The spatial distribution and temporal variation of desert riparian forests and their influencing factors in the downstream Heihe River Basin, China

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Abstract. Desert riparian forests are the main restored vegetation community in Heihe River Basin. They provide critical habitats and a variety of ecosystem services in this arid environment. Since they are also sensitive to disturbance, examining the spatial distribution and temporal variation of desert riparian forests and their influencing factors is important for determining the limiting factors of vegetation recovery after long-term restoration. In this study, field experiment and remote sensing data were used to determine the spatial distribution and temporal variation of desert riparian forests and their relationship with the environmental factors. We classified five types of vegetation communities at different distances from the river channel. Community coverage and diversity formed a bimodal pattern, peaking at the distances of 1000 m and 3000 m from the river channel. In general, the temporal NDVI trend from 2000 to 2014 was positive at different distances from the river channel, except for the region closest to the river bank (i.e., within 500 m from the river channel), which had been undergoing degradation since 2011. The spatial distribution of desert riparian forest was mainly influenced by the spatial heterogeneity of soil properties (e.g., soil moisture and soil physical properties), while the temporal variation of vegetation was affected by both the spatial heterogeneity of soil properties (e.g., soil moisture and soil particle composition) and to a lesser extent, the temporal variation of water availability (e.g., annual average and variability of groundwater, soil moisture and runoff). Since surface (0–30 cm) and deep (100–200 cm) soil moisture, bulk density and the annual average of soil moisture at 100 cm obtained from the remote sensing data were regarded as major determining factors of community distribution and temporal variation, conservation measures that protect the soil structure and prevent soil moisture depletion (e.g., artificial soil cover and water conveyance channels) were suggested to better protect desert riparian forests under climate change and intensive human disturbance.

1 Introduction

Riparian zone is the linkage between terrestrial and aquatic ecosystems (Naiman and Décamps, 1997), which is usually defined as the stream channel between the low- and the high-water marks, in addition to the terrestrial landscape above the high-water mark. Consequently, vegetation in the riparian zone is likely to be influenced by elevated water tables or extreme flooding and by the ability of soils to hold water (Nilsson and Berggren 2000). Riparian zone plays an important role in numerous ecological processes and provides a variety of ecosystem services, such as sand stabilization and carbon sequestration (Décamps et al., 2004). Desert riparian forests, also known as 'Tugai forests', are mainly located in the floodplains of the major Central Asian rivers. They are considered the core of riparian zone in hyperarid areas (Gärtner et al., 2014) by providing critical habitats for various species and functioning as an 'ecological shelter' against desertification (Ding et al., 2016). However, due to their low biodiversity and weak resilience, desert riparian forests are sensitive to disturbance and likely to be threatened by climate change and human disturbance (Li et al., 2013).

Desert riparian forests are the main communities in Heihe River Basin, the second largest inland river in China (Feng et al., 2015). During the past century, an increase of the human population and overexploitation of the upstream water resources have led to a significant degradation in the downstream desert riparian forests (Wang et al., 2014). Since 2000, the ecological water conveyance project (EWCP), a restoration project aiming to deliver water downstream, has been implemented to restore the ecosystems of Heihe River Basin (Wang et al., 2011). Every year, approximately 300 billion m^3 of water is delivered using concrete channels, which were built perpendicular to the river to expand the range of the river impact and to deliver water for irrigation. The influence of ecological water conveyance may reach as far as 2000 m from the river (Si et al., 2005; Zeng et al., 2016). While most of vegetation in the downstream Heihe River has been restored (Lü et al., 2015), nearly 20% of its oasis area covered by desert riparian forests remains degraded despite better downstream water conditions and the rising of groundwater table (Zhang et al., 2011a). To understand what may cause such variations in this desert riparian forest, we need to examine the spatial distribution of community characteristics along an ecological gradient, which can reflect how the spatial distribution of vegetation has been shaped by multiple environmental factors (Goebel et al., 2012; Li et al., 2013).

In hyperarid zone, groundwater is regarded the major driving factor of vegetation distributions and groundwater table should be between 2 m and 4 m deep to support vegetation growth (Zheng et al., 2005). Study in Tarim River, for example, shows that species diversity peaks where groundwater depth is around 2–4 m. Once groundwater tables falls beyond 4.5 m, a deficiency in soil moisture occurs, followed by degradation of vegetation communities (Li et al., 2013). While groundwater drops rapidly away from the river bank to approximately 6 m deep at a distance of 1000 m from Tarim River channel, (Aishan et al., 2013), groundwater table in downstream Heihe River, where most of the desert riparian forest are distributed, remains above 4 m even at the distance of 3800 m from the river channel (Wang et al., 2011; Fu et al., 2014). Yet some sites have not been completely restored in the Heihe riparian zones, and its downstream vegetation community is still dominated by shrubs instead of multiple layers of tree (He and Zhao, 2006; Zhang et al., 2011a). A study by Zhu et al. (2013) shows that Patrick's richness index and the Shannon-Wiener diversity index for the downstream vegetation form a bimodal pattern instead of a unimodal pattern with groundwater depth in the Heihe River Basin, indicating that there may be other factors affecting the spatial distribution of desert riparian forests.

Apart from groundwater, soil properties, such as soil moisture, soil physical and chemical properties also shape the community characteristics and species vitality (Stirzaker et al. 1996; Salter and Williams, 1965). Soil moisture, influenced by precipitation and groundwater, is the direct water source for desert riparian forests (Wang et al., 2012). As different depths of soil moisture affect species diversity in each community layer (D'Odorico et al., 2007; Fang et al., 2016), a decline in soil moisture may reduce the diversity of drought-sensitive species (e.g., herbs), resulting in a community shift towards drought-tolerant vegetation types with distance from the river channel (Zhu et al., 2014). Study also find that variation in soil properties explains the evolution of dominant species in arid areas and the changes in soil nutrients contribute greatly to species diversity (Yang et al. 2008).

The temporal variation in vegetation can reflect how communities respond to the changing environment during ecological restoration (Bakker et al., 1996; Scott et al., 1996). Due to the lack of long-term field-based observational data, long-term series of remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) have been widely used to explore vegetation changes and to evaluate the effectiveness of ecological restoration (Wang et al., 2014; Geng et al., 2014). Since the implementation of ecological restoration, the Normalized Difference Vegetation Index (NDVI) in the downstream Heihe River Basin has significantly increased and the temporal variation in environmental factors, especially water availability (e.g., runoff and groundwater) has been reported as the major driving factor in vegetation recovery (Jia et al., 2011; Zeng et al., 2016). While large-scale remote sensing data (e.g., MODIS-NDVI, SPOT-NDVI) can capture the general trend of the whole study area, they fail to accurately delineate the temporal variation of desert riparian forest vegetation at the fine scale (i.e., <100 m). However, community variation is a result of long-term interactive effects between vegetation and the environment, influenced by both spatial heterogeneity and temporal variation factors during ecological restoration (Zhu et al., 2013; Xi et al., 2016). Until recently, very few studies have incorporated both spatial and temporal variation of desert riparian forests into a single study due to the inconsistency in scale between fine field sampling and coarse remote sensing analysis. As desert riparian forest is the main community that maintains ecosystem functions under hyperarid conditions, comprehensive research that simultaneously examines the spatial and temporal variation of vegetation is crucial for the restoration of degraded riparian zones.

