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ORIGINAL ARTICLE

Influence of soil moisture and electrical conductivity on the growth of *Phragmites australis* (Cav.) in the Keriya oasis, China

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Abstract In this study, we sought to explore the changes of soil moisture and soil electrical conductivity (EC), as well as to study the relationships between these soil properties and the vegetative indexes of plant coverage, height and crown density and diameter during the *Phragmites australis* (*P. australis*) growth period. By combining floristic and edaphic variables (soil moisture and EC), we found that at 0–10 cm depth, the soil moisture varied greatly, while the soil moisture at 10–50 cm depth, EC at 0–50 cm depth, and vegetation properties varied only moderately. A great amount of evaporation offered a possible reason for this moderate variability in soil moisture and EC. Geostatistical analyses revealed that the soil moisture at 0–50 cm depth, and the density of *P. australis* (Cav.) had a strong spatial autocorrelation, while the EC at 0–50 cm depth had only a weak spatial autocorrelation depending on the nugget effect. Furthermore, there was a positive correlation between the soil moisture and vegetation characteristics at the depth of 0–50 cm, but there was a negative correlation between EC and vegetation characteristics at the depth of 30–50 cm. Furthermore, an increase in soil moisture had a positive effect on *P. australis* (Cav.) growth, while an increase in EC had a negative effect.

Keywords Soil moisture · EC · *Phragmites australis* (Cav.) · Soil–vegetation relationship · Keriya oasis

Introduction

The transitional zone between an oasis and desert is a very important part of the ecosystem of the oasis and plays a key role in maintaining its stability. To better understand arid and semi-arid areas, the relationship between the amount of moisture in the soil and the effects on vegetation is an important area that requires further study (Jia and Ci 2003; Daly and Porporato 2005; Chen et al. 2014; Zalewski 2014). The upper soil moisture is important for assessment of area hydrological response. A number of reports showed that a large amount of variability occurs based on location and over time in the surface soil moisture; and it is influenced by factors including soil types, vegetation coverage, topography, land use, and so on (Barajas-Guzmán et al. 2006; Soliveres et al. 2012; Gao et al. 2014; Sun et al. 2014; Vereecken et al. 2014; Zhu et al. 2014). Research on influence of environmental factors on vegetation growing in old fields has drawn more and more interest. Numerous studies have delved into the relationship between edaphic factors and floristic factors (Hedlund et al. 2003; Cayuela et al. 2008). Some studies have demonstrated that soil heterogeneity effects plant competitive interactions, which is particularly influential under stressed environments, such as semi-arid habitats (Cayuela et al. 2008; Soliveres et al. 2012; Badreldin et al. 2014). Consequently, it may be a

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determining factor in the distribution of plants and plant communities (Massaccesi et al. 2015; Zalewski 2014; Zhao et al. 2014). Although many studies have tackled the topic of soil moisture, the spatial heterogeneity of soil quality in desert oases, including the parameters of soil moisture and vegetation, has to be deeply studied (Martínez-Fernández and Ceballos 2003; Molina et al. 2014; Zhu et al. 2014). Furthermore, no agreement has been reached concerning whether the soil moisture variability based on location is positively or negatively correlated with plant growth (Choi et al. 2007; Zhu et al. 2015).

In this study, the soil spatial heterogeneity and vegetation distribution as well as their relationships in a semi-arid area have been analyzed. The semi-arid area in this study was Keriya, an oasis located at the southern rim of Taklimakan Desert, China. Keriya was well suited for this study because it has relatively homogeneous geology, vegetation and climate.

Materials and methods

Study site

The area studied is located on the northern slope of Kunlun Mountains in northwest China. It ranges from 81°09′32″ to 81°11′56″E and from 36°57′01″ to 37°03′00″N with a total area of 41.1 km^2 and an elevation of 1354–1394 m. This area has an arid continental climate with an annual average temperature of 8.1 °C, an average annual rainfall of 124.1 mm that mainly fell between May and September, an average annual evaporation capacity of 2498 mm and an average annual cumulative sun duration of 2833.5 h. The coldest month in a year is January with an average temperature of −7.6 °C, and the warmest month is July with an average temperature of 22.1 °C. The sandstorm was a frequent occurrence in this area. The vegetation within this area was a single community type of *Phragmites australis* (Cav.). *P. australis* covered between 10 and 85 % of this area with an average coverage of 60 % (Wahap et al. 2006). The average height of *P. australis* was 0.6–2.4 plants/m and the average density was 51 plants/m^2.

Plant measurement and soil sampling

A small area of *P. australis* in the Karki Village in the Keriya oasis was selected and observed during the vegetative growth period in 2009. Soil samples were harvested from a 0.5 m × 0.5 m grid designed by GIS (Fig. 1). To obtain the soil profile, a steel core sampler was used to take a stratified sampling at 0–50 cm depth. Totally, soil samples from 126 points distributed across the study area were obtained and the sampling locations were shown in Fig. 1. The soil moisture and EC of each soil sample were measured.

To measure the soil moisture, each soil sample was placed in an aluminum box and weighed, and after dried in an oven at 105 °C for 24 h, they were weighed again. The EC of each soil was tested as follows: first, each of the soil samples was pushed through a 2 mm sieve, and the solution was configurated as soil:water as 1:5, and then an electromagnetic conductivity meter was used for testing (WTW LF, 197).

