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Relationship Between Soil Properties and Plant Diversity in a Desert Riparian Forest in the Lower Reaches of the Tarim River, Xinjiang, China

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*Based on data from soil characteristics of 217 soil samples collected from 31 soil profiles that were located at eight monitoring sections in the lower reaches of the Tarim River in southern Xinjiang, we analyzed the spatial distribution of soil properties using nonparametric tests and ANOVA. Plant species diversity was analyzed based on vegetation data that were collected over several years. In addition, the study also examined the relationship between plant species diversity and soil parameters by using grey correlation analysis. The results show a significant difference ($p < 0.05$) in soil organic matter, total N, and total K between the top layer (0–50 cm) and the deep layers (>50 cm). Along the different monitoring sections, going from the upper to the lower reaches at locations of 150 m away from the right riverbank of the Tarim River, the plant species diversity index (Shannon–Weiner index) has the same trend as total N. Furthermore, plant communities change from compound communities to a single community corresponding to the changes in plant species diversity—namely, from the communities composed of trees (*Populus euphratica* Oliv.), shrubs (*Tamarix* spp), and herbs to a pure *Tamarix* community. Grey correlation analyses indicated that significant relationships exist between plant species diversity, soil organic matter, and total N at the 0–50 cm soil layer.*

Keywords grey correlation, plant diversity, riparian forest, soil, vegetation

In the ecosystem, soil and vegetation resources are closely integrated. Changes in plant diversity are known to affect above-ground ecosystem functioning (Spehn et al., 2000; Tilman et al., 2001). Changes in plant species composition during

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ecological succession are believed to be reflections of gradients from high-light/low-nutrient conditions early in succession to low-light/high-nutrient conditions later (Tilman, 1986). At present, many scholars recognize that plant diversity has an obvious influence on ecosystems, and generally agree that the availability of soil nutrients changes during ecological succession, but there is considerably less agreement on the direction and significance of such changes (Vitousek, Matson, and Cleve, 1989). However, information is lacking on the relationship between soil parameters and species diversity, especially for the arid regions in western China.

The desert riparian forest is an important vegetation type for the inland river valley in the arid zone, which dominates the riparian ecosystems as well as the landscape patterns of vegetation. In the lower reaches of the Tarim River, the riparian forest is named the “green corridor” and has great capacity for breaking wind and fixing sand. The natural riparian vegetation of tree, shrubs, and herbage grew liable to flooding or disappeared with the change of the river course. However, because of the increasing population in the region and large-scale exploitation of water and soil resources in the upper and middle reaches of the Tarim River over the last 50 years, stream flow in the mainstream of the Tarim River had been reduced substantially since the 1960s. For example, the annual stream flow at Kala was reduced by 80%, from $11.6 \times 10^8 \text{ m}^3$ in the 1950s to $2.35 \times 10^8 \text{ m}^3$ in the 1990s (Liu and Chen, 2006). A stretch of 321 km in the lower reaches of the Tarim River has dried up since the 1970s, which has subsequently resulted in a severe drawdown of the groundwater table, and concomitantly, a serious degeneration of the natural riparian forests. Numerous studies have addressed the ecological problems of the riparian forests, such as their distribution pattern, ecological characteristics, species composition, and habitat stability (Wang, Wang, and You, 2002; Zhang, Chen, and Pan, 2005). However, very little comprehensive research has been reported on soil property in relation to the ecological and environmental conditions of degraded riparian forests, especially in regard to the relationships between plant species diversity and soil properties.

In this article, soil properties and their relationship to plant species diversity were analyzed based on data derived from vegetation and soil properties in the desert riparian forest in the lower reaches of the Tarim River, in southern Xinjiang, China. The main objectives of this investigation were to: (i) interpret and evaluate the soil properties towards obtaining a systematic picture of the status quo of soil in the desert riparian forest; (ii) investigate ground vegetation composition and diversity; and (iii) explore whether relationships exist between them and then quantify the degree to which soil characteristics are closely related to variability in the desert riparian forest vegetation composition and diversity.

