0.13	0.01	0.05	0.05	0.29	0.20	0.04	-0.09	0.27
Silt	0.31	**-0.34**	0.12	0.31	-0.12	0.11	0.32	-0.07	0.25	0.17
Sand	-0.33	**0.35**	-0.15	-0.31	0.13	-0.17	-0.31	0.08	-0.17	-0.22
Gravel	0.23	-0.16	0.35	0.18	-0.28	-0.08	-0.19	-0.17	-0.18	0.01
BD	0.17	-0.13	0.28	0.12	-0.04	**-0.35**	**-0.35**	0.05	**-0.47**	0.06
SOM	-0.26	0.19	**-0.40**	-0.10	0.19	0.06	-0.19	0.12	-0.12	-0.30
TN	-0.19	0.14	-0.33	-0.06	0.10	0.03	-0.28	0.11	-0.30	-0.22
TP	-0.24	0.20	-0.30	-0.10	0.12	0.02	-0.18	0.08	-0.09	-0.29
TS	-0.14	0.11	-0.13	-0.10	-0.18	0.27	0.01	-0.09	0.03	-0.13

Significant correlations (P<0.05) are shown in bold and significant correlations (P<0.01) in bold with underline.

R, Patrick richness index; J_{sw}, Pielou evenness index; H, Shannon–Wiener diversity index; C, Simpson domination index; a, total plant community; t, tree layer; s, shrub layer; h, herb layer; SWC1, 0-30cm soil moisture; SWC2, 30-100cm soil moisture; SWC3, 100-200cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content.

3.5 Key environmental factors that influenced community characteristics

To further examine the key environmental factors that controlled the variation of desert riparian forests community, redundant variables were eliminated by a forward selection method. Table 2 showed the changing conditions of marginal and conditional effects of 12 variables under the Monte Carlo test in the process of forward selection. All the environmental factors explained 53.6% variance in total. In the Monte Carlo test of forward selection ($P<0.05$), SWC1, SWC3, BD, and TP were regarded as the key environmental factors influencing the variation of community characteristics. A total 78.74% of the environmental information was extracted by the key environmental factors, and SWC1 contributed the most information (37.69%). To further investigate the variation explained by four key environmental factors, we divided those four factors into three groups for partitioning analysis: (i) SWC1 and SWC3 to represent the effect of soil moisture, (ii) BD to represent soil physical properties, and (iii) TP to represent soil nutrient. The total variation of community characteristics explained by the three groups was 32.8%. SWC1 and SWC3 accounted for 62.7% of explanation power, followed by BD (19.8%) and TP (8.1%). The variation mutually explained by the three groups, however, was small (below 1.5%).

Table 2. Marginal and conditional effects obtained from the summary of forward selection.

Environmental factors	Marginal effects	Environmental factors	Conditional effects	*P* value	*R* value (%)
	Percentage of variance explained (%)		Percentage of variance explained (%)		
SWC1	20.2	SWC1	20.2	0.006	37.69
SWC3	18.8	SWC3	8.2	0.030	15.30
SWC2	12.4	BD	7.9	0.036	14.74
BD	11.4	TP	5.9	0.040	11.01
TN	7.1	Clay	3.8	0.126	——
Silt	7.0	Sand	2.7	0.214	——
Sand	6.1	TN	1.2	0.500	——
SOM	4.1	TS	1.0	0.588	——
Clay	3.8	SWC2	0.4	0.842	——
TP	3.6	Gravel	0.4	0.868	——
Gravel	2.6	Silt	1.9	0.384	——
TS	0.5	SOM	<0.1	0.996	——
		Total	53.6	0.036	——

R value represents the relative proportion of individual explanation to the total explanation.

Table 3. The percentage of community characteristic variations explained by key environmental factors.

Fraction	Variation	% of All	% of Explained	F	*P*
SWC1+SWC3	0.210	20.6	62.7	5.9	0.002
BD	0.065	6.5	19.8	4.0	0.032
TP	0.027	2.7	8.1	2.2	0.132
SWC1+SWC3+BD	0.015	1.5	4.5	5.9	0.002
BD+TP	0.002	0.2	0.5	4.1	0.024
SWC1+SWC3+TP	0.008	0.8	2.6	2.3	0.122
SWC1+SWC3+BD+TP	0.006	0.6	1.8	5.2	0.002
Total Explained	0.330	32.8	100	—	—

Variation: the variance explained by different fraction when the total variance is 1; % of All: the proportion of variation explained by different fraction; % of Explained: the relative proportion of individual explanation to the total explanation;

4 Discussion

4.1 The distribution pattern of desert riparian forests along the distance from the river channel

The desert riparian forests formed a clear pattern along the distance from the river channel in the low reaches of Heihe River Basin. As it went further from the river, the desert riparian forests community shifted from the riparian tree-shrub-herb community (Community I) to riparian–desert transition shrubs community (Community V). Community height and density declined significantly as dominance species changes from trees to riparian-desert shrubs along the distance gradient. The coverage of community formed bimodal pattern and reached high level at the distance of 1000 m and 3000 m where community mainly consisted of shrub and herb layers.