In this study, we aim to (i) explore both the spatial distribution and temporal variation of Heihe desert riparian forest at different distances from the river channel and (ii) disentangle the impacts of spatial heterogeneity in soil properties and temporal variation in water availability on the vegetation community. We studied 3000 m transects running perpendicular to the river channel to include different distances from the river channel and to depict the spatial distribution of vegetation (e.g., changes in floristic composition, community structure and diversity) at each distance from the river channel. We used NDVI variations at different distances from the river channel, derived from high resolution images (e.g., 30 m resolution) from 2000–2014, to depict the temporal variation of the vegetation. Spatial heterogeneity of soil properties (e.g., soil moisture, soil physical properties and soil nutrition) and temporal variation of water availability (e.g., annual average and annual variability of groundwater, soil moisture and runoff) were used to explain the vegetation community variance.

2 Data and methods

2.1 Study area

The study was conducted in the downstream 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 (i.e., 1127 m to 820 m above sea level) from the southwest to the northeast. This region has a typical continental arid climate with a mean annual temperature of 8.77 ℃. Its maximum and minimum temperatures usually occur in July (41°C) and January (−36 ℃) (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).

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 flows into East Juyan Lake and West Juyan Lake in Ejina. The population of the Ejina Oasis is 32,410 (Ejina statistical office, 2012). The local economy mainly depends on cantaloupe farming and animal husbandry (e.g., sheep, cattle and camels). The Ejina Oasis is one of China’s most important tourist attractions with respect to desert riparian forests, attracting almost 200,000 visitors per year during September to October (Hochmuth et al., 2014). One primary road is built parallel to the river channel, and another runs across the south of the oasis.

The desert riparian forests are the main components of the Ejina Oasis. They mainly grow along the river banks and spread across the fluvial plain, with the dominant vegetation including *Populus euphratica*, *Tamarix ramosissima*, *Lycium ruthenicum*, *Sophora alopecuroides*, *Karelinia caspica*, and *Peganum harmala*. Sparse and drought-tolerant desert species, such as *Reaumuria soongarica*, *Zygophyllum xanthoxylon* and *Calligonum mongolicum* are mainly distributed in the Gobi Desert. The main soil types in the area are Gypsi Sali–Orthic Aridosols and Calcaric Aridi–Orthic Primosols. Para–alkalic Aqui–Orthic Halosols and Calcaric Ochri–Aquic Cambosols also exist in the lake basins and lowlands (Chen et al., 2014; Gong.,

2014).

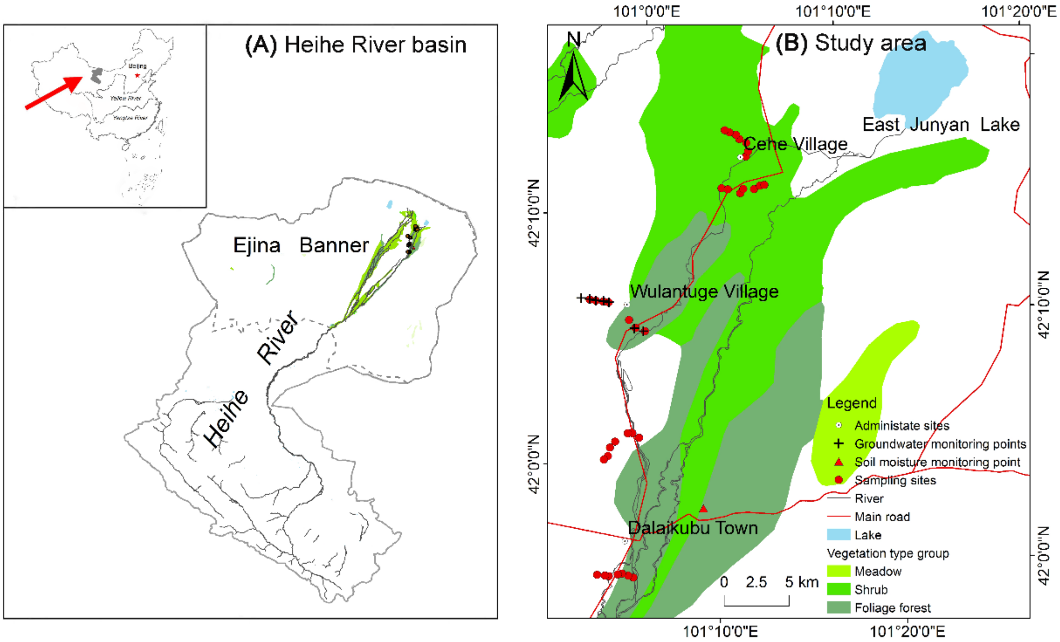

Figure 1. The Heihe River Basin in China (A) and the location of sampling points in the study area (B).

2.2 Spatial field survey and experimental design

In the downstream Heihe River Basin, desert riparian forests make up the core of the desert oasis, mainly composed of tree, shrub and grass communities. However, the spatial extent of the riparian zone is difficult to precisely delineate due to the heterogeneity of the landforms (Décamps et al., 2004). Although previous studies indicates that the forests are distributed between 0 m and 2000 m from the river channel, corresponding to the influence range of ecological water conveyance (Si et al., 2005), our study extended beyond that range (i.e., up to 3000 m from the river channel) to fully cover the distribution pattern of the desert riparian forests in downstream Heihe River.

Our field survey was conducted in July 2015 after the ecological water conveyance was delivered. Ecological water conveyance is implemented according to the water dispatching scheme and is conducted in April, July, August, September and November with a scheduled discharge (Feng et al., 2015). Due to the regulated water discharge, the flooding only affects the sites near the river bank (within a 100-m radius) (Liu et al., 2008). We conducted vegetation and soil sampling perpendicular to the river channel and sampled at distances of 100 m, 500 m, 1000 m, 1500 m, 2000 m, 2500 m, and 3000 m from the river channel. Five replicates were sampled at each distance from the river channel and a total of 35 sampling sites were established. These sites were far from farmlands, irrigated channels and reservoirs to minimize the impact of human disturbance and other water resources. Although there is a main road extending across the oasis and almost parallel to the river channel (Fig. 1), the vegetation community growing near the road is considered to be undisturbed by the road, as the road is separated from the surroundings by iron wire.

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

At each site, soil samples for soil moisture measurement were randomly collected in three replicates using an auger (5 cm in diameter) at 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180 and 200 cm deep. The soil samples were sealed in a freezer and the gravimetric soil water content (SWC) was determined via oven drying at 105 ℃ to a constant weight. Bulk density (BD) was measured by collecting undisturbed soil cores from the surface layer using a stainless-steel cutting ring (100 cm^3 in volume) with three replicates at each site, which were then oven dried at 105 ℃ to a constant weight. Soil samples were collected every 20 cm at a depth of 100 cm in each site to determine the soil composition and chemical properties. Surface soil samples (from a depth of 0–20 cm) were subsequently analyzed in the laboratory to determine their clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2 mm), and gravel (>2 mm) content using a Malvern Mastersizer 2000. Soil organic matter (SOM) was measured using the

$K_2Cr_2O_7$ method (Liu, 1996). Total nitrogen (TN) was determined using the Kjeldahl procedure (ISSCAS, 1978). Total phosphorus (TP) was determined using a UT–1810PC spectrophotometer (PERSEE, Beijing, China), after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). Total salt content (TS) was determined by oven method (Liu, 1996).

