

Original Research

Relationships between Plant Communities and Environmental Factors in an Extremely Arid Area: A Case Study in China

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Abstract

In arid areas, the vegetation is sparse, the ecological environment is fragile, the number of vegetation species is scarce, the community structure is unstable, and the impact of different environmental factors on the plant community is unclear. In this study, the lower reaches of the Tarim River were used as the study area, and the plant community characteristics and environmental factors were investigated. TWINSpan and CCA were used to undertake a multivariate statistical analysis of vegetation in the region. The objectives of this study were to identify: 1) the optimal vegetation structure for controlling desertification and 2) the key factors affecting vegetation characteristics and the relationship between plants and these key factors. The results showed that the tree-shrub-grass community structure is the most stable and provided the best windbreaks and sand fixing abilities. In addition, attention should be paid to the restoration and reconstruction of herbage when constructing shelter forest. The main environmental factors determining the distribution of plant community types are groundwater depth and soil water content in the lower reaches of the Tarim.

Keywords: TWINSpan, CCA, plant communities, environmental factors, lower reaches of Tarim River

Introduction

The development of the social economy and the increase in human exploitation and utilization of natural resources has meant that vegetation is widely used by human beings as an important resource. This has led to a series of problems, including vegetation degradation and environmental deterioration [1-2]. In arid areas, natural and artificial disturbance has seriously damaged sparse vegetation, and species diversity has been lost. This has

led to ecosystem function degradation, and desertification has become a major environmental problem in arid areas [3-4]. At present, one-fifth of the world's population and one-third of the land is threatened by desertification. To sustainably develop the economy in an arid area, the protection and restoration of vegetation must be strengthened, which means that desertification needs to be curbed. This is of great significance to ecological protection and sustainable economic development in arid areas.

The Tarim Basin, which is located in the hinterland of Eurasia, is a typical arid desert area and an ecologically fragile part of China. The Tarim River is the longest inland river in China, and its basin is characterized by rich

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natural resources and a fragile ecological environment with distinctive geographical features and prominent environmental problems [5]. The lower reaches of the Tarim are located between Daxihaizi Reservoir and Taitema Lake. *Populus euphratica* is the dominant plant and is mainly distributed on both sides of the river. *Tamarix chinensis* shrubs are found among *Populus euphratica*, but its distribution area is wider. Herbaceous plants are mainly distributed near the river [6]. The desert riparian forest, which is sparsely distributed along the lower reaches of the Tarim, is mainly found around 1,000 m from the river, and shows considerable spatial variability [7]. The vegetated area decreases rapidly as the distance from the river increases, which reflects the adaptability of desert plants to arid climates and the dependence on the river as a water source. The land along the lower reaches of the Tarim mainly includes unused land, forest land, and grassland, and these three land use types account for more than 95% of the total area of the river basin [8]. Forest land and grassland are important components of desert riparian vegetation, and they play an important role in maintaining the stability of the ecosystem in the lower reaches of the Tarim.

Along the lower reaches of the river, the structure and function of the vegetation are unique because of natural environmental restrictions, such as poor stability and low resistance to interference. Therefore, the vegetation is easily degraded if it is interfered with [9]. Over the past 50 years, human social and economic activities along the river's lower reaches have increased, and water resources development and utilization have increased. This has led to significant changes to natural ecological processes in the watershed [10]. Rivers have been cutoff, lakes have dried up, and the desert riparian vegetation has declined, which has led to desertification and a reduction in biodiversity. Therefore, the lower reaches of the Tarim have become an important ecological and environmental study area in China, and the vegetation community characteristics in this watershed have universal significance for other similar areas around the globe.

The natural oasis ecosystem in the lower reaches of the Tarim has suffered from major vegetation changes, which have been caused by interactions between intrinsic characteristics and external disturbance to the system. There has been no river runoff in the lower reaches of the Tarim, and the river water content mainly depends on a reduced water supply from the Daxihaizi Reservoir water supply. This reduced supply and the cutting off of the river flow are the main reasons for the degradation in natural vegetation [11]. The soil sediment concentration is high, the corrosion resistance is poor, and the scouring effects of the water and wind erosion are relatively strong. These factors have meant that the topography is unstable [12]. Precipitation in the basin is rare, but evaporation is strong, soil texture is poor, the plant material accumulation process is very slow, and productivity is low [13]. In addition, human activity is the fundamental driving force behind natural vegetation degradation, and human disturbance has caused irreversible environmental

changes, such as desertification and salinization of the land [14]. The vegetation cannot be restored to the original ecological communities when the situation is so serious.

The implementation of the ecological water transport project has led to a series of changes in the vegetation on both sides of the river along the lower reaches of the Tarim. A large number of endangered plants have begun to recover, and vegetation coverage and species diversity have increased [15]. However, the vegetation community structure is different and the vegetation stability varies in different sections and at different distances from the river. Therefore, it is necessary to find the vegetation structure characteristics that are most stable and have the strongest windbreak and sand fixing abilities. In addition, there are many factors affecting vegetation growth, which means that there is also a need to identify the factors that affect plant growth in the lower reaches of the Tarim. This study identified the most stable plant structure combination to restrain the increasing rate of desertification. In addition, the important factors that affect the vegetation characteristics along the lower reaches of Tarim River were investigated. These results provide a theoretical reference basis that can be used by land managers to make better use of water resources.