Materials and Methods

Study Area Description

The Tarim River basin, with an area of $1,020,000 \text{ km}^2$, covers the entire southern part of Xinjiang in western China (Figure 1). The main channel of the Tarim River is 1321 km in length, and covers an area of $17,600 \text{ km}^2$. Our study area is a 321 km section located between the Daxihaizi Reservoir and Taitema Lake in the lower reaches of the Tarim River ($39^\circ 38' - 41^\circ 45' \text{ N}$, $85^\circ 42' - 89^\circ 17' \text{ E}$). The channel bed stretches from west to east on alluvial fans along the Taklimakan Desert and the Kuluke Desert. The alluvial plain of the Tarim River is built up by thick quaternary

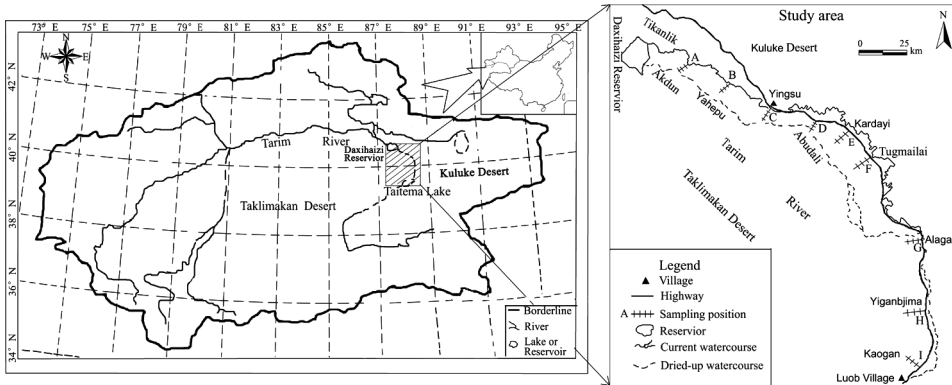


Figure 1. Map showing the study area and the distribution of the sections.

deposits. The deposits consist of fine sand in the upper layer and clay and silt in the deeper layer. According to the USDA soil classification system, the soil of the lower Tarim River is a member of the Aridisol order. The landscape comprises a desert riparian forest on a flat floodplain with slopes up to 3% (altitude 816–852 m a.s.l.) (Liu, 2000). The environmental gradients, especially groundwater level, gradually decline away from the river. The region is classified as an extremely arid and warm temperate zone, and it is windy and dusty. The dry environmental conditions are responsible for the fragility and instability of the ecosystems in the area. Total annual solar radiation varies between 5692 and 6360 MJm⁻², with cumulative daylight hours ranging from 2780 to 2980. Annual accumulative temperature ≥ 10°C varies between 4040 and 4300°C, with an average diurnal temperature ranging from 13 to 17°C. The average temperature for January is 10°C and for July, 26°C. Annual precipitation averages less than 50 mm, but potential annual evaporation is estimated to be in a range from 2500 to 3000 mm. Obviously, plant growth cannot be maintained by relying on natural precipitation only. Among the flora are trees, shrubs, and herbage (Huang, 1993). The community structure is simple and major plant species are listed in Table 1.

Table 1. The major plant species of the desert riparian forest along the lower reach of Tarim River

Family	Plant species	Life form
Salicaceae	<i>Populus euphratica</i> Oliv.	Tree
Tamaricaceae	<i>Tamarix</i> spp.	Shrub
Solanaceae	<i>Lycium ruthenicum</i> Murr.	Shrub
Leguminosae	<i>Halimodendrom halodendron</i> (Pall.)Voss.	Shrub
	<i>Alhagi sparsifolia</i> (B. Keller et Shap.) Shap.	Shrub
	<i>Glycyrrhiza inflata</i> Batal.	Perennial herbage
Gramineae	<i>Phragmites australis</i> (Cav.) Trin.ex Steud.	Perennial herbage
Apocynaceae	<i>Apocynum venetum</i> L.	Perennial herbage
Compositae	<i>Karelinia caspica</i> (Pall.) Less.	Perennial herbage

Sample Sites

Nine study sections were established for monitoring plant at intervals of approximately 20–45 km along the channel between the Daxihaizi Reservoir and Taitema Lake (Figure 1): Akdun (A), Yahepu (B), Yinsu (C), Abudali (D), Kardayi (E), Tugmailai (F), Alagan (G), Yiganbjima (H), and Kaokan (I). All sections run perpendicular to the main channel. At each section, two to three measurement plots were established at 150 m or 200 m intervals along a transect perpendicular to the river based on plant community and species type. In this study, we used data from 23 fixed measurement plots in all at eight sections (B, C, D, E, F, G, H, I). Specifically, the measurement plots were located, respectively, at 150 m, 300 m, and 500 m away from the right riverbank in each of the eight sections. In particular, no plot was established at 500 m in Kaokan (I). Within the center of the plot, soil profiles were excavated. Specifically, two profiles were excavated in the plot located at 150 m and one profile was excavated in the plots located at 300 m and 500 m from each site. In all, 31 soil profiles were excavated.