2.3 Temporal data collection and processing

To understand the long-term vegetation variation since the implementation of ecological water conveyance, we analysed NDVI data from 2000 to 2014. As the NDVI measures the vegetation status, including coverage and vigour, we used the maximum NDVI during growing season as the indicator of vegetation community characteristics (Wang et al., 2014). NDVI data during 2000–2014 were calculated using ENVI (5.0) based on the Landsat TM/ETM image (30 m) acquired from Geospatial Data Cloud (http://www.gscloud.cn/). We calculated the NDVI at each distance from the river channel based on the NDVI derived from the sampling sites. The variable environmental factors, such as 2 cm soil moisture, 100 cm soil moisture and groundwater at each site during the research period, were extracted from remotely-sensed data (1000 m resolution) (doi:10.3972/heihe.0034.2016.db), generated by the land model CLM4.5 using high-resolution ASTER DEM dataset, the multi-source integrated Chinese land cover map (MICLCover), the Heihe watershed allied telemetry experimental research land cover map (HiWATER Land Cover Map), and the China soil characteristics dataset (Zeng et al., 2016). The validation of the retrieved remote sensing data is provided in the Supplementary Material S4. Land use change information from 2000–2014 was extracted from land use data with a scale of 1:100,000 (for 2000 and 2014) (doi:10.3972/heihe.020.2013.db; doi:10.3972/hiwater.155.2014.db) (Zhong et al., 2015). The spatial variation of groundwater table was obtained from groundwater monitoring data recorded by seven wells (i.e., 7.62–9.66 m deep) in the Ejina oasis, located at 50 m, 300 m, 2200 m, 2700 m, 3200 m, and 3700 m from the river center (Fig. 1). These monitoring data of the groundwater table were recorded as 18-hour averages with a three decimal places accuracy using a HOBO automatic groundwater table gauge from October 2010 to December 2014 (Fu et al., 2014). The diurnal and annual variations of soil moisture were obtained from the monitoring data of soil moisture, recorded at 0.5 Hz, as a 10-min average from 2013–2015 using a suite of micrometeorological sensors (CR800, CR23X, CR23XTD, Campbell Scientific Inc.) installed at a site that is located within Heihe riparian forest, about 1500 m from the Heihe river channel (Fig. 1) (doi:10.3972/hiwater.241.2015.db;

doi:10.3972/hiwater.318.2016.db) (Liu et al., 2011). The retrieved remote sensing data, monitoring data, land use data, groundwater monitoring data and runoff data at Donghe station (i.e., a hydrological station in the downstream Heihe) (doi:10.3972/heihe.1009.2013.db) were acquired from the Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

2.4 Statistical analysis

The importance value (P), an index that characterizes the relative importance of plant species in the community (Zhang and Dong, 2010) was calculated for each species at each tree shrub and herb layer in every sampling site using the following formulas (Zhang, 2011):

$$P_{\text{Tree}} = (RDen + RDom + RH)/3 \tag{1}$$

$$P_{\text{Shrub or Grass}} = (RDen + RDom + RC)/3 \tag{2}$$

where P_{Tree} is the importance value in the tree layer. $P_{\text{Shrub or Grass}}$ is the importance value in the shrub or grass layer. *RDen* is the relative density, *RDom* is the relative dominance, *RH* is the relative height and *RC* is the relative coverage.

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

$$W_i = (C_i/C + h_i/h)/2 \tag{3}$$

where C is the total coverage of the community ($C = \sum C_i$); i = 1 for the tree layer, 2 for the shrub layer and 3 for the herb layer; h is the thickness of the leaf layer of various growth types ($h = \sum h_i$); W_i is the weighted parameter of the diversity index for the 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 the different growth types, the thickness of the tree leaf layer is calculated at 33.3% the height of the tree layer, the shrub layer at 50% and the herb layer at 100%.

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

$$A = \sum W_i A_i \tag{4}$$

where A is the total diversity index of the community; i = 1 for the tree layer, 2 for the shrub layer and 3 for the herb layer; W_i is the weighted parameters of the diversity index for the i^{th} growth type; A_i is the diversity index of the i^{th} growth type.

Species diversity indices were calculated (Liu et al., 1997), including the Shannon-Wiener diversity index (H)

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

Simpson dominance index (D) was calculated as

$$D = 1 - \sum_{i=1}^{s} P_i^2 \tag{6}$$

and Pielou evenness index (J_{sw}) was calculated as

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

Finally, Patrick richness index (R) was calculated as

$$R = S \tag{8}$$

where P_i is the relative importance value of the i^{th} species, and S is the total number of species in each growth type at each sampling site.

The least significant difference (LSD) test was used to determine the significance of the variability in vegetation characteristics among five transects (Supplementary Material S3, Table S2). For each distance from the river channel, vegetation community characteristics, soil moisture and soil properties of the five sites were calculated as the mean ± standard error (SE) of the mean. The monitoring data of soil moisture in desert riparian forest showed that soil moisture under 20 cm was relatively stable and could represent water condition at the sampling site (Fig. S1). Thus, to depict the water condition at the sampling sites and to illustrate 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 with the distribution of fine roots 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. The soil chemical properties, however, were analysed using the mean values of 0–100 cm due to the low vertical variation. The NDVI change rate was calculated based on the percentage change of NDVI from 2000 to 2014. The annual average value and annual variability were used to depict the temporal variation of community characteristics and environmental factors. The annual averages of NDVI (NDVI_a), groundwater (GWT_a), 2 cm soil moisture (SWC2cm_a) and 100 cm soil moisture (SWC100cm_a) were calculated using the mean values from 2000–2014. The annual variability of NDVI (NDVI_c), groundwater (GWT_c), 2 cm soil moisture (SWC2cm_c) and 100 cm soil moisture

(SWC100cm_c) were calculated using the mean values of change rate for each year.

Regression analysis was used to examine the variation pattern. Exponential and polynomial regressions were fit to the data to explain the statistical relationship between community characteristics and the distance from the river channel. Pearson correlation was used to determine the strengths of possible relationships between community characteristics and environmental factors. Significant differences were evaluated at the 0.05 and 0.01 levels. Statistical analysis was performed using SPSS (version 18.0).

Two-way indicator species analysis (TWINSPAN, in WinTWINSPAN, version 2.3), a method of community hierarchical classification (Hill, 1979), was used to classify the possible desert riparian forest community types. The importance value data for all plant species, obtained from the vegetation survey, were used in this analysis and the cutoff levels of the importance value for each class were set as: 0, 0.1, 0.2, 0.4, 0.6 and 0.9. To further separate the key influencing factors of the 18 environmental variables, the marginal and conditional effects of the various variables were calculated through Monte Carlo forward selection in RDA (redundancy analysis), which directly showed the significance and the percentage of vegetation variance explained by each factor. Marginal effects reflect the effects of the environmental variables on the community characteristics, while conditional effects reflect the effects of the environmental variables on the community characteristics after the anterior variable is eliminated by the forward selection method. Since the redundant variables are eliminated and a group of key environmental factors is identified through forward selection, this method allows key variables to be determined through the strength of their effects and significance. The variation of community characteristics explained by the different group of environmental factors was analysed 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 were performed using the software program CANOCO (ver. 5.0) (Microcomputer Power, USA) (Braak et al., 2012).