Materials and Methods

Study Area

The Tarim River is 2,637 km long and is located in the southern Xinjiang Uygur Autonomous Region. It is the largest inland river in China. The main section of the Tarim River is 1,321 km long and flows from the confluence of the Akesu, Yerqiang, and Hotan rivers to Taitema Lake. The total area of the basin is 92.06×10^4 km² [16]. The lower reaches of the Tarim is the stream segment from Qiala to Taitema Lake, and the main channel is 428 km long. East of the river is the Kuruk Desert, and the Taklimakan Desert is west of the river. Between the two deserts is the alluvial plain that is part of the lower reaches of the Tarim. The natural vegetation on the alluvial plain contrasts sharply with the surrounding environment, and this "corridor vegetation belt" is also called the "green corridor." The plant species include members of the Salicaceae, Tamaricaceae, Chenopodiaceae, Compositae, Gramineae, and Leguminosae, etc., and they constitute the tree, shrub, and herb communities. The trees are mainly *P. euphratica*, the shrubs are mainly *T. chinensis*, *Lycium ruthenicum*, and *Halimodendron*, and the herbs include *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Karelinia caspica*, and *Glyzyrrhiza inflata*. However, their growth has declined because of a previous long-term cutoff of the river course. Since the launching of ecological water transportation in 2000, a large number of dying plants have begun to recover, and vegetation coverage and diversity is rising again.

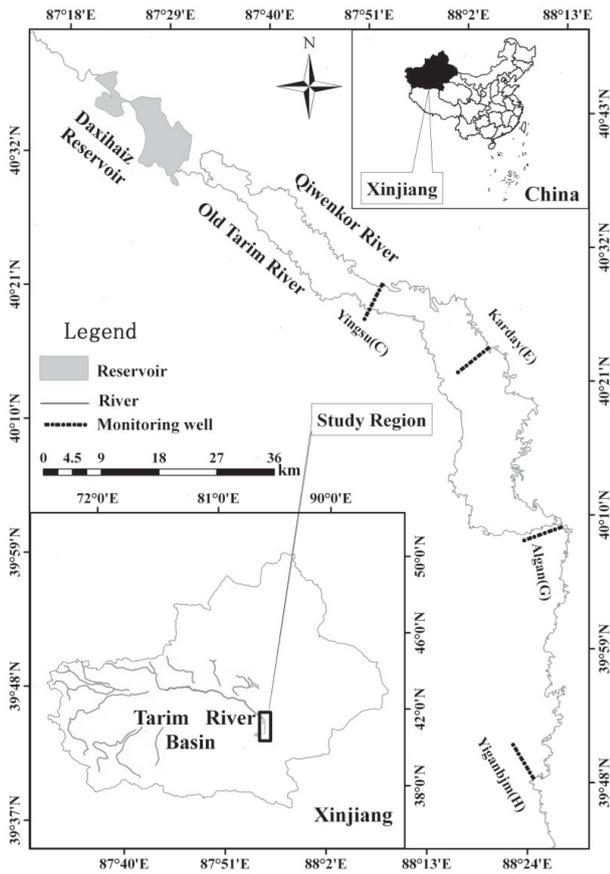


Fig. 1. Layout of sample plots in the lower reaches of the Tarim River.

A large belt of arbor-shrub-grass has appeared on the floodplain and low terraces on both sides of the river.

Field Investigation

The vegetation in typical sections of the river (Yingsu, Karday, Algan, and Yiganbjm) was surveyed from the end of June to the beginning of July 2017. Fixed sample plots were set up along the lower reaches of the Tarim (Fig. 1). The distance between two adjacent sections was 30-50 km (Table 1).

In each monitoring section, a transect was placed in a perpendicular direction to the river course. Then a large 50 × 50 m quadrat was set up near the monitoring wells, which were 50 m (ext 50), 150 m (ext 150), 300 m

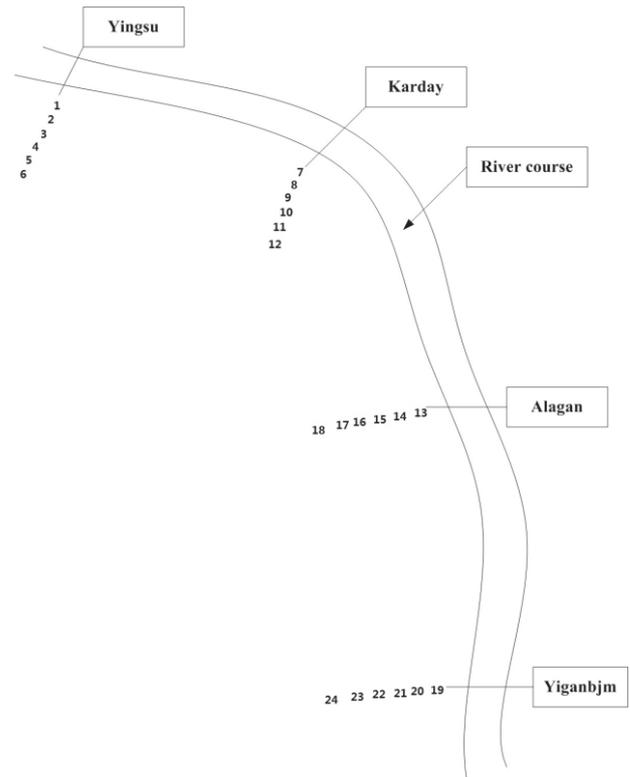


Fig. 2. Sketch map of sample plot numbers in the lower reaches of the Tarim River.