Vegetation Investigation and Soil Sampling

Vegetation investigations were carried out consecutively in the fixed measurement plots in July of 2002, 2003, 2004, and 2005. Plant species composition and abundance were measured. The size of each plot was 50 m × 50 m for mixed communities of trees, shrubs, and herbage, and each plot was further divided into four equal parts (25 m × 25 m) for trees/shrubs. We recorded the number of each species (trees and shrubs), vegetation cover, plant height, and diameter at the breast height of the trees. Alternatively, each shrub/shrubs plot (25 m × 25 m) was divided into four herbaceous plant plots of 5 m × 5 m to record the number of plants, cover, height, and frequency. In most of the research sections, disturbances such as logging, grazing, and burning seldom occurred except in section B.

Soil samples were collected from soil profiles in each plot with a shovel in depths of 0–5, 5–15, 15–30, 30–50, 50–80, 80–120, and 120–170 cm, respectively in 2005. Each sample is a soil composite comprising five different points in the same layer. In order to measure soil moisture content, extra samples were collected in an aluminum box and weighed at the time of sampling, and later were oven-dried at 105°C. Soil samples were sorted for roots air-dried later, and then passed through a 2-mm sieve. Samples were subsequently analyzed in the laboratory for pH (1:5 water soil ratio), soil organic matter ($K_2Cr_2O_7-H_2SO_4$ oxidation method of Walkley-Black), total N (Kjeldahl), total P ($HClO_4-H_2SO_4$ digest-colorimetry), total K (HF- $HClO_4$ digest-flame emission spectroscopy), available N (diffuse), and available P (Bray-P), and available K (NH_4 -acetate) (Laboratory of Soil Physics, 1978).

Statistical Analysis

The mean of every soil property was chosen for representing soil property status quo, which was obtained through averaging the soil property on the same soil layer in all profiles. Soil property data on the same layer were tested for normal distribution by calculating the P-P probability plot statistics at first (SPSS Proc P-P Plots, SPSSv11.5, SPSS Inc., Chicago, IL, USA). Then for normal distribution, soil moisture content and pH value were compared among the different soil layers by

ANOVA and least significant difference (LSD), respectively ($p < 0.05$). We tested non-normal distributions, i.e., organic matter, total N, total P, total K, available N, available P, and available K using nonparametric tests (Friedman test and Kendall's W test, $p < 0.05$).

The abundance and uniformity of the species in plant community or habitats can be used to assess the plant species diversity (Magurran, 1988). The species abundance refers to the quantity of species in a community or habitat, while the species uniformity refers to the distribution of individuals across all species in a community or habitat. The species diversity index is a composite index of the abundance and uniformity. The diversity index used was the Shannon–Weiner index (Whittaker, 1972):

The Shannon–Weiner index:

$$H' = - \sum_{i=1}^s p_i \ln(p_i)$$

where p_i is the proportion of the species i in community, equals n_i/N , n_i is the individual number of species i on a plot where species i is found, N is the total number of individuals across all species in each plot; S is the total number of species in the plot. In this study, we used the mean species diversity index to study plant species diversity, which was calculated by averaging the species diversity index in 2002, 2003, 2004, and 2005.

Based on the mean data of all species diversity indices on the 20 plots in sections (C–I) and the soil parameters in the 0–50 cm depth within the plots, the method of grey correlation analysis (Deng, 1989) was used to examine the relative importance of soil parameters in determining plant species diversity represented by the Shannon–Weiner index. Compared to traditional statistical correlation theory, which can only reveal the linearity among random sequences of large sample, grey correlation theory can deal with small sample sequences containing limited information about the complete system, even when the data of the sequences are strongly contaminated by random noise (Deng, 2002).

The basic concept of grey correlation analysis (Deng, 1989) is to determine whether a relationship among a series of variables is close, based on the degree of similarity among the geometric shapes of the variable's data curves. Closer curves indicate stronger correlation among the relative data series. The grey correlation grades are determined from the grey correlation coefficients, which measure the degree of similarity among sequences. The more adjacent the soil parameters and species indices sequences are, the stronger the correlation grade is and vice versa.

Grey data processing must be performed before grey correlation coefficients can be calculated. A series of variables must be transformed to be dimensionless. Usually each sequence is normalized by dividing the data in the original sequence by their average. Let the original reference sequence (data from species diversity indices) and sequence for comparison (data from soil property parameters) be represented as $x_0(k)$ and $x_i(k)$ $i = 1, 2, \dots, m$; $k = 1, 2, \dots, n$, respectively, where m is the total number of factors to be considered and n is the total number of observation data. Data preprocessing converts the original sequences (data from species diversity indices and soil property parameters, respectively) to comparable sequences by normalization. After the data have been preprocessed, a grey correlation coefficient is determined using the preprocessed sequence (Deng, 1989; Fung, 2003; Yeh and Chen, 2004; Gau, Hsieh, and Liu, 2006). The distinguishing coefficient p has

values between 0 and 1. A smaller value of the distinguishing coefficient will result in a larger range of grey relational coefficients, but it will not influence the final priority of the comparison series. Generally, p is taken as 0.5 (Deng, 1989). The grey correlation grade is an average of the grey correlation coefficients. The grey correlation grade represents the degree of correlation between the original reference and comparison sequences. If a particular sequence for comparison is more important for the original reference sequence than for other comparison sequences, its grey correlation grade is larger than the others. If the sequence for comparison is consistent with the original reference sequence, then the grey correlation grade is close to unity.