3 Results

3.1 Vegetation community types and temporal changes in vegetation composition

The species composition at each site in the downstream Heihe River Basin is shown in Table S1 in the

Supplementary Material, and the following five plant community types distributed across the 3000 m transect from the river channel were obtained based on the TWINSPAN classification (Fig. 2):

(i) Community I was an association of (Ass.) *Populus euphratica–Tamarix ramosissima* + herbs. Characterized by multiple layers of tree–shrub–herb, the community coverage was low (38.05%) and dominated by the tree species *Populus euphratica* with sparse understory vegetation. This community was mainly distributed near the river bank, mostly within 500 m from the river channel.

(ii) Community II was Ass. *Tamarix ramosissima–Lycium ruthenicum* + herbs. This community was composed of shrub and herb layers with high community coverage (81.43%). *Tamarix ramosissima* was the dominant shrub species of the shrub layer, while the herbs were dominated by both hygrophyte and xerophyte species, such as *Kochia scoparia* and *Peganum harmala*. This community was mainly distributed near the river bank (approximately 1000 m from the river channel).

(iii) Community III included *Tamarix ramosissima*. This community was mainly composed of shrub layers and dominated by *Tamarix ramosissima* with average community coverage of 75.93%. It was mainly distributed at the distance between 1000 m and 2000 m from the river channel.

(iv) Community IV was Ass. *Lycium ruthenicum–Tamarix ramosissima* + xerophyte herbs. This community was mainly composed of shrub and herb layers with average community coverage of 68.86%. *Lycium ruthenicum* was the dominant shrub species (importance value = 0.42–0.77), while the dominant xerophytic herb species were *Sophora alopecuroides* and *Suaeda salsa*. It was mainly distributed between 1500 m and 2500 m from the river channel.

(v) Community V was Ass. *Tamarix ramosissima–Lycium ruthenicum–Reaumuria soongarica*. This community was the transition community from desert riparian shrub forests to desert shrubs, indicated by the presence of *Reaumuria soongarica*, a typical desert shrub. *Tamarix ramosissima* was the dominant species of the shrub layer, mainly existing in the form of shrub dunes. This community was mainly distributed approximately 2500–3000 m from the river channel, with low community coverage (54.40%).

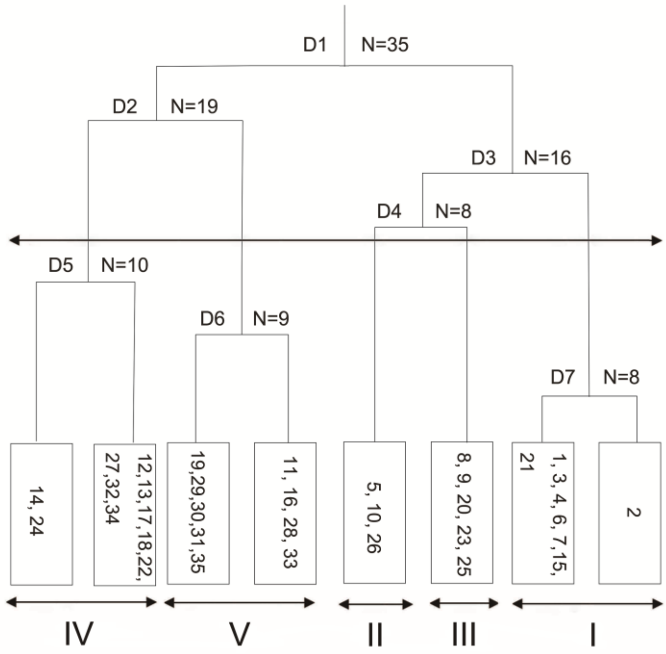

Figure 2. The dendrogram of the sampling sites based on the TWINSPAN classification.

Notes: Numbers 1–35 represent the site numbers of the sampling sites. D indicates the classification levels, and N indicates the number of sampling sites for the classification. I to V represent communities I to V. Arrows indicates that all the sites were divided into five major groups after the fourth classification.

Between 2000 and 2014, changes in the vegetation composition of each community type (I to V) were obtained from changes in the land use map (Fig. 3). Among the five community types, community V underwent the most changes, with 22.22% of the sites changing from sparse forest to grassland, 22.22% from grassland to shrubland and 22.22% from bareland to grassland. The majority (>60%) of the vegetation composition remained unchanged in communities I to IV, with the following exceptions: (i) 37.5% of the sites in community I changed from shrubland to sparse forest and from bareland to grassland, (ii) 33% and 20% of the sites in communities II and III changed from bareland to grassland and from sparse forest to grassland, respectively, and (iii) 20% of the sites in community IV changed from sparse forest to grassland and another 20% from grassland to shrubland (Fig. 3).

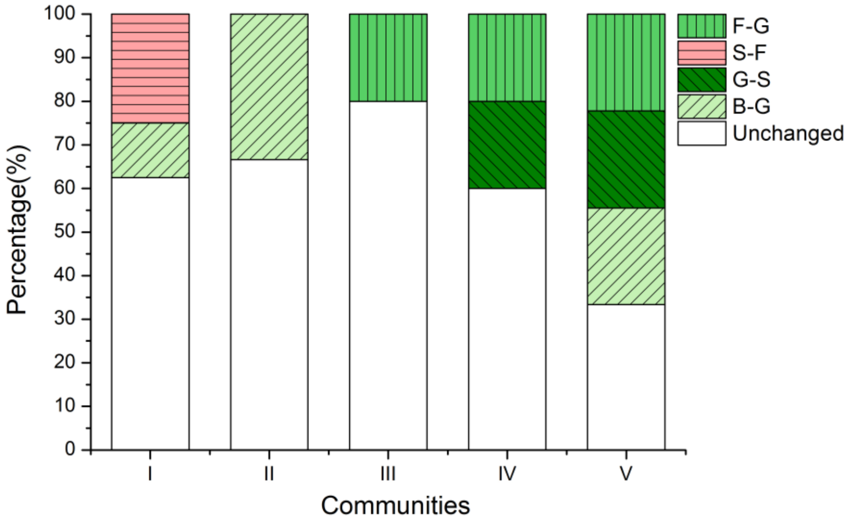

Figure 3. The percent changes of vegetation composition in each community from 2000–2014.

Notes: F–G: change from sparse forest to grassland; S–F: change from shrubland to sparse forest; G–S: change from grassland to shrubland; B–G: change from bareland to grassland.

3.2 The spatial distribution and temporal variation of community characteristics in desert riparian forest

Community characteristics varied with distance from the river channel (Fig. 4). Vegetation community height and density dropped rapidly after 500 m (Fig. 4a, b), while community coverage formed a bimodal pattern, peaking at the distances of 500–1000 m and 3000 m (Fig. 4c). The variation of vertical structure was depicted by the following hierarchical coverage (Fig. 4d): (i) the tree layer mainly existed within 1000 m, (ii) the shrub layer peaked at approximately 1500–2000 m, and (iii) the herb layer fluctuated with distance from the river channel, peaking at 500 m and 2500–3000 m from the river channel. All diversity indices showed a bimodal pattern with distance from the river channel. The Shannon-Wiener diversity index, Pielou evenness index and Patrick richness index peaked at 1000 m and 3000 m (Fig. 4e–g). Simpson dominance index, however, formed an opposite trend to the other three diversity indices, by peaking at 500 m and 2000 m, where the other indices were at their low level (Fig. 4h).

