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Arbuscular mycorrhizal fungi infection in desert riparian forest and its environmental implications: A case study in the lower reach of Tarim River

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Abstract

This study was conducted on the desert riparian forest along the lower reach of the inland Tarim River, which is located in the arid region of Northwest China. Fifteen plant species in 10 families were collected from five monitoring sections, and examined for the infection of arbuscular mycorrhizal fungi (AMF). The impact of different soil factors on AMF infection rate and intensity was compared using the principal component analysis (PCA) method. The results indicate that 11 species are AM and only 4 are non-AM plants. The estimated capacity of AMF infection depends on families of plants and also the parameters (infection rate, infection intensity, fungal spore density) used. The density of fungal spores was relatively higher in *Phragmites communis* and *Populus euphratica* in Graminaceae and Salicaceae families, respectively. The infection rate was above 50% in all the AM plants, except *Calligonum junceum.* The highest infection rate appeared in *Alhagi sparsifolia* (97%) and *Glycyrrhiza inflata* (92%). However, when compared by AMF infection intensity, *Tamarix* spp. became the top one, followed by *Alhagi sparsifolia*, and *Glycyrrhiza inflata* was in the middle range of all the species. The PCA has identified that soil total salt, moisture, organic matter, total nitrogen, total P, available K and pH were closely associated with the AMF infection.

Keywords: Arbuscular mycorrhiza; Infection; Ecological restoration; Desert riparian forest; Soil

1. Introduction

Arbuscular mycorrhizal fungi (AMF) are distributed widely as one major component of the natural ecosystem in the world. They have been playing a very important role in vegetation succession of ecosystem, species diversification and productivity, as well as restoration of damaged ecosystems [1–3]. An appropriate and stable AMF species population is an essential part for a healthy ecosystem.

Desert riparian forest is the major forest resources in a desert environment; it is also the natural protection shield for the ecological system in the arid region of Northwest China [4]. Normally, only a few plant species are contained in a desert riparian forest ecosystem, which has a relatively simple vegetation structure. Even though, this natural vegetation has an irreplaceable role in protecting the desert environment. Along the Tarim River basin, the river stream and groundwater support the salt tolerant plants including *Populus euphratica*, *Tamarix* spp., *Phragmites communis* and others. These species form a scenery corridor of natural vegetation zone [5], which functions as a barrier to the desert to protect the oasis. In the last five decades, large scale usage of water and soil resources and the global climatic changes [6] have led to discontinuous water flow in the lower reach of Tarim River. Consequently, groundwater has seriously declined, larger areas of natural vegetation have degenerated, and wind erosion and desert-

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ification process are becoming very intense. Tarim River lower reach area is now one of the most problematic regions in the Northwest China. The very serious ecological and environmental situation has caught the attention from both administration and community [7].

Relevant studies on AMF focus on investigation and identification of AM resources [8], function of the AM on plant growth, community structural regulation and soil property changes [1–3,9], AM structural types and infection states [10], AMF species distribution, and AMF diversity affected by environmental factors [11–13]. These researches were mostly performed on tropical forest and steppe plants. Very little is known about the AMF infection in the desert riparian forest ecosystem, and the associated relationship between the AMF and soil environment. Even more scarce is the information about the extreme drought conditions, such as whether the desert riparian forest plant roots are infected with AMF, the infection efficacy of the AMF in this area, and the main soil factor affecting AMF infection.

This study targets the desert riparian forest in the lower reach of Tarim River in Xinjiang, China. The objectives were to determine the relationship between the AMF status and soil conditions under the extremely arid environment, to understand the AMF infection in desert riparian forest, and to investigate the interaction among plants–microbes-environmental factors in this ecosystem. The information obtained from this study will help to understand the desert riparian forest ecosystem as a whole, and enrich the knowledge on distribution range of AMF. Additionally, it will be very useful to reveal the drought and salt tolerant mechanism of the few dominant species of *Populus euphratica* and *Tamarix* spp. This study will provide the foundation for designing the strategies for ecosystem restoration in the lower reach of Tarim River.