(ext 300), 500 m (ext 500), 750 m (ext 750), and 1,050 m (ext 1050) from the river. The GPS position and altitude of each large quadrat was recorded. This meant that 24 large fixed quadrats were set up and numbered (Fig. 2). Then, each large quadrat was divided into four smaller quadrats that were 25 × 25 m on average, and indexes, including the individual number, coverage, DBH, basal diameter, height, and crown width of each tree (or shrub) were recorded. Finally, three herbaceous 1 × 1 m quadrats were set up in each 25 × 25 m quadrat. Then the following parameters were measured: individual number, coverage, height, crown width, and frequency. This meant that 96 tree and shrub quadrats and 288 herbaceous quadrats were completed. In each 50 × 50 m quadrat, the surface soil from the upper, middle, and lower points along the quadrat diagonal were taken and mixed. These were then analyzed in the laboratory for soil water content, soil conductivity, and pH of

Table 1. Environmental characteristics of the 4 typical transects of the lower reaches of the Tarim River.

Sections	Distances from Daxihaizi reservoir /km	Desertification grades	Vegetation coverage /%	Degradation degrees
Yingsu	61	2.97	15-20	Mild
Karday	95	4.14	10-15	Moderate
Algan	188	5.48	7-10	Severe
Yiganbjm	284	3.87	2-7	Extreme

Table 2. The list of plant species in 24 sites in the lower reaches of the Tarim River Basin.

No.	Species	Family	Genera	Collection sites
1	<i>Populus euphratica</i>	Salicaceae	Populus	1, 2, 3, 7, 11, 12, 13, 14, 15, 19, 20, 22, 24
2	<i>Tamarix ramosissima</i>	Tamaricaceae	Tamarix Linn.	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 16, 19, 21, 23
3	<i>Polygonum aviculare</i>	Polygonaceae	Polygonum L.	2, 8, 15
4	<i>Nitraria sibirica</i>	Zygophyllaceae	Nitraria L.	4, 9, 14
5	<i>Lycium ruthenicum</i>	Solanaceae	Lycium L.	1, 7, 13, 15, 20, 21
6	<i>Potentilla chinensis</i>	Rosaceae	Potentilla L.	15
7	<i>Capparis hainanensis</i>	Capparaceae	Capparis Tourn. ex L.	11, 21
8	<i>Asparagus persicus</i>	Liliaceae	Asparagus	16
9	<i>Elaeagnus angustifolia</i>	Elaeagnaceae	Elaeagnus	1, 7, 13, 14, 15, 22
10	<i>Poacynum hendersonii</i>	Apocynaceae	Poacynum Baill.	2, 13
11	<i>Poacynum hendersonii</i>	Apocynaceae	Apocynum	1, 2, 3, 8, 11, 17, 19, 20
12	<i>Cynanchum sibiricum</i>	Asclepiadaceae	Cynanchum Linn.	20
13	<i>Cynanchum sibiricum</i>	Asclepiadaceae	Cynanchum Linn.	7, 13
14	<i>Mulgedium tataricum</i>	Compositae	Mulgedium	12
15	<i>Karelinia caspica</i>	Compositae	Karelinia	2, 4, 9, 13, 14, 19, 20, 21, 22
16	<i>Inula salsoloides</i>	Compositae	Inula	19, 21
17	<i>Taraxacum sp.</i>	Compositae	Taraxacum F. H. Wigg.	7
18	<i>Phragmites communis</i>	Gramineae	Phragmites Adans.	1, 2, 5, 7, 13, 15, 19, 21, 22
19	<i>Setaria viridis</i>	Gramineae	Setaria Beauv.	2, 19
20	<i>Aeluropus pungens</i>	Gramineae	Aeluropus Trin.	1, 2, 12, 13, 20
21	<i>Astragalus membranaceus</i>	Leguminosae	Astragalus Linn.	13, 21
22	<i>Alhagi sparsifolia</i>	Leguminosae	Alhagi Gagneb	3, 4, 6, 8, 9, 10, 12, 16, 18, 21, 23, 24
23	<i>Glycyrrhiza inflata</i>	Leguminosae	Glycyrrhiza Linn.	5, 13, 19, 22
24	<i>Halimodendron halodendron</i>	Leguminosae	Halimodendron Fisch. ex DC.	5, 8, 10, 11, 17, 22, 23
25	<i>Sophora apopecuroides</i>	Leguminosae	Sophora	15, 19
26	<i>Anabasis aphylla</i>	Chenopodiaceae	Anabasis L.	20
27	<i>Hexinia polydichotoma</i>	Chenopodiaceae	Nitraria	2, 3, 7, 13
28	<i>Halogeton glomeratus</i>	Chenopodiaceae	Halogeton C. A. Mer.	1, 13
29	<i>Kalidium foliatum</i>	Chenopodiaceae	Kalidium Miq	2, 19
30	<i>Salsola ruthenica</i>	Chenopodiaceae	Salsola	16, 21
31	<i>Salsolacollina</i>	Chenopodiaceae	Salsola	1, 5, 13, 16
32	<i>Halocnemum strobilaceum</i>	Chenopodiaceae	Halocnemum Bieb.	14, 15, 20

the soil water. Groundwater depth data from 2000 to 2016 were collected, and the average value was calculated. In addition, the groundwater at each monitoring well was

extracted and put in a sealed container. These were then taken back to the laboratory for groundwater pH and mineralization analyses.

Mathematical Analysis Method: Two-Way Indicator Species Analysis and Canonical Correspondence Analysis

Two-Way Indicator Species Analysis (TWINSPAN)

This hierarchical classification is the most effective quantitative community classification method. It can classify the species and the sample plots at the same time. The method first sorts the data by correspondence analysis. Then it obtains the first sort axes, and classifies them after sorting the axes. There is an international general purpose software for two-way indicator species analysis. When there is no sample environmental factor data, then TWINSPAN can analyze the characteristics of the plant communities to determine the relationships between plant distribution and the environment. This analysis is accepted by a majority of plant ecology researchers.