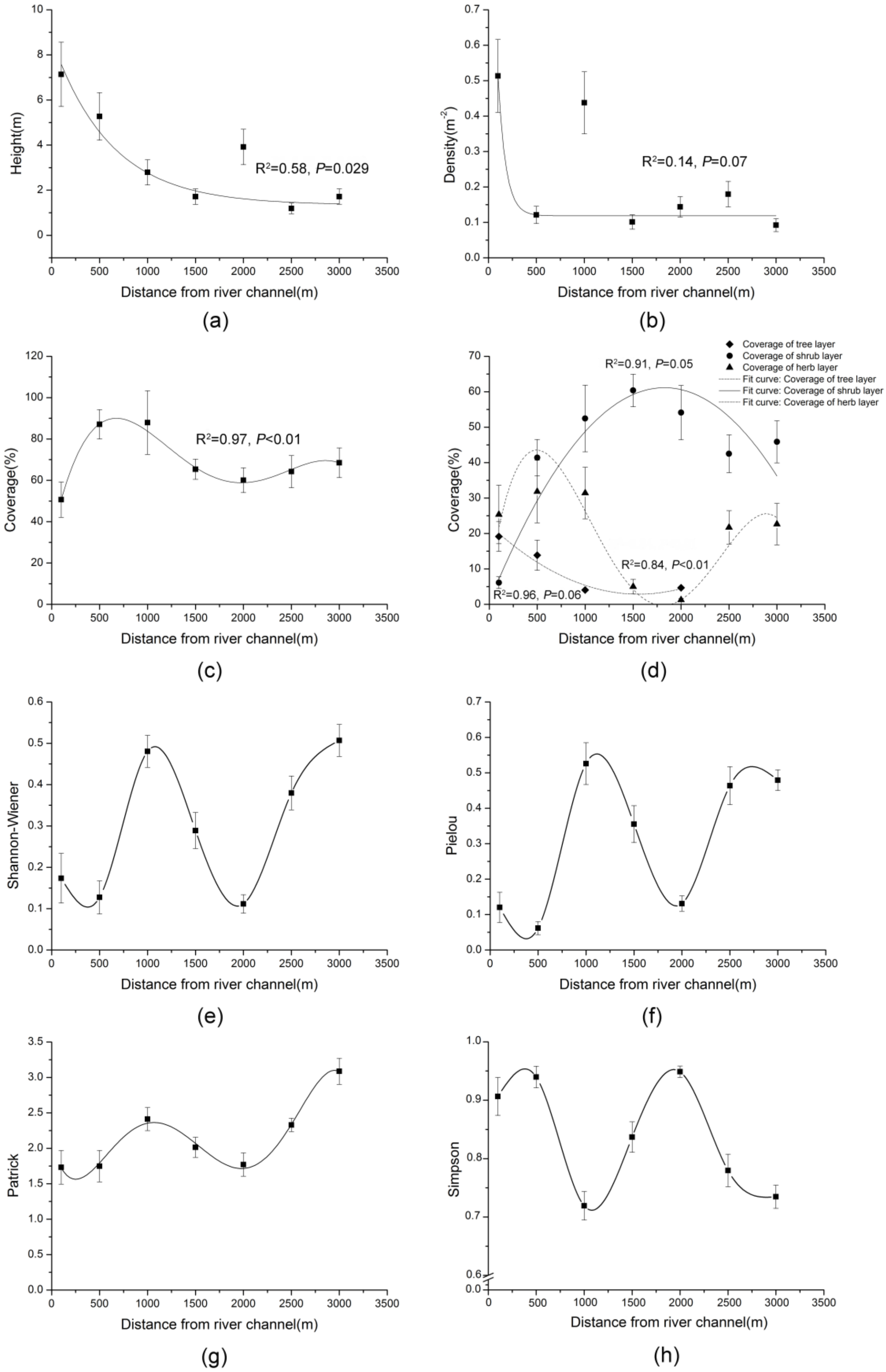

Figure 4. The variation of community structure and diversity with distance from the river channel.

The temporal variation in community characteristics was depicted by the variation in NDVI (Fig. 5). At different distances from the river channel, the NDVI showed an increasing trend throughout the research period except for a small decrease during the initial years (2000–2002). The NDVI decreased with distance from the river channel, peaked at 100 m and 500 m from the river channel, and reached the lowest values at the furthest distance from the river channel (3000 m) (Fig. 5a). The annual variability in the NDVI, however, showed a contrasting trend, increasing with distance from the river channel (Fig. 5b).

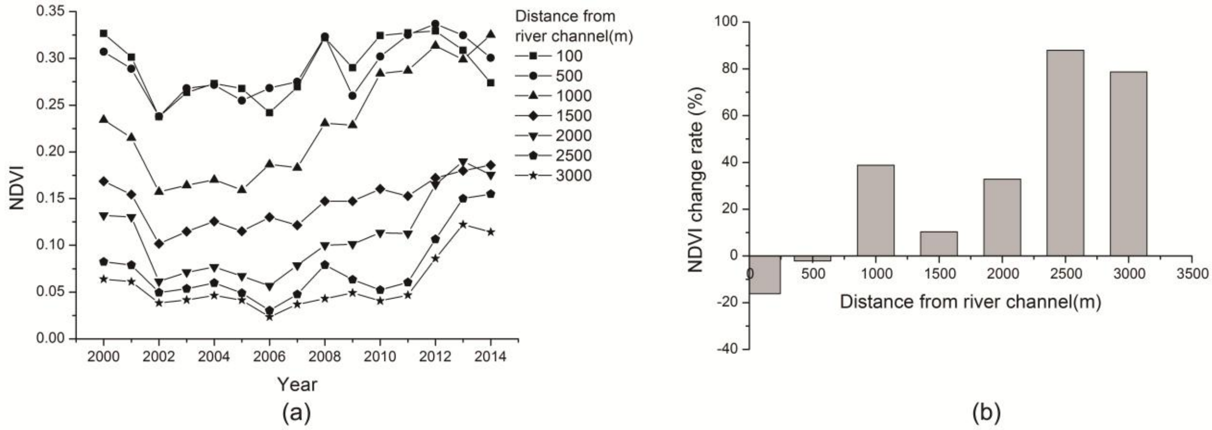

Figure 5. The temporal variations of NDVI (a) and annual variability of NDVI (b) from 2000 to 2014 at different distances from the river channel.

3.3 Pearson correlation between community characteristics and environmental factors

The result of the Pearson correlation analysis between community characteristics and environmental factors is shown in Table 1. The community density showed significant positive correlations with SWC2, SWC3, SWC2cm_a and SWC100cm_a, but negative correlations with BD and GWT_a. The community coverage was positively correlated with all the three soil moisture layers (P<0.0.1) but negatively correlated with BD. The tree and shrub layers were influenced by GWT_a and BD, respectively, while the herb layer was positively correlated with SWC1 and SCW3. Among the diversity indices, the Patrick richness index was significantly correlated with SOM and gravel, while Simpson dominance index was significantly correlated with sand and silt. For the temporal variation of community characteristics, NDVI_a was mainly influenced by soil moisture (SWC1, SWC2 and SWC3), soil particle composition (clay, gravel) and bulk density, while NDVI_c was significantly correlated with SWC3, gravel and TS.

The correlation coefficient between NDVI and runoff was measured to examine the relationship between runoff and NDVI (Fig. 6). The relationship between runoff and the NDVI of the following year was significantly stronger than the relationship between runoff and the NDVI of the same year, indicated by the higher correlation coefficient and significance in the one-year lag NDVI–runoff correlation compared to the NDVI–runoff correlation.