2. The outline of the study sites and methodology

2.1. Outline of the study sites

The Tarim River basin, with an area of 1,020,000 km^2, covers the entire southern Xinjiang in Western China. The main channel of the Tarim River is 1,321 km in length, and covers an area of 17,600 km^2. Our study area is located between Daxihaizi Reservoir and Taitema Lake in the lower reaches of the Tarim River (39°38'-41°45' N, 85°42'-89°17'E) [7]. The river has a stable structure with 350 m thick clay sediment from Quaternary period. Geographically, the area is a flat land with an annual precipitation between 17.4 and 42.0 mm and average evaporation (potential) at 2,500 and 3,000 mm. It has a temperate continental type of climate with extremely arid conditions. The ecological environment is very fragile. The lower reach of Tarim River has on its east side the Kuluke desert, on the west side Taklamakan desert, and an alluvial plain between the two deserts. The natural vegetation in this region is very different from the surrounding areas. The major plant species growing here mainly belong to the following families: Salicaceae, Tamaricaceae, Leguminosae, Apocynaceae, and Gramineae. The species include trees like *Populus euphratica*, shrubs of *Tamarix* spp., *Lycium ruthenicum*, *Halimodendron halodendron*, etc., and herbaceous plants consisting of *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Karelinia caspica*, *Glycyrrhiza inflate.* Because of the long-term flow cutoff of mainstream in the river, these plants grow very poorly.

2.2. Materials and methods

2.2.1. Sample collection and processing

Samples were collected along the river in the lower reach of Tarim River from the existing monitoring sections in the fall of 2006. We selected a total of 15 species including *Populus euphratica* and *Tamarix* spp. The root system with fine roots and the rhizosphere soil was dug from the ground, each soil sample weighed ca. 1 kg. These 15 species in 10 families and their respective biological properties are listed in Table 1. For *Populus euphratica* and *Tamarix* spp., samples were collected from one tree on each site. All the other species only had a small number unevenly distributed, therefore samples were randomly collected from 2 to 3 trees on the selected sites. The sampling size was 9 trees for *Populus euphratica*, *Tamarix* spp., *Karelinia caspica* and *Phragmites communis*, and 3–5 trees for the other species. *Populus euphratica* and *Tamarix* spp. trees have a deep and big root system, therefore the sample collection depth started from where fine roots appeared, normally at 70/60 cm below ground. Using the multi-layer sampling strategy, fine roots together with the surrounding soil were sampled once every 30 cm, and the total sampling depth reached 230 cm. Because the fine roots of *Populus euphratica* and *Tamarix* spp. appear at different depths of soil, the starting position for collecting the samples in the same monitoring section was adjusted accordingly. The additional spatial heterogeneity of soil properties makes it very difficult to obtain highly reproducible root samples for these two species.

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

Family	Plant species	Life form
Salicaceae	*Populus euphratica*	Tree
Elaeagnaceae	*Elaeagmus angustifolia*	Tree
Tamaricaceae	*Tamarix* spp.	Shrub
Leguminosae	*Alhagi sparsifolia*	Shrub
	Halimodendrom halodendron	Shrub
	Glycyrrhiza inflata	Perennial herbage
Solanaceae	*Lycium ruthenicum*	Shrub
Apocynaceae	*Poacynum hendersonii*	Perennial herbage
Gramineae	*Phragmites communis*	Perennial herbage
Composiate	*Hexinia polydichotoma*	Perennial herbage
	Karelinia caspica	Perennial herbage
Polygonaceae	*Calligonum junceum*	Shrub
Chenopodiaceae	*Haloxylon ammodendron*	Shrub
	Salsola collina pall.	Annuals
	Salsola ruthenica	Annuals

Therefore, root and the rhizosphere soil samples collected at different depths (layers) were treated as separate samples for these two species.

Fresh roots (ca. 0.2 g) were isolated from each sample. For *Populus euphratica* and *Tamarix* spp. fine roots collected from each layer of soil were considered as an individual sample. These roots were washed in tap water and cut into 1.0–2.0 cm in length, and then placed into small glass bottles containing the FAA fixing solution (formaldehyde 5 ml, glacial acetic acid 5 ml, 70% ethanol). They were stored at 4 °C after being brought back to the laboratory. These root segments were used to examine AMF infection rate and infection intensity. The air dried soil samples were used to analyze soil physical and chemical properties, identify AMF and count the spores.