The data analyses were conducted in Microsoft Excel and SPSS 11.5 for Windows (SPSS Inc., Chicago, IL, USA), with the exception of the grey correlation analysis. The grey correlation analysis was conducted with DPS 3.01 (Bayabat-Data Processing Systems L.L.C., Dubai, UAE). Because the vegetation at the Yahepu (B) section near the Daxihaizi Reservoir is saline meadow and was severely disturbed by human activities between 2004–2005, site B was omitted from our analysis.

Results

Soil Properties Status Quo

Averages for soil properties in different depths are given in Table 2. In the lower reaches of the Tarim River, the soil is barren with low organic matter and high alkalinity in general and almost all soil parameters vary with depth with the exception of total P. Therefore, using nonparametric tests, we found significant differences in soil nutrient content between individual layers in various depths including organic matter, total N, total K, available N, available P, and available K content, with the exception of total P content (Friedman test and Kendall's W test, $p < 0.05$). In particular, due to strong wind erosion in the 0–5 cm layer, soil organic matter content including total N, total K, total P, available P, and available K contents in this layer are comparatively lower than those found in the 5–15 cm layer. Soil moisture content and pH value show significant differences between individual layers using ANOVA and LSD ($p < 0.05$). As nonparametric test results cannot specifically identify significant differences between individual layers, these

Table 2. Average values of soil properties on different soil layers in the lower reaches of Tarim River ($n = 31$)

Layer (cm)	OM ($\text{g} \cdot \text{kg}^{-1}$)	TN ($\text{g} \cdot \text{kg}^{-1}$)	TP ($\text{g} \cdot \text{kg}^{-1}$)	TK ($\text{g} \cdot \text{kg}^{-1}$)	AN ($\text{mg} \cdot \text{kg}^{-1}$)	AP ($\text{mg} \cdot \text{kg}^{-1}$)	AK ($\text{mg} \cdot \text{kg}^{-1}$)	MC (%)	pH
0–5	6.915	0.356	0.551	11.747	46.871	3.809	452.742	1.518	8.95
5–15	7.192	0.371	0.536	11.775	35.601	4.686	534.065	2.585	9.03
15–30	5.587	0.313	0.523	11.866	34.815	2.472	416.419	2.449	9.14
30–50	4.785	0.275	0.520	12.164	30.387	1.366	349.677	4.767	8.75
50–80	4.231	0.246	0.534	13.186	16.029	1.048	251.129	6.134	8.66
80–120	3.476	0.215	0.526	12.443	11.319	0.566	209.00	5.902	8.60
120–170	3.434	0.221	0.515	12.551	10.179	0.580	194.355	6.325	8.71

OM: organic matter; TN: total N; TP: total P; TK: total K; AN: available N; AP: available P; AK: available K; MC: soil moisture content.

Table 3. The results of nonparametric test on soil parameters of 0–50cm and 50–170cm layers ($n = 31$)

Layer (cm)	OM ($\text{g} \cdot \text{kg}^{-1}$)	TN ($\text{g} \cdot \text{kg}^{-1}$)	TP ($\text{g} \cdot \text{kg}^{-1}$)	TK ($\text{g} \cdot \text{kg}^{-1}$)	AN ($\text{mg} \cdot \text{kg}^{-1}$)	AP ($\text{mg} \cdot \text{kg}^{-1}$)	AK ($\text{mg} \cdot \text{kg}^{-1}$)	MC ($\text{g} \cdot \text{kg}^{-1}$)	pH
0–50	5.720a	0.314a	0.528	11.956a	34.407a	2.606a	416.88a	33.10a	8.95
50–170	3.647b	0.225b	0.523	12.674b	12.022b	0.693b	213.43b	61.36b	8.66

Note: The different letters in the same column indicate significant difference (LSD, $p < 0.05$).