Table 1. Pearson correlations between community characteristics and environmental factors.

	H	R	C	J_{sw}	Height	Density	Cover-a	Cover-t	Cover-s	Cover-h	NDVI_a	NDVI_c
SWC1	0.255	0.167	-0.286	0.182	-0.088	0.251	**0.545**	-0.017	0.168	**0.514**	**0.430**	0.188
SWC2	0.046	-0.072	-0.098	0.067	-0.114	**0.382**	**0.439**	0.007	0.280	0.263	**0.469**	0.254
SWC3	0.142	0.157	-0.147	0.111	-0.242	**0.362**	**0.448**	-0.142	0.175	**0.382**	**0.445**	**0.506**
Clay	0.112	0.005	-0.128	0.045	0.048	0.290	0.204	0.037	-0.093	0.272	**0.398**	0.125
Silt	0.308	0.117	**-0.344**	0.311	-0.121	0.111	0.321	-0.071	0.247	0.168	0.185	-0.115
Sand	-0.327	-0.148	**0.354**	-0.306	0.130	-0.165	-0.307	0.076	-0.166	-0.217	-0.212	0.125
Gravel	0.226	**0.350**	-0.155	0.179	-0.284	-0.081	-0.185	-0.173	-0.179	0.011	**-0.413**	**-0.396**
BD	0.174	0.282	-0.127	0.123	-0.041	**-0.353**	**-0.350**	0.049	**-0.465**	0.063	**-0.354**	-0.050
SOM	-0.256	**-0.398**	0.187	-0.102	0.193	0.058	-0.192	0.116	-0.121	-0.296	-0.025	-0.009
TN	-0.191	-0.333	0.138	-0.060	0.101	0.032	-0.278	0.112	-0.296	-0.223	-0.006	0.108
TP	-0.238	-0.303	0.198	-0.098	0.116	0.022	-0.181	0.084	-0.090	-0.288	-0.018	0.194
TS	-0.139	-0.125	0.111	-0.099	-0.184	0.271	0.011	-0.086	0.034	-0.131	-0.140	**0.382**
GWT_c	0.094	-0.028	-0.133	0.228	-0.074	0.001	-0.137	0.102	-0.060	-0.189	-0.286	0.040
SWC2cm_c	0.113	0.085	-0.117	0.084	-0.161	0.098	-0.027	-0.093	-0.029	-0.024	-0.177	0.119
SWC100cm_c	0.171	0.185	-0.165	0.109	-0.116	-0.080	0.073	-0.096	0.107	0.038	-0.198	0.141
GWT_a	-0.022	-0.226	-0.050	0.127	0.300	**-0.343**	-0.092	**0.352**	0.017	-0.131	0.042	0.004
SWC2cm_a	-0.169	-0.270	0.129	-0.096	0.013	**0.405**	-0.184	0.103	-0.224	-0.183	0.160	0.144
SWC100cm_a	-0.085	-0.194	0.047	-0.014	-0.094	**0.403**	-0.137	-0.046	-0.206	-0.150	0.090	0.140

Notes: Significant correlations with P<0.05 and P<0.01 are shown in bold and in bold with underline, respectively. H, Shannon-Wiener diversity index; R, Patrick richness index; C, Simpson dominance index; J_{sw}, Pielou evenness index; a, total plant community; t, tree layer; s, shrub layer; h, herb layer; NDVI_a, annual average of NDVI; NDVI_c, average annual variability of NDVI; SWC1, 0–30 cm soil moisture; SWC2, 30–100 cm soil moisture; SWC3, 100–200 cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content. GWT_a, annual average of groundwater table; SWC2cm_a, annual average of 2 cm soil moisture; SWC100cm_a, annual average of 100 cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2 cm soil moisture; SWC100cm_c, annual variability of 100 cm soil moisture;

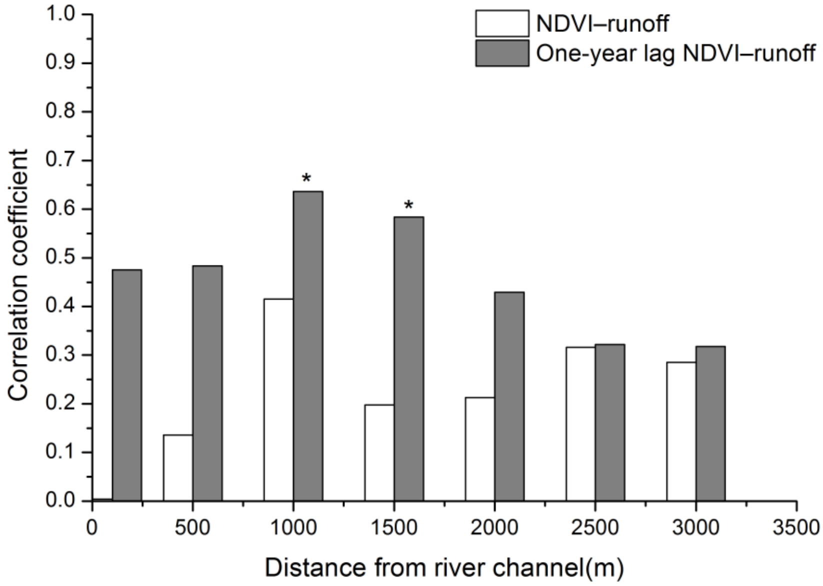

Figure 6. Pearson correlation coefficients of NDVI–runoff and one-year lag NDVI–runoff at different distance from the river channel.

Notes: * above the bar indicates significant correlations (P<0.05).

3.4 Key environmental factors that influenced community characteristics

To further examine the key environmental factors that controlled the variation in the vegetation indices, redundant variables were eliminated by a forward selection method. Table 2 shows the key influencing factors based on the marginal and conditional effects of 18 variables under the Monte Carlo test in the process of forward selection. All the environmental factors explained 74% of the total variance. In the Monte Carlo test of forward selection ($P<0.05$), SWC1, SWC3, BD and SWC100cm_a were regarded the key environmental factors that influenced the variation of community characteristics. Spatial heterogeneity factors explained 43.5% of the variation of community characteristics and accounted for 98.4% of the variance explanation explained by all the investigated environmental factors (Table 3). This result indicated that spatial heterogeneity of environmental factors was the major driving force of the spatio-temporal variation in this desert riparian forest. In contrast, temporal variation factors only explained 15.9% of the variation of community characteristics, accounting for 35.9% of the total explanation that was explained by all the investigated environmental factors (Table 3). This result suggested that temporal variation of the environmental factors exerted less impact on community characteristics compared to spatial heterogeneity of environmental factors in this desert riparian forest. While each factor group affected community characteristics separately, the spatial heterogeneity factors and temporal variation factors also jointly shaped the variation of community characteristics in downstream Heihe riparian forest. When combined, these factors explained 15.2% of the community characteristics variation, accounting for 34.3% of the total explanation that was explained by all the investigated environmental factors (Fig. S7).

Table 2. The selection of the key influencing factors based on the marginal and conditional effects obtained from the forward selection of the Monte Carlo test.