2.2.2. Sample analysis

2.2.2.1. AMF infection rate. Roots were stained with acid fuchsin after being lysed in alkaline solution (Berch and Kendrick) [14]. Briefly, roots in 10% KOH were steamed by autoclave at 121 °C (1.05 kg/cm^2 or 0.1 MPa/cm^2) for 10 min. After removal of KOH, the roots were washed until complete disappearance of the brownish color. The clean roots were then destained by soaking in alkaline H_2O_2 (3 ml NH_4OH, 30 ml 10% H_2O_2 in 567 ml H_2O, freshly prepared) for 20–60 min. The older and bigger root segments were soaked in H_2O_2 for 10–60 min. The clear roots were then soaked in 1% HCl for 3–4 min following a rinse in tap water. After removal of the exudates, and adding 0.01% acid fuchsin–lactic acid (lactic acid 874 ml, glycerin 63 ml, H_2O 63 ml, acid fuchsin 0.1 g), the roots were hot-stained in an autoclave at 121 °C (1.05 kg/cm^2 or 0.1 MPa/cm^2) for 10 min. Eventually, these roots were destained with lactic acid (same solution for acid fuchsin staining without the dye) for 30 min. After that, the stained roots were prepared into permanent slides and observed under a microscope.

Thirty fine roots of 1.0 cm in length were examined under an Olympus BX15 microscope. The number of root segments forming AM was counted with criss cross lacing method and used to calculate AMF infection rate [15]. Simultaneously, occurrence of AM typical structure, arbuscles or vesicles, was recorded as "+" or "−" for presence or absence, respectively. If the roots only had hyphae, the plants were not considered as AM plants, only those with AM typical structure were considered as AM plants. (In this study, if at least one root segment was observed to contain coils/arbuscles or vesicles, then the plant was recorded as an AM plant and denoted as "+".) If the root cortex was found to be colonized by fungal mycelia without coils/arbuscles or vesicles, the plant was recorded as possibly AM. According to AMF infection intensity of plant root, the infection was graded into 4 levels, 0 for no AMF infection, low for infection intensity less than 10%, medium for 10–30%, high for above 30%. AMF infection rate and intensity were calculated using the following equation:

$$\text{AMF infection rate } (F_a)\ (\%) = \text{infected root segments/total root segments} \times 100 \quad (1)$$

$$\text{Infection intensity of the whole root system } (M_a)\ (\%) = (95n5 + 70n4 + 30n3 + 5n2 + n1)/\text{total root segments} \quad (2)$$

where $n5$ means the number of root with infection level of 5 (infection rate 90–100%), $n4$ is the root number at level 4 infection (infection rate 50–90%, $n3$ is root number at level 3 (infection rate at 10–50%), $n2$ is root number at infection level 2 (infection rate 1–10%), $n1$ is root number at level 1 (infection rate 0–1%).

2.2.2.2. Extraction and counting of AM fungal spore. About 20 g of air dried soil randomly taken from the original collected sample was used to isolate spore or sporocarps using the triple wet sieving method. Those spores or sporocarps passing the sieve (53 μm pore size) were placed onto a piece of fine grid filter paper (4 mm × 4 mm). After being washed three times with distilled water, they were spread out in the grid, and then were counted under an optical microscope (amplification 30×). Each sporocarp was counted as one spore. Three replicates of the same procedure were conducted for every soil sample. AMF spore density was defined as AMF spore number in 20 g air dried soil.

2.2.3. Determination of soil properties

Soil samples were subsequently analyzed in the laboratory for pH and electrical conductivity (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 (colorimetry), total K (flame emission spectroscopy), available N (diffuse), available P (Bray-P), available K (NH_4–acetate). Total soluble salts were measured by weighing method. Soil water content was determined using oven-dry method [16].

2.3. Data analysis

The mean of AMF infection data from all the plants of each species was used to evaluate the AMF infection status. Soil is spatially heterogeneous, especially the properties are different depending on the depth of the soil in the lower reach of Tarim River [17]. Consequently, the root of *Populus euphratica* and *Tamarix* spp. and their rhizosphere soil collected from each layer (depth) was treated as individual samples when performing the analysis of the AMF living environment, and relationship between AMF infection rate and soil properties. All statistical analyses were conducted with SPSS11.0 software.

3. Results and analysis

3.1. Soil environment for AMF

The basic soil properties where the AMF lived along the lower reach of the Tarim River are presented in Table 2.