While many studies in relatively humid region (e.g., coastal region or boreal forest) suggested that riparian forest species diversity either decreased or formed a unimodal pattern with increasing distance from the stream (Pabst and Spies, 2011; Macdonald et al., 2014), we found the bimodal pattern of Shannon-Wiener diversity, Pielou evenness, Patrick richness and Simpson dominance indices along the distance from river channel(Fig. 4a-c). These variation patterns of community diversity can illustrate how community response to the ecological gradient depends not only on water availability, either from the river or from groundwater (Zhu et al., 2013), but also on variation in soil properties and their interactions in the resource limited region (Oksanen and Minchin, 2002). Vegetation community flourished near the river (1000m) with the multiple layers of tree-shrub-herb, where tree *Populus euphratica* could benefit the growth of other species by redistributing the deep soil water to the shallow layer as a strategy of mutualism reported by Hao et al. (2013). At greater distance from the river (3000 m), the community was mainly a transition community of riparian and desert shrubs. Though situated at the transition region from riparian forest to desert shrubs, the soil still consisted of 35.6% fine particle (clay and silt), which mainly caused by the interaction between wind erosion and shrubs (Ravi et al., 2009). The removal of nutrient-rich fine soil particles from the intercanopy areas driven by wind erosion could effectively be trapped by shrubs (especially 2 m high from the ground) (Ravi et al., 2010; Zhou et al., 2015). This redistribution of soil particles resulted in relatively high soil infiltration capacity and soil nutrition around the shrub patches, which made it possible for the growth of some xerophytic herbs, consequently increasing the level of diversity in this gradient (Stavi et al., 2008; Ravolainen et al., 2013).

By contrast, Simpson dominance index showed different trend to other indices, peaking at the distance of 500 m and 2000 m where other indices reached their low level (Fig. 4d). We suggested that inter-species competition for the scarcely water and nutrient resources in this harsh environment could be responsible for the trend (Maestre et al., 2006; Boever et al., 2015). The dominant species with high important value (i.e., tree and shrub at 500 m and 2000 m, respectively) often had high competition for resources, halting the growth of other species (i.e., herbs) (Koerselman and Meuleman, 1996). In these sites, low number of species indicated low community diversity and the dominant species made a large contribution to the diversity index of the community (Zhu et al., 2013), which resulted in a large domination index (Fig. 4d). Our findings thus indicated that interactions between species and extreme environmental stress could cause skewed or non-unimodal responses in hyperarid area, which were different from studies in humid riparian zone (Pabst and Spies, 2011; Macdonald et al., 2014).

4.2 The effects of soil moisture and other soil properties on the desert riparian forests

The interactions between vegetation and environmental factors resulted in the distribution pattern of desert riparian forests. Among the environmental factors, changes in water availability associated with soil properties are considered as the most important selective forces shaping ecosystem stability in hyperarid zone (Rosenthal and Donovan, 2005; Ravi et al., 2010; Feng et al., 2015). Our study showed that soil moisture and soil properties explained 53.6% community variance in total (Table 2), which indicated that they play important role in desert riparian forests distribution in the low reaches of Heihe River Basin.

Soil moisture alone (i.e., SWC1 and SWC3) contributed to 62.7% of the total explanation of vegetation variance. High level of SWC1 often indicated high water availability and vegetation coverage. It accounted for most information of environmental factors (37.69%) and mainly influenced the coverage of herb layer and the whole community (Table 1). This 0-30 cm soil moisture was the main water resource for dominant herb species, such as *S. alopecuriodes* and *K. caspica* whose fine roots mainly distributed within 30 cm from the surface soil (Fu et al., 2014). SWC2 (30-100 cm soil moisture) was the main water resource for shrubs such as, *T. ramosissima* which mainly utilized the 40-80 cm soil moisture (Yi et al., 2012) and SWC3, recharged by flood-raised groundwater table (Liu et al., 2015), was the water resource for phreatophyte like *P. euphratica* or desert shrubs that mainly depended on the groundwater and deep soil moisture (Yi et al., 2012). Similar to the study by Ridolfi et al. (2007) , our results showed that high content of SWC1 contributed to rich herb layers and community coverage while SWC2 and SWC3 played important role in supporting the growth of shrub and tree layer in desert riparian forests which contributed greatly to the community density and coverage.

Apart from soil moisture, soil physical properties were also important in determining vegetation community with BD accounted for 19.8% of the total explanation of vegetation variance. Bulk density and soil composition are critical for water holding capacity and the ability of absorbing soil nutrition (Stirzaker et al., 1996; Meskinivishkaee et al., 2014). Bulk density negatively correlated with the community density, community coverage and shrub coverage, while soil composition such as silt and sand showed positive relationship with the Simpson domination index (Table 1). In hyperarid zone, soil with high bulk density often consisted of high silt and sand, but low percentage of clay which resulted in low water holding capacity in the surface soil (Ravi et al., 2010) and may inducing the drought stress in the surface soil (Stirzaker et al., 1996). Such process constrained the growth of herbs, which contributed greatly to the community coverage, density and diversity, resulting in low diversity and a large domination index in community.