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	0.002	27.03
SWC3	18.8	SWC3	14	0.004	18.92
SWC2	12.3	BD	10	0.006	13.51
BD	11.4	SWC100cm_a	9	0.018	12.16
TN	7.1	GWT_a	4	0.078	——
Silt	7.0	GWT_c	3	0.096	——
Sand	6.1	TP	2	0.250	——
SOM	4.1	Clay	2	0.282	——
Clay	3.8	TN	2	0.296	——
SWC2cm_a	3.7	SWC2cm_a	2	0.308	——
TP	3.6	SWC100cm_c	1	0.444	——
Gravel	2.6	SWC2cm_c	3	0.112	——
SWC100cm_a	2.5	SWC2	1	0.620	——
GWT_c	1.8	Silt	1	0.636	——
GWT_a	1.4	TS	<0.1	0.788	——
SWC100cm_c	0.6	SOM	<0.1	0.932	——
TS	0.5	Sand	<0.1	0.992	——
SWC2cm_c	0.1	Gravel	<0.1	0.960	——
		Total	74	0.036	——

Notes: *R* value represents the relative proportion of individual explanation to the total variance explanation.

SWC1, 0–30 cm soil moisture; SWC2, 30–100 cm soil moisture; SWC3, 100–200 cm soil moisture; BD, bulk density; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; TS, total salt content. GWT_a, annual average of groundwater table; SWC2cm_a, annual average of 2 cm soil moisture; SWC100cm_a, annual average of 100 cm soil moisture; GWT_c, annual variability of groundwater table; SWC2cm_c, annual variability of 2 cm soil moisture; SWC100cm_c, annual variability of 100 cm soil moisture.

Table 3. The percentage of community characteristic variation explained by different groups of environmental factors.

Fraction	Variation	% of all	% of explained	F	*P*
a	0.435	43.5	98.4	5.9	0.008
b	0.159	15.9	35.9	4.0	0.088
c	0.152	15.2	34.3	2.2	0.016
Total explained	0.442	44.2	100	——	——

Notes: a: spatial distribution factors, including 0–30 cm soil moisture (SWC1), 30–100 cm soil moisture (SWC2), 100–200 cm soil moisture (SWC3), bulk density (BD), clay, silt, sand, gravel, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total salt content (TS); b: temporal factors, including annual average of groundwater table (GWT_a), annual average of 2 cm soil moisture (SWC2cm_a), annual average of 100 cm soil moisture (SWC100cm_a), annual variability of groundwater table (GWT_c), annual variability of 2 cm soil moisture (SWC2cm_c), annual variability of 100 cm soil moisture (SWC100cm_c); c: variation that jointly explained by group a and b. 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 spatial distribution in Heihe desert riparian forest and its influencing factors

In the downstream Heihe River Basin, community height and density declined significantly as the dominant species changed from trees to riparian-desert shrubs with increasing distance from the river channel. Community coverage reached two local maxima at 1000 m and 3000 m from the river, with diverse shrub and herb layers. The spatial distribution of community diversity can illustrate how vegetation responds and interacts with numerous environmental factors along different ecological gradients (Oksanen and Minchin, 2002). Different from studies in the relatively humid regions (e.g., coastal regions or boreal forest), which suggest that riparian forest species diversity either decreases or forms a unimodal pattern with increasing distance from the stream (Pabst and Spies, 2011; Macdonald et al., 2014), our findings in the downstream Heihe (i.e., hyperarid conditions) showed that community diversity formed a bimodal pattern along the distance from the river channel. We attributed fine-textured soils found in the upper soil layer to the high species diversity at sites located about 1000 m from the river channel. Previous study shows that fine-textured soils increase the soil water holding capacity and improve the gravimetric moisture content in the upper soil layer, which provide suitable habitat for the growth of diverse herb species with shallow rooting systems (Liu et al., 2008). At the same time, other study find that the presence of the deep-rooted tree, *Populus euphratica*, can redistribute deep soil water to the shallow layer as a strategy of mutualism, benefiting the growth of shallow-rooted herbaceous species (Hao et al., 2013). Similar mechanism also occurs at further distance (i.e., 3000 m) from the river. Although situated in the transition region (from riparian forest to desert shrubs), soils at the distance of

3000 m from river channel were still rich in fine particles (clay and silt; 35.6%) (Table S3), brought by the interaction between wind erosion and shrubs (Ravi et al., 2009). The presence of fine soil particles can increase the soil water holding capacity and soil nutrients around the shrub patches (‘fertile islands’) (Ravi et al., 2010), allowing the growth of some xerophytic herbs and increasing the community diversity in arid region (Stavi et al., 2008). By contrast, Simpson dominance index peaked at the distances of 500 m and 2000 m (Fig. 4 h), likely due to inter-species competition for water and nutrient resources reported by previous studies (Maestre et al., 2006). At these sites, dominant species with high importance value (i.e., trees and shrubs at 500 m and 2000 m, respectively) often has high competition for resources, thus, hindering the growth of other species (i.e., herbs) and increasing the dominance index of the community (Koerselman and Meuleman, 1996).

Among different environmental factors, changes in water availability associated with soil properties are considered to be the most important selective forces which shape ecosystem stability in hyperarid zones (Rosenthal and Donovan, 2005, Ravi et al., 2010, Feng et al., 2015). Our study showed that spatial heterogeneity of soil properties was the major driving force for the spatial distribution of vegetation, with SWC1, SWC3 and BD contributing 59.46% of the total explanation of vegetation variance (Table 2). As the fine roots of most herb species are mainly distributed within the top 30 cm of the surface soils (Fu et al., 2014), surface soil moisture (0–30 cm soil moisture; SWC1) likely became the main water source for the herb layers and contributed to a high coverage of dominant herb species, such as *S. alopecuroides* and *K. caspica*. Meanwhile, deep soil moisture (SWC2 and SWC3) mainly influenced the community density and coverage. SWC2 (30–100 cm soil moisture) is the main water resource for shrubs such as *T. ramosissima*. SWC3 (100–200 cm soil moisture), recharged by the flood-raised groundwater table (Liu et al., 2015), is the main water source for phreatophytes such as *P. euphratica* or desert shrubs (Yi et al., 2012). As trees and shrubs contributed greatly to community composition, the increase in SWC2 and SWC3 could significantly promote vegetation growth, community density and coverage.

Apart from soil moisture, soil physical properties were also important in determining the spatial distribution of vegetation community in our study. Bulk density and soil composition (clay, silt, gravel), which are critical for water and nutrient holding capacity (Stirzaker et al., 1996; Meskinivishkaee et al., 2014), mainly influenced community density, community coverage, shrub coverage and diversity indices (Table 1). Previous study shows that soil with low bulk density usually has high water and nutrient holding capacity associated with fine soil particles as opposed to soil with high bulk density (Ravi et al., 2010). Low water holding capacity associated with coarse soil particles can induce water stress and limit vegetation growth, especially for herb species, which contribute greatly to community coverage, density and diversity (Stirzaker et al., 1996). Interestingly, we found that soil nutrients explained no more than 0.1% of the vegetation variance and that SOM (soil organic matter) was negatively correlated with the species richness (Table 1, Table2). Our findings were different from the positive relationship commonly found between SOM and species richness in semiarid zones (e.g., the Loess Plateau) (Jiao et al., 2011; Yang et al., 2014). Although SOM determines soil nutrient storage and the supply of available nutrients, our sites in the hyperarid zone were characterized by barren soil with less than 1% SOM (Fig. S5d, Table S3). Such a low amount of SOM might not be able to boost the growth of various species in desert riparian forests. At the same time, the dominant species (i.e., *P. euphratica* and *T. ramosissima*), despite producing a high amount of litter, also has high competition for resources, hindering the diversity and growth of other species (Su, 2003).