Table 2
The basic soil properties of AMF living in the lower reach of Tarim River ($n = 76$)

Items	Min	Max	Mean	Std. deviation	Variance	Mode	Median
pH	7.65	9.48	8.47	0.416	4.92	8.58	8.58
TS (g kg^{-1})	0.275	9.925	1.96	2.217	113.16	0.375	1.15
WC (%)	0.28	23.92	5.40	6.456	119.54	0.33	2.71
OM (g kg^{-1})	0.6	6.827	2.83	1.615	57.02	1.241	2.3
TN (g kg^{-1})	0.03	0.5	0.16	0.092	57.34	0.06	0.14
TP (g kg^{-1})	0.3	0.64	0.48	0.073	15.15	0.49	0.49
TK (g kg^{-1})	15.63	24.87	17.90	1.642	9.17	17.08	17.43
AN (mg kg^{-1})	0	29.4	8.21	7.024	85.55	0	6.53
AP (mg kg^{-1})	0.96	4.55	1.55	0.525	33.89	1.28	1.44
AK (mg kg^{-1})	56	500	137.82	88.116	63.94	154	111

Note. TS, total salt; WC, water content; OM, organic matter; TN, total N; TP, total P; TK, total K; AN, available N; AP, available P; AK, available K (the symbols are the same as in Table 4).

The soil environmental conditions, the soil properties and the associated extent of variance, all have significant differences. Generally speaking, the AMF lives under poor and very unstable soil conditions. Those soils contain high content of salt and low moisture, and the organic matter was in the shortage or extremely shortage status (<10 g kg^{-1}). There was a lack of total N (<0.75 g kg^{-1}), and the available N content was also very low. The available P content was extremely low (<3 mg kg^{-1}), and available K was in the medium level (100–150 mg kg^{-1}). The mode, median, and mean of soil pH value were ca. 8.5 with very slight variance, which indicates that the AMF can live in slightly alkaline soil (pH 7.5–8.5), some can even tolerate high pH condition.

3.2. Formation of AM from the plants in the lower reach of Tarim River

The AMF infection status and spore density in the rhizosphere soil can be seen in Table 3. Among the 15 plant species, 73.33% (11 species) formed the typical AM structure on their roots. These plants are from Salicaceae, Elaeagnaceae, Tamaricaceae, Leguminosae, Solanaceae, Apocynaceae, Gramineae, Composiate families. *Calligonum junceum* had a low AMF infection rate and intensity and no typical AM structure, and it was therefore classified as a non-AM plant. There were 4 species (26.67%) that did not form AM. The 4 non-AM plants are from the two families of Polygonaceae and Chenopodiaceae. When classified according to the vegetation types (arbor, shrub, and herbage), arbor and perennial herbage are all AM plants. For the shrubs, two species (*Calligonum junceum* and *Haloxylon ammodendron*) are non-AM plants, and all the rest are AM plants.

3.3. The variance of AMF infection among plants in different families

The AMF spore density varied significantly among plants in different families, indicating AMF infection status is affected by the host species (Table 3). For instance, the AMF spore density obviously did not match between *Phragmites communis* in Gramineae family and *Populus euphratica* in the Salicaceae family. When compared by the infection rate, all the other AM plants, except *Calligonum junceum*, had infection rate >50%. *Alhagi sparsifolia*

Table 3
The AMF infection status in the rhizosphere soil in the lower reach of Tarim River

Plant species	Infection intensity	Vesicles	Arbuscle	Hyphae	Spore density
Populus euphratica	High	+	+	+	69–150
Elaeagmus angustifolia	Medium	+	/	/	/
Tamarix spp.	High	+	+	+	70
Alhagi sparsifolia	High	+	−	+	10–15
Halimodendrom halodendron	Medium	+	−	+	40
Glycyrrhiza inflata	Medium	+	−	+	15–20
Lycium ruthenicum	Medium	+	−	+	100
Poacynum hendersonii	High	+	−	+	5
Phragmites communis	Medium	+, −	−	+	140–400
Hexinia polydichotoma	Low	+	−	−	/
Karelinia caspica	Medium	+	−	+	13–51
Calligonum junceum	Low	−	−	−	/
Haloxylon ammodendron	0	−	−	−	/
Salsola collina pall.	0	−	−	−	/
Salsola ruthenica	0	−	−	−	/

(a) 0, no infection; low, <10%; medium, <30%; high, >30%; (b) −, non-existence; (c) +, yes; (d) /, not available.