Canonical Correspondence Analysis (CCA)

This is a ranking method based on correspondence analysis. The method, which is also called “multivariate direct gradient analysis,” combines correspondence analysis with multiple regression analysis. Each step of the calculation is regressed with environmental factors. The basic ideas behind CCA is that the iterative process of the correspondence analysis sorts the coordinate values of the quadrat, which are not always available. Then the data is subject to multivariate linear regression with the environmental factors. In other words, Z_j is the sorting value of quadrat j , b_0 is the intercept, b_k ($k = 1, 2, 3 \dots q$, where q is number of environmental factors) is the regression coefficient between the quadrat and environmental factor k , and U_{kj} is the observations of environmental factor k in quadrat j :

$$Z_j = b_0 + \sum_{k=1}^q b_k U_{kj}$$

This method first calculates a set of quadrat sorting values and species sorting values. It also carries out a correspondence analysis. Then the quadrat and environmental factor ranks are combined using regression analysis. The obtained quadrat sorting value not only reflects the effects of species composition and the ecological importance of the quadrats on the community, but also the influence of the environmental factors. The sort value of the species is obtained from the weighted average of the quadrat sorting value. The species sort coordinate value is also indirectly associated with environmental factors.

In this study, statistical software WinTWINSPAN 2.3 was used to calculate the TWINSPAN community classification, and analysis software CANOCO 4.5 was used for mapping.

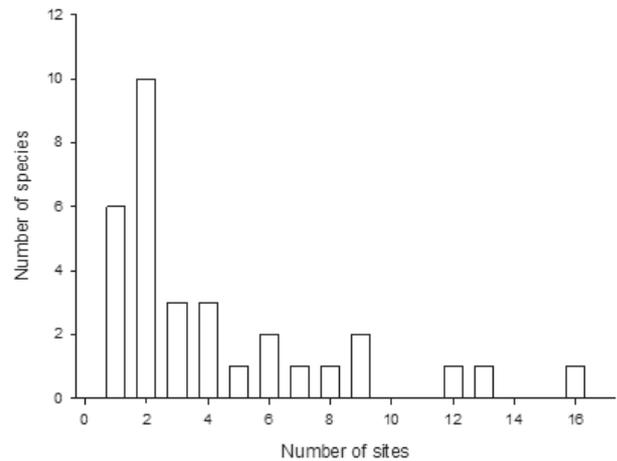


Fig. 3. Pattern of species abundance, presented as number of species plotted against number of collection sites in which a species was found.

Results and Discussion

Occurrence Frequency of the Plant Species in the Quadrats

The occurrence frequency of the plant species in the quadrats can reflect the richness of the plant species in the surveyed area. Table 2 shows the plant species that appeared in the quadrats. There were 32 species of plants belonging to 15 families and 30 genera.

Fig. 3 shows the species richness pattern as represented by the number of species against the number of collection sites in which a species was found. This indicates that most of the plant species have a lower frequency of occurrence in quadrats beside the lower reaches of the Tarim. Among the 32 plants species, 6 species only occurred in one quadrat and accounted for 18.75% of all plants; 10 species occurred in 2 quadrats, and accounted for 6.25% of all plants; and 3 species occurred in 3 quadrats, which accounted for 9.38% of all plants. *T. chinensis* had the highest frequency of occurrence and occurred in 16 quadrats (66.67% of all quadrats) and 4 transects. The second was *P. euphratica*, which occurred in 13 quadrats (54.17% of all quadrats). The third was *A. sparsifolia*, which occurred in 12 quadrats (37.50% of all quadrats).

The frequency of most plant species in the quadrats was low along the lower reaches of the Tarim. This shows that the species richness of this region is poor and the ecosystem is unstable. These results confirm the findings reported by Xi et al. [17] and Chen et al. [18] who also showed that the desert ecosystem in arid and semi-arid areas was more fragile when water and environmental problems are particularly prominent.

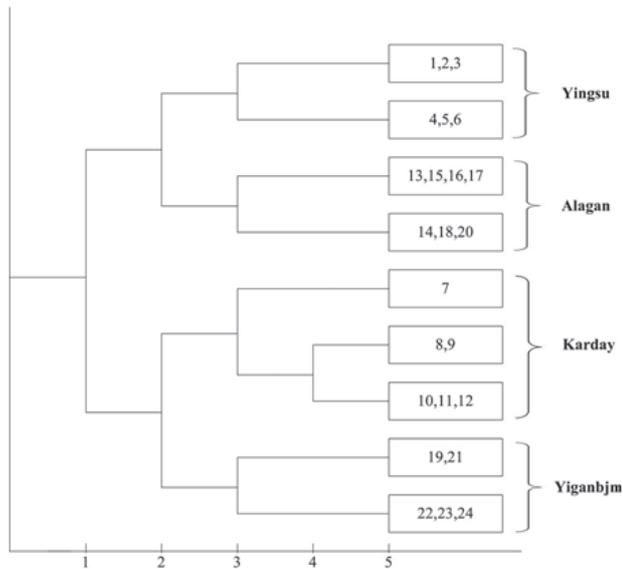


Fig. 4. Graph of TWINSpan classification for 24 samples in lower reaches of the Tarim River Basin.

Classification of Sample Plots and Species

In this study, TWINSpan was used to classify 24 sample plots and 32 plant species. In the division process, all the samples and types are first divided into 2 categories, which were 0 and 1. Then, these 2 categories were divided into 2 further categories and so on until the required level of division was reached. The division level was up to 7, and the maximum number of categories was 2 each time. The index values of the species in the 24 quadrats were used to create TWINSpan clustering maps of the quadrats in the lower reaches of the Tarim (Fig. 4).