Soil nutrition also accounted for the variance of vegetation community, with TP represented 8.1% of the explanation and SOM was negatively correlated with Patrick richness index (Table 1, Table3). While soil P is an essential element for photosynthesis and mainly provided by the decomposition of SOM (Runyan and D’Odorico, 2012; Xu et al., 2016), it did not show significant relationship with community characteristics. We suggested that low groundwater table (i.e., above the degradation threshold of 4 m) as well as the low fluctuation range of groundwater were mainly responsible for the insignificant influence of TP in our study. Previous study at Tarim River found that the effect of TP was more obvious with the rapidly decrease of groundwater table (Zhang et al., 2015b), which was quite different in the low reaches of Heihe River Basin where the perennial groundwater table remained above the degradation threshold (4 m) at the distance of 3800 m from river channel(Wang et al., 2011; Fu et al., 2014). Our results were also different from previous studies which found positive relationship between SOM and species richness in semiarid zone such as Loess Plateau (Jiao et al., 2011; Yang et al., 2014). Although SOM content determined soil nutrient storage and supply of available nutrients, our sites in hyperarid zone were often characterized by barren soil with less than 1% soil organic matter (Fig. 5d). Such low amount of SOM might not be able to boost the growth of various species in desert riparian forests (Wang et al., 2016). At the same time, the dominant species (i.e., *P. euphratica* and *T. ramosissima*), producing high amount of litter, often had high competition for resources, thus halted the development of other species and result in low community richness (Su, 2003).

4.3 Critical distribution range of desert riparian forests and implications for ecological protection

Our results showed that the distance up to 1000 m from the river channel provide the optimum condition for desert riparian forests, indicated by high level of community characteristics and favorable environmental factors. With appropriate groundwater table and flourish community, this range is the main vegetation restoration area influenced by the implement of ecological water conveyance (Wang et al., 2011). Yet this living range was also the most suitable region for grazing due to the abundance of herbs and prone to human disturbance due to its vicinity to the main roads. Since our result showed that soil physical properties also influenced the community structure, exposure to human disturbance, including trampling by livestock might potentially destroy the soil physical properties, leading to vegetation degradation and aggravated wind erosion on bare land (Greenwood and Mckenzie, 2001; Zhao et al., 2012; Daryanto et al., 2013). We therefore suggested multiple conservation measures to protect the soil structure and promote vegetation growth in this critical range such as: (i) setting critical fence area for ecological protection and (ii) constructing artificial shield or establishing straw checker boards on the bare land to prevent land degradation caused by wind erosion.

While desert riparian forests survived up to 2500 m from the river channel, this critical distance was considered as the ecotone between oasis and peripheral desert, characterized by lower environmental quality and low self-recovery capability (Zhao et al., 2006; D’Odorico et al., 2013; Lü et al., 2014). After this distance, soil moisture, soil fine particle and soil nutrients decreased sharply, followed by the appearance of desert species. With projected rise in temperature, more intense evaporation and more frequent drought (Zhang et al., 2015a), the desert riparian forests might experience high deficiency of soil moisture, leading to vegetation degradation and desertification in the low reaches of Heihe River Basin (Wang et al., 2014). Since this distance was also far from the influence of ecological water conveyance (Si et al., 2005;Guo et al., 2009), desert riparian forests could experience narrowed living range and a sharp community transition away from the river channel with more frequent drought scenario. To halt degradation in this critical zone, we suggested the development of natural channels that perpendicular to the river to fully extend the influence scope of ecological water conveyance and benefit the regions far from the river bank (Zhang et al., 2011b). So far, the existing artificial channels were built out of concrete for irrigation purpose and consequently, they did not have the seepage property of natural channels, generating little benefit to these dry areas. In addition, fence and additional regulation should be set to minimize human disturbance (e.g., grazing, firewood cutting) in this gradient as vegetation on the surface of shrub dune was extremely important for stabilizing the sand dunes and preventing desertification process.

5 Conclusion

Through extensive field observations at multiple desert riparian forests locations, we found that: (i) vegetation community in the desert riparian forests shifted from the riparian tree-shrub-herb community to desert riparian forests community with increasing distance from river channel, and (ii) species diversity indices formed bimodal patterns instead of unimodal pattern due to the interactions between vegetation and soil properties. While desert riparian forests were distributed within 2500 m from the river channel, the first 1000 m provided the optimum condition based on the variation of community characteristics and environmental factors. Since soil moisture, supported by favorable groundwater depth, and other soil properties (e.g., BD, SOM, TN) accounted for 53.6% of desert riparian forests variance, future ecological restoration should emphasize the importance of soil factors in the low reaches of Heihe River Basin. Extending the influence scope of ecological water conveyance, for example, was recommended in regions that far from river bank to recharge the surface soil moisture and benefit the growth of herb species which contribute greatly to the community diversity in hyperarid zone. In addition, multiple conservation measures that protect the soil structure (e.g., build artificial soil cover and livestock grazing exclusion) were recommended for this region to reduce the adverse effects of grazing on soil properties. Unless these necessary precautions are taken, desert riparian forests may become restricted to the periphery of the river and experience significant community transition under projected climate change scenario and more intensive human disturbance.

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