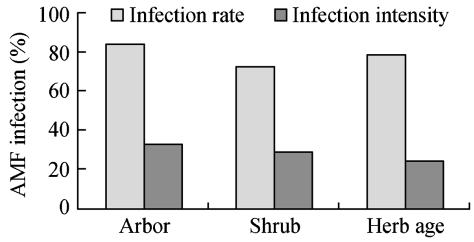

Fig. 1. Variation of AMF infection among different vegetation types.

and *Glycyrrhiza inflata* had the highest infection rates of 97% and 92%, respectively. When measured by infection intensity, *Tamarix* spp. had the highest AMF infection intensity, followed by *Alhagi sparsifolia*, and *Glycyrrhiza inflate* was in the middle. Further variance analysis revealed a big difference among the different species in both AMF infection rate ($F = 2.187$, $P = 0.019 < 0.05$, $df = 11$) and AMF infection intensity ($F = 3.377$, $P = 0.000 < 0.05$, $df = 11$).

Difference in terms of AMF infection rate was observed among arbor, shrubs and herbage plant (Fig. 1). However, further variance analysis confirmed that the variation was not statistically significant ($F = 0.10$, $P = 0.99$, $df = 2$). In contrast, the infection intensity was significantly different among the three types of vegetations ($F = 7.833$, $P = 0.001$, $df = 2$). Such a disparity between the infection rate and intensity indicates that the two parameters can differentially represent AMF infection capacity. On the other hand, the difference of AMF infection intensity reflects the genus specificity of both AMF and its host, it also reflects the heterogeneity in the host growth environment. The negligible difference in AMF infection rate emphasises that the AMF can remain active in an adverse environment to benefit all the plant species.

When compared by the life forms (annuals and perennials), the AM formation was also different among the AM plants. No AMF infection was observed on the roots of the annuals, but all the perennial grasses had AMF infection, some plants actually had a quite high AMF infection rate and intensity. The two annual species *Salsola collina pall* and *Salsola ruthenica* in Chenopodiaceae had no AMF infection, which agrees with a reported research. Plants in this family have been considered as non-AM plants; however, more studies have also found AMF infection in these plants [18,19]. O'Connor et al. observed the vesicular structure in the root systems of two *Salsola kali* and *Sclerolaena diacantha* in Chenopodiaccae [20].

3.4. The relationship between soil properties and AMF infection

Environmental factors greatly affect the AMF diversity and their infection capacity of plant roots [12]. Soil as an important habitat factor, its heterogeneity in the soil properties (organic matter, N, P, K, water and salt) can directly influence the activity of soil microorganisms. The comprehensive effect from all these factors will result in a complex impact on soil microorganism. For the AM plants in the lower reach of Tarim River, the correlation relationships among the AMF infection intensity, infection rate and soil properties are shown in Table 4. The AMF infection intensity was strongly correlated with soil organic matter, soil water content and total P ($P < 0.01$), also with total N, total salt, available N and K ($P < 0.05$). Infection intensity had a significant linear correlation with infection rate and all the soil property parameters had a significant correlation ($P < 0.01$). Therefore, all the soil property parameters were grouped into several comprehensive indexes with PCA, in order to determine their relationship with AMF infection intensity and rate.

The KMO statistics is used to compare correlation and partial correlation coefficients. A KMO test being closer to 1 indicates that the factor analysis has a better effect for those variances. In this study, the KMO index was 0.760 for all the soil property indices after KMO and Bartlet tests, which has validated that those data were appropriate for factor analysis and are expected to yield reliable results. Subsequently, all the factors with a property value above 1 were extracted with PCA, and the eigenvalue of the common factor and the contribution rate was calculated after varimax rotation (Table 5). The three comprehensive factors scores can be calculated using multiple regression

Table 4
Pearson correlation index between AMF infection parameters and soil factors