OM: organic matter; TN: total N; TP: total P; TK: total K; AN: available N; AP: available P; AK: available K; MC: soil moisture content.

parameters were grouped into the 0–50cm and 50–170cm layers for further analysis because almost all of them have obvious changes in the 50cm depth. Therefore, the weighted means of these parameters in the 0–50cm layer were calculated through averaging those of the 0–5, 5–15, 15–30, and 30–50cm layers, and the weighted means of these parameters in the 50–170cm layer were calculated by averaging those of the 50–80, 80–120, and 120–170cm layers. Subsequently, the soil organic matter, total N, total K, available N, available P, and available K contents were tested using nonparametric tests and soil moisture content and pH value were tested by ANOVA to assess differences between the top (0–50cm) and the deeper (50–170cm) soil layers. The results (Table 3) show that the soil organic matter, total N, total K, available N, available P, available K, and soil moisture content, with the exception of total P contents and pH value, are significantly different ($P < 0.05$) between the surface 0–50cm and the deeper 50–170cm soil layers. Nutrient content, with the exceptions of total K and soil moisture content in the top soil layer (0–50cm), are higher than those in the deeper soil layers. Organic matter, total N, total K, available N, available P, available K contents, and soil moisture content gradually decrease with depth and significant changes appear in the depth of 50cm.

The Changes of Soil Properties Along the River Course

Soil properties are spatially and temporally heterogeneous (Jonathan, Robert, and Stanley, 2002), which is also true in the lower reaches of the Tarim River

Table 4. Soil properties on 0–50cm layer of different sections located at 150m away from river course

Section	OM ($\text{g} \cdot \text{kg}^{-1}$)	TN ($\text{g} \cdot \text{kg}^{-1}$)	TP ($\text{g} \cdot \text{kg}^{-1}$)	TK ($\text{g} \cdot \text{kg}^{-1}$)	AN ($\text{mg} \cdot \text{kg}^{-1}$)	AP ($\text{mg} \cdot \text{kg}^{-1}$)	AK ($\text{mg} \cdot \text{kg}^{-1}$)	MC ($\text{g} \cdot \text{kg}^{-1}$)	pH
C	5.31	0.27	0.55	11.66	24.65	3.62	289.77	40.6	8.76
D	8.95	0.42	0.54	11.08	37.24	2.83	496.30	55.2	9.01
E	5.16	0.34	0.58	11.59	44.80	2.57	328.40	16.1	8.40
F	5.25	0.28	0.54	11.54	29.50	1.82	324.50	50.9	9.12
G	4.46	0.25	0.54	10.13	19.82	0.95	454.80	45.0	9.03
H	3.98	0.21	0.52	12.11	20.26	0.40	180.20	14.4	8.53
I	2.98	0.16	0.46	11.26	9.71	1.89	533.60	12.2	8.28

OM: organic matter; TN: total N; TP: total P; TK: total K; AN: available N; AP: available P; AK: available K; MC: soil moisture content.

(Table 4). Along different monitoring sections located at a distance of 150 m away from the riverbank going downstream from west to east, soil parameters have diverse changes. Based on linear regression analysis (dependent variable was soil property of different sections located at 150 m away from river course, respectively, the independent variable is the sequence of natural numbers from 1 to 7), total N and available P content have a significant descending trend ($F = 6.93$, $p = 0.046 < 0.05$; $F = 9.80$, $p = 0.026 < 0.05$). Soil organic matter and available N show the same declining trend, but the trend is not significant ($F = 5.59$, $p = 0.064$; $F = 4.33$, $p = 0.092$). Total P and total K contents do not show significant variation between the different monitoring sections ($F = 5.81$, $p = 0.061$; $F = 0.03$, $p = 0.874$). The changes in available K content are complex and it is difficult to find an apparent trend. All pH values exceed seven, which means that the soil is largely alkaline and alkaline soil is a more serious problem in the area. Changes in the soil parameters in the plots located at 300 m and 500 m away from the riverbank are similar to those in the plots located at 150 m.

Changes in Species Diversity Along Different Monitoring Sections

The plant species diversity index across different sections has a descending trend as soils along the monitoring sections which were located 150 m away from the riverbank (Figure 2). As reflected in the species diversity index, vegetation cover and species number declined along the different monitoring sections in the lower reaches of Tarim River (from the upper part to the lower part; Table 5). Desert riparian forest vegetation also changed from compound communities composed of tree species (*Populus euphratica*), shrub species (*Tamarix spp.*), and herb species to single species communities (pure *Tamarix*). Specifically, in the Yinsu (C) and Abudali (D) sites, in the upper part of the lower reaches, *Populus euphratica* was a dominant tree species and shrubs were composed of *Tamarix ramosissima*, *Tamarix hispida*, *Lycium ruthenicum*, and *Halimodendron halodendron*. Herbs consisted mainly of *Glycyrrhiza uralensis* Fisch., *Apocynum venetum*, *Alhagi sparsifoli*, *Phragmites australis*. The *Populus euphratica* and *Tamarix spp.* were the dominant species. On the Kardyai (E), Tugmailai (F), and Alagan (G) sites, there are three types of the plant communities: *Populus euphratica*, *Tamarix chinensis*, and mixture of *Populus euphratica* and *Tamarix chinensis*, but vegetation is dominated by *Populus*