The right side of Fig. 4 shows the 9 sample types that were divided by TWINSpan. The classification of the quadrats coincides with the arrangement of the actual sections, except site 20, which should belong to the Yiganbjm section. Therefore, the classification results are mainly in line with the actual situation. Yingsu and Alagan, which belong to the same class, were very different from Karday and Yiganbjm. Yingsu is near the outlet of the Daxihaizi Reservoir and has higher groundwater levels, but Alagan is located at the confluence of the QiwenKor River and Old Tarim River, where the large water inputs lead to higher groundwater levels. There is more vegetation in these 2 sections than at Karday and Yiganbjm. The plant species that most benefit from the improved groundwater levels are *P. euphratica*, *Tamarix ramosissima*, *A. sparsifolia*, and *Hexinia polydichotoma*, which grow well and in large quantities. In addition, other plants, such as *K. caspica*, *Halogeton glomeratus*, and *Glyzyrrhiza inflata*, can also be found.

There is a close relationship between Karday and Yiganbjm. The water conditions along the 2 transects are poor, the groundwater level is low, vegetation growth is

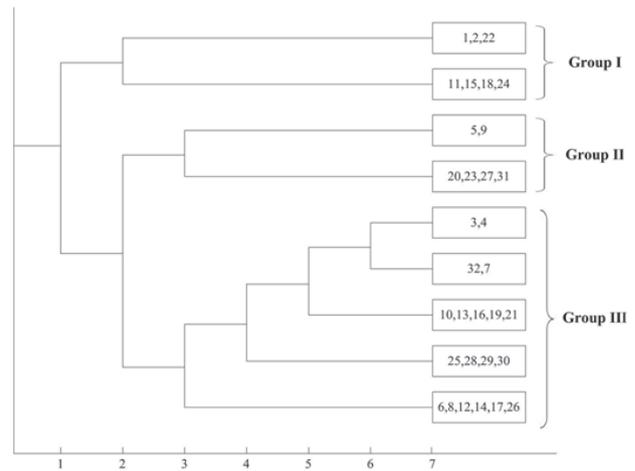


Fig. 5. Graph of TWINSpan classification for 32 species in lower reaches of the Tarim River Basin.

poor, and some of the quadrats are simply large, empty spaces. The constructive species along these 2 transects are *P. euphratica*, *T. ramosissima*, *L. ruthenicum*, and *A. sparsifolia*.

Fig. 4 shows that the quadrats further away from the river are also clearly different from those near the river. Along the Yingsu transect, sample plots 4, 5, and 6 were farther away from the river and were separated at the third divide level from plots 1, 2, and 3, which were near the river. This shows that there are differences among the quadrats as you moved away from the river. The ground surfaces of sample plots 4, 5, and 6 were mainly bare and flat. They contained almost no *P. euphratica*, and *T. ramosissima* growth was extremely poor, but there were a few residual roots distributed at the base of the bush fallow. There were also some similar landscapes along other transects.

The right side of Fig. 5 shows the TWINSpan results that classified the 32 plant species. The plants were divided into 3 species groups. There were 7 species in group I (species 1, 2, 11, 15, 18, 22, and 24), 6 species in group II (5, 9, 20, 23, 27, and 31), and 19 species in group III (3, 4, 6, 7, 8, 10, 12, 13, 14, 16, 17, 19, 21, 25, 26, 28, 29, 30, and 32). The occurrence frequency of most species in group III was low. The TWINSpan classification was mainly based on plant species data. Therefore, environmental effects were not taken into account.

Figs 4 and 5 suggest that there were many trees and shrubs, including *P. euphratica*, *T. chinensis*, *H. halodendron*, and *L. ruthenicum*. Furthermore, herbaceous plants such as *P. communis*, *K. caspica*, *A. sparsifolia*, and *H. glomeratus* were common and formed a good tree-shrub-grass structure in Yingsu and Alagan. However, in Karday and Yiganbjm, there were some trees and shrubs such as *P. euphratica*, *T. chinensis*, and *L. ruthenicum*, etc., but there were few herbaceous plants, such as *A. sparsifolia*. Therefore, a tree-shrub structure had formed in these places. According to Zhang [19], the plant community is highly stable and

has a strong protection ability in Yingsu and Alagan, but the plant community was not so stable in Karday and Yiganbjm. Furthermore, the wind and sand fixing effects suggest that the tree-shrub-grass structure has stronger windbreak and sand fixation abilities than the tree-shrub structure. This confirms the study by Zhou et al. [20]. The tree-shrub structure in Karday and Yiganbjm was similar to that in Yingsu and Alagan, but there were considerable differences in the herbaceous structure. This shows that herbs have a stronger effect on wind and sand fixation, which was similar to the study by Cheng et al. [21]. Therefore, the tree-shrub-grass structure has good windbreak and sand fixation abilities, and the herbs

in forests are especially effective as a windbreak and at sand fixation.

CCA Sorting of Sample Plots and Species

First, the environmental factor data was standardized and the variation characteristics of the environmental factors at different distances from the river in each section were obtained (Fig. 6).