Items	F_2	F_a	M_a	pH	TS	WC	OM	TN	TP	TK	AN	AP
F_a	0.30[b]											
M_a	0.25[a]	0.54[b]										
pH	−0.30[b]	−0.22	−0.17									
TS	0.66[b]	0.28[a]	0.22	−0.49[b]								
WC	0.36[b]	0.29[b]	0.27[a]	−0.37[b]	0.67[b]							
OM	0.53[b]	0.30[b]	0.23[a]	−0.65[b]	0.63[b]	0.69[b]						
TN	0.49[b]	0.27[a]	0.25[a]	−0.66[b]	0.68[b]	0.71[b]	0.95[b]					
TP	0.85[b]	0.33[b]	0.29[a]	−0.37[b]	0.45[b]	0.45[b]	0.60[b]	0.54[b]				
TK	0.09	0.17	0.22	−0.41[b]	0.67[b]	0.80[b]	0.60[b]	0.66[b]	0.14			
AN	0.07	0.26[a]	0.07	−0.31[b]	0.43[b]	0.46[b]	0.54[b]	0.50[b]	0.19	0.53[b]		
AP	0.03	0.11	−0.09	−0.40[b]	0.13	−0.03	0.34[b]	0.26[a]	0.06	0.04	0.48[b]	
AK	0.75[b]	0.29[a]	0.17	−0.17	0.74[b]	0.45[b]	0.51[b]	0.46[b]	0.48[b]	0.37[b]	0.43[b]	0.22

Note. [a]Significant difference ($p < 0.05$); [b]significant difference ($p < 0.01$); F_a, infection rate; M_a, infection intensity.

Table 5
Total variance explained

Component	Initial eigenvalue			Rotation sums of squared loadings		
	Total	% of variance	Cumulative%	Total	% of variance	Cumulative%
1	6.096	55.421	55.421	3.413	31.027	31.027
2	1.380	12.548	67.970	2.950	26.818	57.845
3	1.035	9.411	77.381	2.149	19.536	77.381
4	0.994	9.033	86.414			
5	0.652	5.925	92.339			
6	0.302	2.746	95.085			
7	0.242	2.203	97.287			
8	0.144	1.311	98.598			
9	0.119	1.078	99.675			
10	0.034	0.309	99.984			
11	0.002	0.016	100.000			

method. For this study, the three comprehensive factors, F_1, F_2 and F_3 had a cumulative rate of 77.38%, which indicates that they can represent enough information of the original data about the soil property parameters.

The correlation analysis found that F_1, F_3 had no significant correlation with AMF infection intensity and infection rate. Because F_2 was positively correlated with these two parameters (Table 4), it was considered as the "promoting factor" for AMF activity. The soil properties that had significantly positive correlation include soil salt content, water content, organic matter, total N and P, and available K, but soil pH was negatively correlated. Based on the analysis, these soil properties associated with F_2 should form the soil microenvironment that affects AMF infection intensity and rate. Although pH value did not affect the infection intensity and its rate, it had a negative correlation with F_2 (Table 4). As indicated earlier F_2 is the "promoting factor" of AMF, the negative relationship between F_2 and soil pH led us to postulate that lower pH can benefit the activity of the AMF, and enhance the infection intensity and rate in the desert riparian forest. Therefore, managing soil pH is a feasible way for restoring the ecological system along the lower reach of Tarim River.

The relationship between soil properties and comprehensive factor F_2 can be expressed using the equation $F_2 = -0.30\mathrm{pH} + 0.66\mathrm{TS} + 0.36\mathrm{WC} + 0.53\mathrm{OM} + 0.49\mathrm{TN} + 0.85\mathrm{TP} + 0.09\mathrm{TK} + 0.07\mathrm{AN} + 0.03\mathrm{AP} + 0.75\mathrm{AK}$ (the symbols are the same as those in Table 4), when using the score of F_2 from each sample as an independent variable, and AMF infection rate and intensity as dependent variables, the stepwise regression analysis established the regression correlation $F_a = 0.923 + 0.05F_2$ and $M_a = 0.0539 + 0.061F_2$, where the independent variable coefficient and constant in the equation all passed statistics analysis ($p < 0.05$). In addition, F_2 was positively and significantly correlated with total salt, which is conflicting with the role of F_2 as "promoting factor". Some researches suggest that high salt content can inhibit AM formation because AMF infection reduces as soil salt content increases [13]. In this analysis, the positive correlation between total salt and F_2 only indicates that salt contributes largely to F_2, and thereby affecting the "promoting factor". Good soil condition should essentially have high nutrients, appropriate water and lower salt content. What F_2 represents actually is the soil microenvironment affecting AMF growth. The conclusion is that good soil condition with appropriate water status and lower salt is beneficial for AMF infection, otherwise, it will inhibit the process.