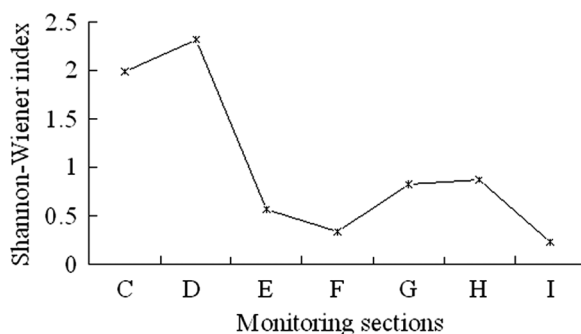


Figure 2. Shannon-Wiener Index on different sections located 150 m away from the river bank.

Table 5. Basic status of the vegetation in different section

Sections	Longitude	Latitude	Altitude (m)	Community composition	Vegetation cover (%)	Species number
C	E87°56.5'- E87°56.3'	N40°25.7'- N40°25.9'	830–831	Tree, shrub, and herb	25.75 ± 4.77	10
D	E88°03.1'- E88°03.0'	N40°24.8'- N40°24.9'	828–829	Tree, shrub, and herb	39.25 ± 9.72	10
E	E88°10.3'- E88°10.4'	N40°22.4'- N40°22.2'	825–826	Tree, shrub, and herb	15.59 ± 6.18	9
F	E88°15.2'- E88°15.0'	N40°16.16'- N40°16.2'	828–829	Tree and shrub	11.62 ± 3.32	8
G	E88°21.7'- E88°21.4'	N40°08.7'- N40°08.7'	822–9824	Tree and shrub	8.734 ± 4.45	4
H	E88°22.7'- E88°22.6'	N39°47.3'- N39°47.2'	819–821	Tree and shrub	6.71 ± 3.23	4
I	E88°25.5'- E88°25.3'	N39°36.5'- N39°36.4'	820–822	Single shrub	3.24 ± 4.91	7

euphratica and *Tamarix chinensis* with companion species of *Lycium ruthenicum* and *Halimodendrom halodendron*. Many of the plants grow very poorly. Because of the deep groundwater level (down to 8–12 m), herbs are sparse with sporadic growths of *Alhagi sparsifolia* that have long and penetrating roots. In the Yiganbjima (H) and Kaogan (I) sites, the vegetation is in an extremely degenerated state, the structure of the plant communities is simpler, and *Tamarix ramosissima* Ledeb. and *Tamarix hispida* Willd. are the dominant plants comprising the shrub community in moving dunes. In addition, the ground surface is barren in some sections at the lower reaches.

According to the above analyses along the monitoring sections, we know that the declining trends in soil organic matter, available N, and P content are similar to the trend of plant species diversity change, but whether or not there is a link between the soil property and species diversity index requires further research.

Relationships Between Soil Properties and Species Diversity

A grey correlation analysis was employed to explore possible relationships between soil properties and plant species diversity. The order of soil parameter sensitivity to species diversity can then be determined based on the grey correlation grades. Table 6 presents the grey correlation grades for the original reference sequence $x_o(k)$ (O = Shannon–Wiener, cover degree, species number, respectively) and the comparison sequence $x_i(k)$ (i = Organic matter, Total N, Total P, Total K, Available N, Available P, Available K, and pH, respectively). The results of the grey correlation grade show that the relationship between organic matter and the Shannon–Wiener index is closer than that between Available K and the Shannon–Wiener index because the value 0.775 for organic matter is larger than the value 0.690 for Available K and the Shannon–Wiener index. In addition, the grey analyses show that there are high-level grey correlation grades for every soil parameter and species diversity index. Therefore, it can be inferred that the main

Table 6. Grey correlation grades and their orders existed among plant species diversity and soil factors

Diversity Index	OM	TN	TP	TK	AN	AP	AK	pH
Shannon–Wiener	0.775	0.771	0.749	0.742	0.703	0.694	0.690	0.745
Order	1	2	3	5	6	7	8	4
Vegetation cover	0.754	0.744	0.740	0.730	0.706	0.690	0.765	0.740
Order	2	3	5	6	7	8	1	4
Species number	0.781	0.793	0.746	0.740	0.735	0.733	0.709	0.744
Order	2	1	3	5	6	7	8	4

OM: organic matter; TN: total N; TP: total P; TK: total K; AN: available N; AP: available P; AK: available K; MC: soil moisture content.

properties correlated to plant species diversity are organic matter, total N, and total P. However, according to the results received on the changes in soil properties and species diversity, total P content does not apparently vary across the different monitoring sections, although the plant species diversity index descends across different sections. Thus, it can be inferred that changes in organic matter and total N could be indicators of species diversity.