4.2 The temporal variation in Heihe desert riparian forest and its influencing factors

Our results showed that NDVI generally increased since the implementation of the ecological water conveyance project in 2000, except for an initial decrease between 2000 and 2002, likely due to the lagging effect and the relatively low amount of runoff during these years (Jin et al., 2008). With better water availability (e.g., increased surface soil moisture and groundwater table), the conversion of sparsely forested land or bareland to shrubland and grassland likely contributed to the increase of NDVI, especially at the furthest distance from the river (2000–3000 m) (Fig. 3). By contrast, NDVI near the river bank underwent a slight decrease during some recent years (2012–2014) (Fig. 5), likely due to the conversion of shrubland to sparse forest land (Fig. 3). Other factors such as increasing grazing pressure and tourism pressures as reported by Hochmuth et al. (2014), may also contribute to the decrease in NDVI around the periphery of the river.

Our results indicated that the NDVI at different distances from the river channel was affected by the spatial heterogeneity of soil properties, particularly soil moisture and bulk density, explaining 45.95% and 13.51% of the vegetation variance respectively (Table 2). All three soil moisture layers (SWC1, SWC2 and SWC3) positively affected the annual average of NDVI (NDVI_a) by supplying water to both shallow- and deep-rooted riparian vegetation (Fu et al., 2014). Deep soil moisture (SWC3), recharged by the increasing groundwater table, is particularly important for the shrub and tree layers (e.g., *P.*

euphratica and *T. ramosissima*) (Yi et al., 2012), which contributed largely to the increase rate of NDVI in Heihe desert riparian forest. Bulk density accounted for 13.51% of the total explanation of the vegetation variance and was negatively correlated with the annual average of NDVI (NDVI_a) and the annual variability of NDVI (NDVI_c). Study shows that, in the hyperarid zone, soils with high bulk density are often characterized by a high proportion of coarse soil particles but low clay content (Ravi et al., 2009). In general, low water holding capacity in the upper soil layer may constrain the growth of shallow-rooted vegetation, lower the average NDVI and inhibit the NDVI increase.

Apart from soil, the temporal variation in runoff driven by the ecological water conveyance played an important role in influencing the annual variability of the NDVI in this desert riparian forest. However, the correlation between runoff and NDVI was stronger with that of the following year than that of the same year (Fig. 6), consistent with previous findings (Jin et al., 2010) which indicate the lagging effects of runoff. The lagging effects were unsurprising, considering that the increase in runoff needs to undergo a series of hydrological (e.g., seepage, interflow, groundwater movement) and ecological processes (e.g., vegetation water uptake and water utilization) to increase groundwater, soil moisture, and vegetation growth (Williams et al., 2006; Liu et al., 2012). Compared to the significant relationship between the spatial heterogeneity of soil moisture (e.g., SWC3) and the annual variability of NDVI (i.e., NDVI_c) (Table 1), there was weaker relationship between the annual variability in water availability (i.e., SWC2cm_c, SWC100cm_c, GWT_c) and the annual variability of NDVI (i.e., NDVI_c). We suggested that a combination of hydrological and ecological processes in the Heihe riparian zone may result in a more stable increase of groundwater and soil moisture during 2000–2014 (Fig. S6a, b, c) compared to the amount of runoff that showed significant annual fluctuations (Fig. S6d), thus contribute less to the NDVI variability. In addition, temporal variation of soil moisture and groundwater was derived from retrieved remote sensing dataset. The deviations between simulations and observations in temporal variation of soil moisture and groundwater could also partly account for its weak correlations with the community characteristics.

Compared to the spatial heterogeneity of the soil properties, the temporal variation factors only accounted for 35.9% of the total explanation (Table 3). Except for the possible influence of the accuracy of the retrieved remote sensing dataset, lack of data regarding the temporal variation of soil properties could also partly accounted for the low explanatory power of temporal influencing factors. Although studies show that most of the physical and chemical properties of the soils remain unchanged during the

15 years' ecological restoration (Cao et al., 2010; Chen et al., 2014), some of those soil properties, such as soil organic matter, might change due to vegetation recovery during ecological restoration. Future studies that include the temporal variation in soil properties might therefore be required to comprehensively address how temporal variation in environmental factors impacts on vegetation variation.

4.3 Community resilience of desert riparian forests and implications for ecological restoration

Although community diversity was generally low at most sites in the downstream Heihe River Basin, our findings suggested that there were some sites with significantly higher community diversity, for example those at distances of 1000 m and 3000 m from the river channel (Fig 4). Consistent with other finding (Hao et al., 2013), high resistance to water stress was observed at these distances from the river channel, with trees and shrubs can lifting water up from the deeper to shallower layers as a strategy for mutualism. Different species contribute differently to the ecosystem functions (e.g., trees and shrubs with large crowns mainly contribute to sand fixation, while diverse herbs contribute to biodiversity), maintaining a stable habitat after drought stress and/or human disturbance (Krieger et al., 2001). Indeed, species-rich communities can maintain ecosystem functions during stress-based perturbations due to the complementary of functional traits and ecological redundancy (Luck et al., 2013; Isbell et al., 2015).

In contrast, communities at the other distances from the river channel could easily undergo degradations, such as that at the distance of 500 m from the river channel, indicated by the decreasing NDVI in recent years (Fig. 5a). Exposure to human disturbance (e.g., tourism, grazing) may exacerbate the effects of projected rise in temperature and drought frequency in regions that are far from the river channel and experience the limited influence of ecological water conveyance (Si et al., 2005; Zhang et al., 2015a) by changing soil physical properties and reducing ecosystem services such as water and soil conservation (Zhao et al., 2012; Daryanto et al., 2013). Our study showed that water availability and spatial heterogeneity of soil properties were the main driving forces for the spatial distribution and temporal variation of restored desert riparian forest at Heihe River Basin. To halt degradation in this critical zone, we suggested to build natural channels perpendicular to the river to fully extend the influencing scope of the ecological water conveyance and benefit the regions far from the river bank (Zhang et al., 2011b). At the same time, multiple conservation measures such as establishing critical fenced areas for ecological protection and constructing artificial shields or establishing straw checker boards on the bare land to prevent erosion, were recommended around the periphery of the river.

5 Conclusions

Through extensive field observations at multiple desert riparian forest locations and analyses of long-term remote sensing images, we found that community characteristics differed spatially and temporally with distance from the river channel. In locations with high diversity indices, high community resilience could be maintained by the multiple interactions between vegetation and soil properties. In contrast, regions with low diversity might face greater challenges under climate change and intensive human disturbance. Since the influence of ecological water conveyance is currently limited to a distance of 1000–2000 m from the river (Si et al., 2005; Zeng et al., 2016), extending the distance of ecological water conveyance was recommended to recharge the surface soil moisture and benefit the growth of ground cover (i.e., herb species), which contribute greatly to species diversity. In addition, multiple conservation measures that protect the soil structure (e.g., artificial soil cover and livestock grazing exclusion) were recommended for regions close to the river to reduce the adverse effects of grazing on soil properties.

Data availability. The spatial field experiment data in this study was available on request. The temporal data used in this study were obtained from reliable public data repositories. Landsat TM/ETM image (30 m) were acquired from Geospatial Data Cloud (http://www.gscloud.cn/). The retrieved remote sensing dataset, land use data, soil moisture monitoring data, groundwater monitoring data and runoff data were obtained from the Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn).

Competing interests. The authors declare that they have no conflict of interest

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