Soil salt content is also closely associated with AMF infection. The Pearson correlation analysis indicated that for AM plants, the AMF infection intensity was significantly correlated with SO_4^{2-} ($R = 228*$, $P < 0.05$) and Ca^{2+} ($R = 228*$, $P < 0.05$). An inter-correlation between ions was also observed, and most of them were with HCO_3^-. Further analysis of the partial correlation by controlling the content of HCO_3^- has found that AMF infection intensity was significantly and positively correlated with SO_4^{2-}, Ca^{2+}, Mg^{2+} contents. To summarize, AMF infection intensity is possibly correlated with soil salt components of SO_4^{2-}, Ca^{2+}, Mg^{2+} in the lower reach of Tarim River.

4. Conclusions and discussion

The presence of the arbuscular mycorrhiza is the key indicator for determining if a plant species is the AM plant. Among the 15 species investigated in the lower reach of the Tarim River, 11 are AM plants; however, no AM structure was observed on most of the root system of these plants, which supports the results from other studies [21]. The reason is that active AM only appears transiently in the growing roots. At the time when samples were collected, the AM structure had disappeared, and consequently could not be observed in the root tissues. However, most plants from the tropical secondary forest in Xishuangbanna, Yunan province, China have the AM structure.

This study has confirmed that *Calligonum junceum* is a non-AM plant. However, this species has been reported to be infected by AMF, and hyphae but not vesicle has an AM structure and low spore density on the plant roots [8]. This disparity may result from different growth habi-

tats, microorganism composition and activity. In addition, different plants standing can have varied impacts on the rhizosphere microorganism. Consequently, the possibility of the same plant species being infected by AMF also depends on the growth environment.

According to the AMF infection rate, all AM plant species are rated as *Alhagi sparsifolia* > *Glycyrrhiza inflata* = *Phragmites communis* > *Populus euphratica* > *Karelinia caspica* = *Poacynum hendersoni* > *Tamarix* spp. > *Lycium ruthenicum*. Based on infection intensity, they are rated as *Tamarix* spp. > *Alhagi sparsifolia* > *Populus euphratica* > *Poacynum hendersonii* > *Karelinia caspica* > *Glycyrrhiza inflata* > *Lycium ruthenicum*. When compared by the spore density, the leguminous plants *Alhagi sparsifolia*, *Glycyrrhiza inflata* and *Halimodendrom halodendron* are all in the upper range of infection rate and intensity. However, they are still much lower than *Phragmites communis* in the Gramineae family and *Populus euphratica* in the Salicaceae. Based on these results, using different parameters to compare AM plants will lead to different conclusions, which may be caused by the developmental stages of the AMF. Spores are the major reproduction form that lives in soil for relatively long time period. In contrast, the AM are short lived, they will degrade completely within a few to 10 days. While the hyphae composes the major body of colonization structure of the AM, it distribute widely in plant roots. Vesicular-mycorrhizal (VM) structure begins to form when the arbuseular mycorrhiza starts to degrade. These VM structure has a longer colonization period and appears on roots in a large population. It sometimes enters into soil through wounded tissues and continues to infect other plant root system [22]. When the experiment was conducted, the host plants were at different developmental stages, single indices (infection rate or intensity) cannot reflect the real difference of AMF infection among the host species. Consequently, multiple parameters should be used to evaluate the plant AMF situation.

The relationship between AMF colonization rate and spore density is still a disputing issue. Some reports that the highest AMF colonization rate (infection rate) is often accompanied by relatively higher spore number [23,24], but others propose that they have no correlation because higher spore number can produce lower colonization rate (infection rate), or vice versa [25,26]. In this study, AMF infection intensity, infection rate and spore density have no correlations. The legume species, *Alhagi sparsifolia*, *Glycyrrhiza inflata* and *H. halodendron*, all had higher AMF infection rate and intensity, but their spore density was much lower than the herbaceous *Phragmites communis* and the tree *Populus euphratica*. This happens because AMF with stronger infection ability can have lower spore production capacity, while those with higher spore production ability does not necessarily form efficient infection [27]. Besides, even for the same AMF symbiotic on different host plants at different growth stages, the host can provide different amounts of carbohydrates to the AMF, which will subsequently result in varied productions and accumulations of AMF spores in the rhizosphere [28]. *Alhagi sparsifolia* and *Glycyrrhiza inflata* have higher infection rates, probably because they are all legumes, their roots normally have rhizobium which have a mutualism relationship with AMF [29].