Discussion

Soil Properties Vertical Difference

According to the significant differences that were found to exist between the 0–50 cm and 50–170 cm soil layers, we can infer that the riparian forest has a considerably favorable influence on soil properties, but that the influence gradually decreases with vegetation degeneration in the lower reaches of the Tarim River. On one hand, many plants grew well in the lower reaches of the Tarim River in the past. For example, in Alagan, the grassland was almost completely dominated by *Phragmites communis* before the year 1923, and soil organic matter content was $10.15 \text{ g} \cdot \text{kg}^{-1}$ in 1957 (Yang, Chen, and Li, 2007). However, in 2005 in Alagan, there were three types of plant communities: *Populus euphratica*, *Tamarix chinensis*, and a mixture of *Populus euphratica* and *Tamarix chinensis*, but the vegetation was dominated by *Populus euphratica* and *Tamarix chinensis* with companion species of *Lycium ruthenicum* and *Halimodendrom halodendron*. Much of the vegetation was in a poor growth, and soil organic matter content was $4.13 \text{ g} \cdot \text{kg}^{-1}$. Soil properties in the top soil layer (0–50 cm) were correlated with plant community type and due to the considerably favorable influence on soil properties produced from plants, soil nutrients were enriched during that period. In addition, soil organic matter, total N, and available N in the top soil layer, at present, are still higher than those found in the deeper layer (Yang et al., 2007), even though the soil nutrients in the top layer have been reduced by strong wind erosion. The soil nutrient loss from strong wind erosion can be explained by changes in soil clay particle composition. In the 0–30 cm soil layer, clay particle content ($<0.005 \text{ mm}$) in Tikanlike, Yinsu, and Kaogan was 8.34%, 5.52%, and 4.05%, respectively, in 2002, and serious wind erosion is one of the main factors responsible for small clay particle content (Zhang et al., 2004). On the other hand, in the lower reaches of the Tarim River, the stream flow throughout the river section located 321 km down from the Daxihaizi Reservoir

had completely dried up by the 1970s, which led to the accumulation of leaf litter and wood debris in the desert riparian forest. A large amount of leaf litter and wood debris accumulated in the top soil because of a low decomposition rate, so the nutrient amounts released from the litter or debris were comparatively small, which may have inhibited plant growth. At the same time, total plant biomass dropped due to desiccation of the surface water courses. This event can be expressed in vegetation cover and the number of species (Table 5): Vegetation cover is the highest and the number of species is the greatest in Abudali (D), where there are higher contents of organic matter, total N, and available K contents. Therefore, the riparian forest's influence on soil property gradually decreases in the lower reaches of the Tarim River. The lack of significant differences in the value of total P content might be attributed to its lower mobility.

Change of the Plant Diversity

Species diversity changes with elevation and water availability (Itow, 1991). Different soil nutrient conditions influence the plants' biomass, which affect plant species composition and diversity (Critchley et al., 2002). This study shows that some soil parameters, like soil organic matter and total N, are related to species diversity. The reason soil organic matter reflects changes in plant species diversity is because there is a close relationship between soil organic matter content and plants. In natural ecosystems, plant litter and roots are the origin of soil organic matter and higher plant diversity may lead to higher litter diversity, which in turn supports a greater diversity of decomposers and detritivores (Hansen, 2000) that increase soil organic matter content. As for total N content, it is positively correlated with soil organic matter content (Yang et al., 2007). Hence, it is reasonable to conclude that soil organic matter and total N in the top layer can play an essential role in reflecting changes in plant species diversity across a desert riparian forest in the lower reaches of the Tarim River.

Changes in plant community are related to certain environmental conditions: For instance, the original water stressed ecosystem turns into water and N stressed ecosystem, while the perennial grassland ecosystem evolves into an ecosystem dominated by shrubs (Whitford, Reynolds, and Cunningham, 1987). In particular, water is an acknowledged stress factor for vegetation degradation in the lower reaches of the Tarim River. However, the appearance of a single preponderant *Tamarix* shrub community probably suggests that other factors might become stressors for trees and herbaceous plants, e.g., N, P, and K contents. For example, in desert habitats, shrubs concentrate soil nutrients (e.g., N, P, and K content) in "islands of fertility" that are localized beneath their canopies, while adjacent barren intershrub spaces are comparatively devoid of biotic activity (Shlesinger and Pilmanis, 1998; Jonathan et al., 2002). According to Xu, Luo, and Chen (2006), in the 0–40 cm soil sampling depth, a significant "fertility island" effect was observed under *Tamarix ramosissima* and bare land shrub (Xu et al., 2006). Soils under shrub canopy have significantly higher contents of soil organic matter and total N than those in open spaces, but soil salinity accumulates in the open spaces. The total salinity is approximately $18 \text{ g} \cdot \text{kg}^{-1}$ and $17.5 \text{ g} \cdot \text{kg}^{-1}$ in the 0–20 cm and 20–40 cm depths, respectively, in the open spaces, and the total salinity is approximately $8.5 \text{ g} \cdot \text{kg}^{-1}$ and $7 \text{ g} \cdot \text{kg}^{-1}$ in the 0–20 cm and 20–40 cm depths, respectively, under *Tamarix ramosissima* (Xu et al., 2006). Therefore, in conjunction with the results derived from