Fig. 6 shows that the altitude decreases as you move downstream. The pH of the groundwater and soil salinity were not obviously affected by the changes in distance from the river. In each section, the soil water content

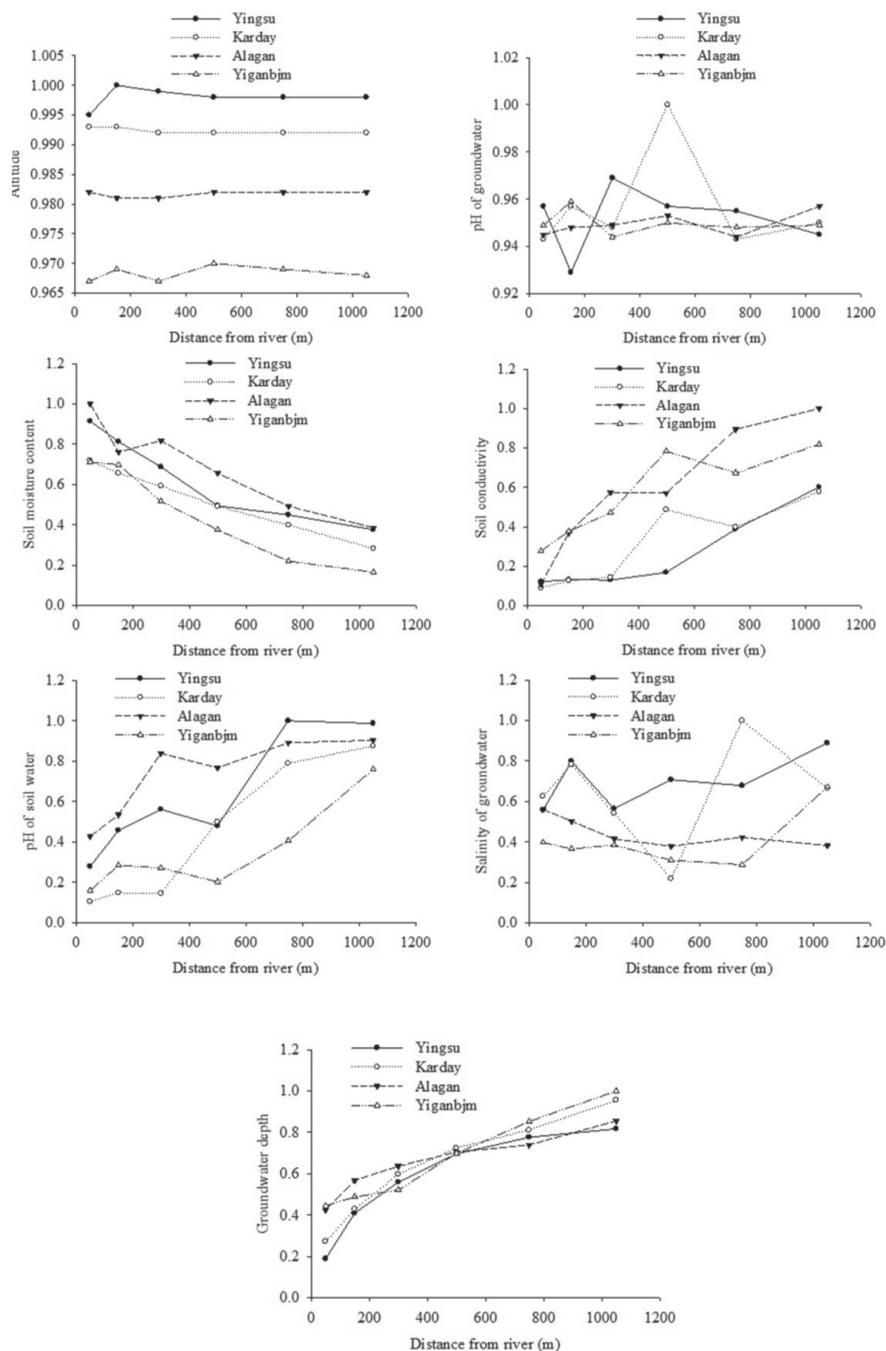


Fig.6. Environmental variables for collection locations standardized by max value.

Table 3. Correlation coefficients among 7 environmental factors.

	Altitude	pH of groundwater	Soil water content	Soil conductivity	pH of soil water	Mineralization of groundwater	Groundwater depth
Altitude	1						
pH of groundwater	0.129	1					
Soil water content	0.193	-0.074	1				
Soil conductivity	-0.481*	0.015	-0.677**	1			
pH of soil water	0.221	-0.014	-0.394	0.566**	1		
Mineralization of groundwater	0.611**	-0.410*	-0.040	-0.358	0.240	1	
Groundwater depth	-0.138	0.098	-0.860**	0.747**	0.705**	0.027	1

*Correlation is significant at the 0.05 level (2-tailed)
 **Correlation is significant at the 0.01 level (2-tailed)

gradually decreased as the distance from the river increased, whereas the groundwater depth gradually increased; soil electrical conductivity and soil water pH rose as the distance from the river increased.

In addition, a correlation analysis of the data for 7 environmental factors was carried out (Table 3).

Table 3 shows that the soil water content is negatively correlated with groundwater depth (-0.860) and soil conductivity (-0.677). Soil conductivity was also negatively correlated with altitude (-0.481), groundwater salinity (-0.410), and groundwater pH (-0.394); The salinity of the groundwater had a significant positive correlation with altitude (0.611), soil water pH (0.566), soil conductivity (0.747), and groundwater depth (0.705). As a result, the water and salt dynamics and their interaction are the main factors that influence environmental factor changes in this area.

Table 3 was taken as the data source for the environment (*env). In this study, the species coverage, which was used as the growth index for species in the quadrats, was used as the species data source for CANOCO (*spe).

This allowed a data matrix of environmental factors and species to be constructed. Then CCA was used to carry out the sorting analysis of the 32 kinds of plants in the lower reaches of the Tarim River, and a CCA two-dimensional sorting map was obtained (Fig. 7).