Soil environment can greatly affect life and activity of microorganism. Previous studies have shown that in the Tibet Plateau, AMF spore density in steppe plants is significantly and positively correlated with pH value, but AMF infection rate has no such a relationship [30]. This study also found that soil pH value had no direct impact on AMF infection rate. All these results indicate a complicated relationship between soil and AMF infection. High soil available P content inhibits AMF growth, development, and AM formation as well as their functions [30]. However, there are some studies where the soil available P has no obvious effect on AM spore formation and infection [31]. Mille et al. [9] and Dhillion et al. [32] pointed out that AMF infection intensity is negatively correlated with soil nutrient contents, especially the available P and N. Our study found that available P had no obvious correlation with AMF infection rate and intensity, indicating a lack of connection between available P content and AMF infection.

Drought is the most important abiotic stress for plant growth and development. The lower reach of Tarim River is one of the most drought inflicted region in China. Due to water limitation, there are very few sketchy species to form a very simple vegetation structure in this area. During the process of environmental changes, more drought tolerant species can survive, such as the arbor (*Populus euphratica*), shrub (*Tamarix* spp., *N. sibirica*, *Halimodendrom halodendron*) and the herbage (*Glycyrrhiza inflata*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Phragmites communis*, etc.). However, this study found most of the plants in the investigated area have AM. Moreover, as more detailed examinations will be performed on these plant samples, the ratio of AM plant is expected to increase. Some researches indicate that under drought condition, AM can improve water relationship of the host plants, and thereby increasing host survival ability [33]. Morte et al. found that under water stress, the water potential of AM plant increased by 26% compared to the non-AM plant, transpiration increased by 92%, the stomata conductance increased by 45%, and net photosynthesis increased by 88% [34]. In addition, the formation of AM network in the soil can improve the formation of soil aggregates to improve its structure, and the fungi help to effectively absorb and transport mineral nutrients to the plants under poor soil conditions [35], or redistribute these nutrients among these plants [36,37]. Besides under specific conditions, AMF with the established symbiont relationship with the fine roots will exhibit high infection intensity, which plays key roles in stabilizing the whole plant habitat [38]. Therefore, under drought and poor soil conditions, AMF should be one major reason for the survival of species like *Populus euphratica* and *Tamarix* spp., and others. It is also the major contributor for maintaining the stability of the desert river bank forest along the Tarim River.

During restoration of a biotic community, AMF will have a significant impact on the structure of the vegetation. Particularly, the human-introduced AMF inoculates can speed up the restoration process of the damaged habitat. Although the successful rate is still quite low, there are some cases where the AM biotechnology has applied to restore the degenerated ecosystem. For instance, Sylvia et al. reported inoculating AMF on the wild *Avena fatua* L. to enhance their survival and growth in the poor coast soil so that to protect the large area erosion in the Florida coast [39]. Another case is using the AM biotechnology for the soil re-plantation project in the vicinity of the mineral mines in Australia [40]. In southern Spain of the Mediterranean area, Requena et al. inoculated the allochthonous and indigenous AMF onto the seedlings of legumes *Anthyllis cytisoides* to restore the degenerated vegetation. Those plants inoculated with the indigenous AMF have higher height and rhizosphere organic matter content [41]. Therefore, when using allochthonous and indigenous plants to restore the vegetation in the lower reach of Tarim River, it is very important to predetermine whether soil contains the corresponding AMF. Furthermore, as one component of the ecosystem, the presence and polymorphism of AMF contribute to the maintenance of plant diversity and the ecosystem functions [42]. When the AMF host plant is a dominant or constructive species, it can become a keystone species. Losing it will cause significant changes of the whole ecosystem [43]. Therefore, in the lower reach of the Tarim River, adopting the AM technique is very important to boost vegetation restoration, and speed up the progress of restoration projects, especially for the protection of the two major construction species *Populus euphratica* and *Tamarix* spp.

Development of AM, vesicles and hyphae has its specific timeliness; these structures can appear on the root segments at different times and developmental stages. This study has accumulated some information about the AMF infection in a desert riparian forest along the lower reach of the Tarim River. Future studies will further identify the AM types of the 15 plant species. At the same time, we will identify the AMF species, this will establish a solid basis for protection of the forest species (*Populus euphratica* and *Tamarix* spp.) and application of AMF technology.

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