the grey correlation analysis, it can be deduced that in the desert riparian forest in the lower reaches of the Tarim River, the degeneration of compound communities composed of trees (*Populus euphratica*), shrubs (*Tamarix spp.*), and a mixture of herbs to a single species community (pure *Tamarix*) may be due to water and N stress instead of just water stress, to some extent.

In the nonequilibrium ecology theory, water availability in soil is the main factor in system dynamics (Xiong, Han, and Zhou, 2005). Dynamics of vegetation are triggered by natural "events" (e.g., flood, weather, fire) or by management "actions" (grazing, destruction, or introduction of plant populations and fertilization; Archer and Stokes, 2000). In the lower reaches of the Tarim River, water is an acknowledged driving force in vegetation dynamics throughout the desert riparian forest, which means that the desert riparian forest possesses characters typical of a nonequilibrium system. State and transition models built on the nonequilibrium ecology theory are proposed as a practicable way to organize information for documenting the dynamics of nonequilibrium systems like rangelands (Westoby, Walker, and Noy-Meir, 1989; George, Brown, and Clawson, 1992; Milton, Dean, and Ellis, 1998). However, disturbances such as grazing, logging, and fire are not the main factors that account for dynamic variations in the desert riparian forest system in the lower reaches of the Tarim River as in a rangeland. Rangeland state and transition models cannot be directly applied to the management of the desert riparian forest. Therefore, based on large amounts of data that have been collected continuously on soil properties and vegetation, more suitable state and transition models need to be built in the desert riparian forest for the lower reaches of the Tarim River, and this will continue to be a main aspect in future research.

In the desert riparian forest in the lower reaches of the Tarim River, floods and changes in river course provide essential conditions for plant seed germination and plant growth. The ripening and dispersal periods of *Populus euphratica* seeds overlap largely with flood occurrence periods, and the sprouting and natural regeneration of seeds depend greatly on flood events in natural riparian forests (Cheng et al., 2007). Moreover, after several occurrences of river overflowing, *Populus euphratica* and *Tamarix ramosissima* germinate easily and can gradually dominate the plant community in the lower reaches of the Tarim River (Xu, Ye, and Li, 2009). However, over the last 50 years, the desert riparian forest has degenerated due to a lack of water in the river. Specifically, a serious degeneration arose because a stretch of 321 km in the lower reaches of the Tarim River dried up by the 1970s. Especially, *Populus euphratica* and *Tamarix spp.* seeds cannot germinate for lack of flood. Therefore, it is necessary to take some measures such as seed bank activation through irrigation and the planting of young trees to facilitate the restoration of the desert riparian forest in the lower reaches of the Tarim River until the limitations from water availability are eliminated.

Soil organic matter plays an important role in plant colonization and establishment because it acts as a reservoir for essential elements, particularly N and P. In the southeastern fringe of the Tengger Desert, China, soil organic matter had a positive effect on herbaceous plant species richness and productivity (Li, Kong, Tan, and Wang, 2007). In the southwestern deserts of the United States, water and nitrogen availability controlled species diversity and abundance of annual plants (Rundel and Gibson, 1996). Annual plant species diversity decreased in response to the long-term amendment of nitrogen fertilizer, but absolute density

and above-ground biomass of some species, which contribute most to above-ground biomass, increased significantly with fertilization in the Chihuahuan Desert (Mun and Whitford, 1989). Based on the analyses of the relationship between soil properties and plant species diversity in the lower reaches of the Tarim River, it can be deduced that the soil nutrients, especially soil organic matter and total N content in the 0–50 cm soil layer, will become an important influencing factor in the desert riparian restoration when the water deficiency question is solved. Consequently, the use of fertilizer, especially nitrogenous fertilizer, is very important during seed bank activation and young tree planting. Maintenance or enhancement of soil organic matter and nitrogen content in the upper layer is extremely necessary for increasing herbaceous plant species richness and plant growth in vegetation restoration and reconstruction, but amendment of nitrogen may become a disadvantage for increasing annual plant species diversity.

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