In Figure 7, “Δ” represents the species of plants, and the species number is the same as in Table 2. In the sort diagram, environmental factors are represented by the lines with arrows. The length of the line indicates the size of the relationships between plant species and the environmental factors. The angle between the arrow line and the sorting axis indicates the size of the correlation between environment factors and the sort axis. The direction of the line shows the change trend for the environmental factors. In the analysis, when a vertical line links a species with environmental factors, the nearer the intersect of the vertical line and the environment factor distance are to the lines with arrows, the greater the positive correlation between the species and the environmental factor. The further away they are, the more negative the correlation. Fig. 7 shows that individual species – such as 12 and 26, 8 and 30, and 19 and 29 – overlap due to overcrowding.

Plant species and the environmental factor lines reflect the variation in the distribution of plant species along the gradient direction of each environmental factor. The first ordination axis is positively related to groundwater salinity and groundwater pH (0.5031 and 0.4279, respectively), but is negative correlated with soil moisture content (-0.4362). The second sorting axis was positively related to soil conductivity and soil water pH (0.6745 and 0.5370, respectively), but was negative related to groundwater depth and altitude (-0.4671 and -0.4824, respectively).

Sixteen plants accounted for 50% of all species, and they were found in the first and second quadrants. The distribution of these plants decreased as the groundwater depth increased, which indicated that these plants were distributed in areas with shallow groundwater. In the third quadrant, there were 9 species of plants that showed improved growth due to the increase in soil

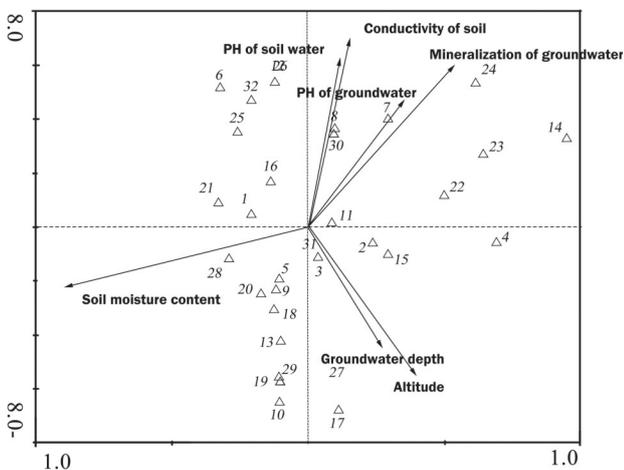


Fig.7. Two-dimensional graph of CCA ordination for plant communities in lower reaches of the Tarim River Basin.

water. The fourth quadrant was affected by groundwater and elevation and contained the least number of plants. Therefore, it can be seen that water condition has an important effect on the distribution of plants in the Tarim Basin. In addition, pH, soil conductivity, and salinity also affect the vegetation distribution pattern, and the distribution area of most species increased when pH, soil conductivity, and salinity decreased.

Relationship between Community Distribution and the Main Environmental Factors

Plant coverage was the index used to investigate the dominant factors affecting vegetation distribution in the area, and a multivariate stepwise regression analysis between coverage by the 32 plant species and 7 environmental factors in 24 sample plots was undertaken. The results show that plant coverage is most closely related to groundwater table depth (L, $P < 0.01$) and soil water content (W, $P < 0.01$). The stepwise regressions were as follows:

$$X_1 = -3.9957L + 33.769$$

$$R^2 = 0.7645, F = 71.421, \text{sig} = 0.000, \text{df} = 23$$

$$X_2 = 37.23W - 9.5796$$

$$R^2 = 0.6339, F = 38.095, \text{sig} = 0.000, \text{df} = 23$$

The results suggest that groundwater depth is the dominant factor that determines the distribution of the plant communities in the lower reaches of the Tarim River. Furthermore, changes in soil water content also affect plant growth. The distribution patterns of the different plant community types were also affected by topography, geomorphology, temperature, light, and human disturbance, which lead to an increase in the complexity and variability of the vegetation distribution patterns. These results were consistent with the actual distribution of the plant communities and habitat conditions in this region.

In arid areas, the water conditions are an important factor that affects vegetation change [22-24]. Different plant species have different root depths. Therefore, changes in the groundwater depth will directly affect the water absorption range of plant roots, which alters the surface ecological characteristics of vegetation [25]. In addition, the soil water content is also affected by changes in groundwater depth, and this can restrict the growth of plants at the surface [26]. When the groundwater depth is too low, groundwater cannot transport water to the plant roots via capillary action. Therefore, plants with shallower roots die due to a lack of water, and the growth of deep root plants is inhibited [27]. *P. euphratica* and *T. chinensis*, for example, can utilize soil water in the 0-100 cm soil layer near the river [28]. However, when they are growing farther from the river, *P. euphratica* mainly uses groundwater and soil water that is below 120 cm, and the utilization ratio of the groundwater

reaches 40-50%, whereas the groundwater utilization rate for *T. chinensis* is up to 95% [29]. In addition, *P. euphratica* and *L. ruthenicum* seedlings mainly use soil water that is in the 0-20 cm soil layer, *K. caspica* uses soil water that is in the 50-100 cm soil layer, and *Sophora alopecuroides* uses soil water that is in the 5-10 cm soil layer [30]. Therefore, groundwater and soil water are closely related to plant growth in arid areas, which is consistent with the results produced by this study.

In arid areas, the groundwater depth increases and soil water content decreases with increasing distance from the river [31]. In other words, water conditions become worse as the distance from the river increases. Therefore, the changing characteristics of the vegetation at different distances from the river can reflect the change in water conditions. This study selected the following dominant species: *P. euphratica*, *T. chinensis*, *H. halodendron*, *A. sparsifolia*, *K. caspica*, *P. communis*, and *P. hendersonii*. Then the importance values for these species were calculated at different distances from the river (Fig. 8).

Fig. 8, shows that the important values for *H. halodendron*, *K. caspica*, and *P. communis* etc. decreased as distance from the river increased. Up to 500 m from the river, all of the tree, shrubs, and herbaceous plants assessed were found. When the distance was more than 500 m away, *P. euphratica* and *T. chinensis* were the most dominant plants, *A. sparsifolia* was also common, but other species were sparsely distributed. Overall, the soil water content is high and the groundwater depth is close to the surface near the river. Therefore, the trees, shrubs, and herbaceous plants grow well. As the distance from the river increased, soil water content decreased and groundwater depth was lower. The herbaceous plants became scarce, gradually disappeared, and were replaced by *P. euphratica* and *T. ramosissima*.

These results from the ecological investigation of the plant community and environmental factors in the lower reaches of the Tarim River, combined with

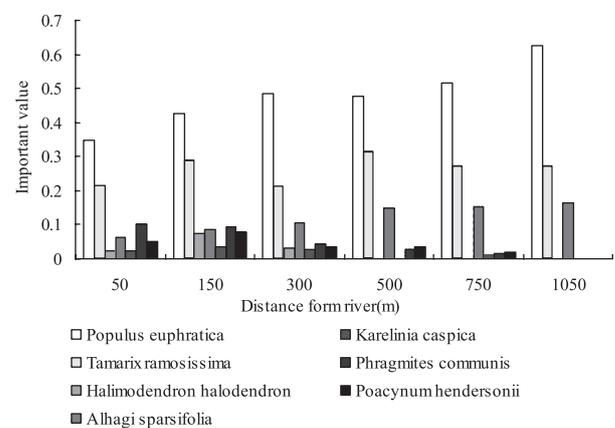


Fig. 8. Variation characteristics of important values of dominant species at different distances from the river.

the two-way indicator species analysis, show that the optimum community structure to prevent and control desertification was a tree-shrub-grass structure. The herbaceous characteristics in the different areas varied considerably in the lower reaches of the Tarim. The good windbreak performance of the herbs suggests that attention should be paid to restoring herb cover during vegetation ecological construction, which would improve desertification prevention and control. In areas where herbs are rare, such as the Karday and Yiganbjm sections and other similar areas, water diversion irrigation and river flooding can be used, and artificial rain propagation techniques, such as artificial falling water seeding, can be adopted to improve the growth conditions of herbaceous plants. These measures would increase density and coverage by herbaceous plants and lead to a large tree-shrub-grass belt. Finally, an effective ecological barrier and sand filter zone that can protect soil stability and sustainable development has already been created in front of the oasis.

The lower reaches of the Tarim are sparsely populated, and there is little industrial activity. At present, the most important project is vegetation and ecological restoration based on river water flow. The key factors affecting the vegetation characteristics are groundwater depth and soil water content in the lower reaches of the Tarim. In previous studies, the relationship between vegetation and water has focused on the changes in vegetation characteristics as varied water levels [32-33]. In the present study, the relationship between vegetation and water has been described quantitatively, and the results show that there is a high correlation between vegetation characteristics and groundwater level and soil water content. As a result, vegetation characteristics can be used as indicators of water conditions (groundwater and soil water) in the lower reaches of the Tarim. Therefore, the main environmental factors mentioned above should be taken into account during the restoration and reconstruction of the damaged ecosystem in the lower reaches of the river. In particular, rational development and utilization of the water resources must be emphasized, and suitable irrigation methods should be used to prevent the decline in the groundwater level and the occurrence of soil salinization.

To date, ecological water transportation has been implemented 18 times in the lower reaches of the Tarim. Generally speaking, there are some changes in the composition and coverage by plant communities during different water transport seasons [34-35]. However, the results of the present study only represent the plant community situation in summer 2017, which means it only covers a small part of the changes in the distribution and composition of plant communities in the lower reaches of the Tarim. Therefore, further studies on the dynamics between plant coverage and composition, and the environmental factors affecting the plant communities in this region need to be undertaken.

Conclusions

- 1) There were 32 plant species that belonged to 15 families and 30 genera in the lower reaches of the Tarim River. Furthermore, the frequency of most plant species was very low, which shows that plant species richness was also low in this area. *Tamarix chinensis* had the highest frequency of occurrence. It was found in 16 sample plots in four transects, which accounted for 66.67% of all sample plots. The next most frequent were *P. euphratica* and *A. sparsifolia*.
- 2) The classification of the 24 sample plots and the number of species showed that the 24 sample plots in this region can be divided into 4 groups and 9 types. This analysis was consistent with the physical survey of the 4 transects, and there are also obvious differences among different plot types. Furthermore, the 32 plant species were divided into 3 groups by TWINSpan, and most of the species in group III were less frequent in the actual sample plots. The quantitative classification results for the sample plots and species showed that the tree-shrub-grass structure had the highest stability, and strongest windbreak and sand fixing capacities. Furthermore, the restoration of windbreak and sand fixing vegetation should focus on the construction of understory herb layers.
- 3) The most important environmental factors affecting the distribution of the plant communities and the 32 plant species in the lower reaches of the Tarim were groundwater depth and soil moisture content. This study quantitatively revealed the relationship between vegetation characteristics, groundwater depth, and soil water content. The results show that there is a significant correlation between vegetation characteristics and groundwater depth and soil water content. Therefore, the vegetation characteristics can be used as an indicator of water condition changes in the lower reaches of the Tarim River.

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Conflict of Interest

The authors declare no conflict of interest.

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