A plant growth index of *P. australis* was also recorded which included the plant coverage, height, and crown density and diameter. These values were recorded as average values of each 0.5 m × 0.5 m plot, where five *P. australis* had the same amount of growth. Correlations between the soil moisture, soil EC and the growth index of *P. australis* listed above were determined. It is to be noted that samples of each 1 m × 1 m are located in the flat or gentle slope areas at similar altitudes (Massaccesi et al. 2015).

Statistical analysis methods

Calculation of descriptive statistical parameters was performed using Microsoft 2007, which included the mean values, standard deviation (SD), and coefficients of variation (CV) for the soil moisture and salinity at 0–50 cm depth, as well as the vegetation coverage, height, and crown density and diameter. Kolmogorov–Smirnov (K–S) test was used to test these data for a normal distribution, and kurtosis and skewness were also calculated. To identify relationships between these parameters, correlation analysis was performed using the Pearson coefficient between soil moisture and soil EC and the vegetation parameters listed previously. In this research all statistical analyses were performed using SPSS 19.0 (USA) software.

To study the spatial variability of the soil properties of moisture and EC, geostatistical methods were applied (Corwin and Lesch 2005; Liu et al. 2014). The experimental semivariogram for the given distance, h, was calculated using the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [\mathrm{Z}(x_i) - \mathrm{Z}(x_i + h)]^2 \tag{1}$$

where $r(h)$ is the semivariance at a given distance h, $Z(X_i)$ is the variable Z value at the location of X_i, $\mathrm{Z}(X_i + h)$ is the variable Z value at the location of $X_i + h$, h is the lag distance, and $N(h)$ is the pairs number separated by lag h (Wang 1999; Weindorf and Zhu 2010; Juan et al. 2011). Here, the nugget effect, the semivariogram range and sill were used to describe the spatial dependence. The nugget effect represents random variation in the data that was

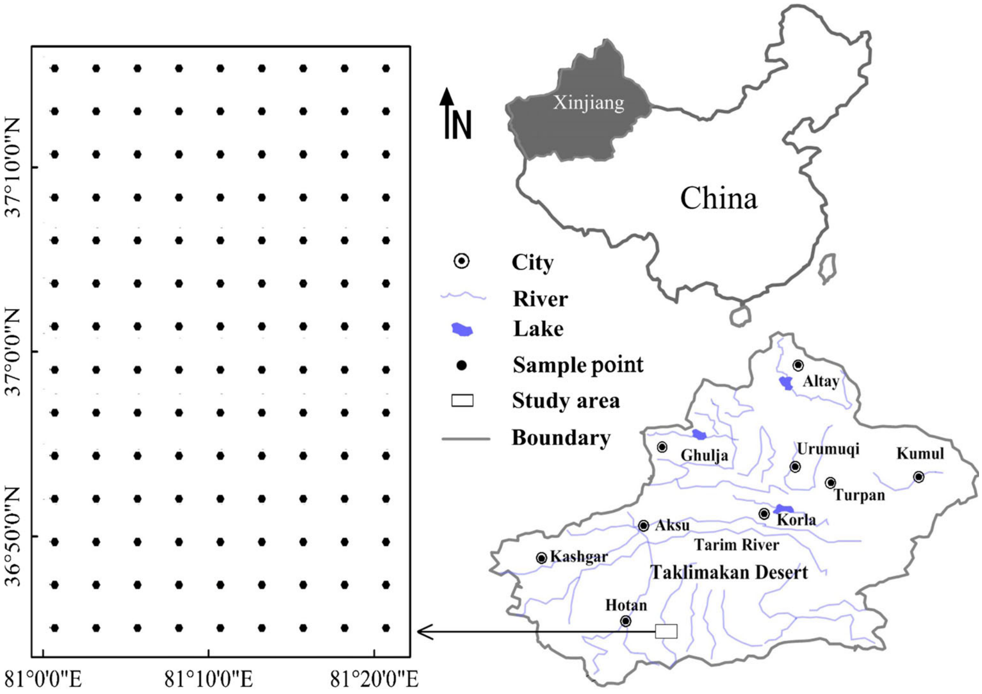

Fig. 1 The location of the study area and sampling sites

primarily due to the error or variation of measurement which was undetectable at the minimum sampling distance. Sill represents the system total variation (Lesch 2012). The separation distance at which the sill was obtained is considered as the range of spatial dependence. Samples separated by distances closer than this range are considered spatially related, while samples separated by greater distances are not spatially related (Wang et al. 2008). The cross-validation value was used to determine the coefficient (R^2) of the correlation between the measured values and the predicted cross-validation values based on the semivariogram and the neighbor values (Su et al. 2006; Weindorf and Zhu 2010).

In the study, the GS$^+$ software (Version 7.0, Gamma Design Software) was used to create semivariogram and to choose the best suitable models for the experimental semivariogram (modeled variogram) based on the coefficients (R^2) and residual sum of squares (RSS) values. The positively skewed data were log transformed according to Finzgar et al. (2014) because the log-normal kriging yields better results as compared to other kriging methods.

Results and discussion

Statistics analysis of soil and vegetation properties

Statistical analysis was performed on the measurements of soil moisture and EC, and vegetation properties. As shown in Table 1, CV was the most critical one in description of variability in soil properties. Overall, a CV of lower than 10 % means a low amount of variability, while a CV of higher than 100 % means a large amount of variability (Wang et al. 2008).

As shown in Table 1, the statistical analysis determined that the mean soil moisture was the lowest with a value of 8.1 %, and the CV value was the highest with a value of 99.5 %, for the soil samples obtained from the depth of 0–10 cm, which is indicative of a large amount of variation. These data, combined with previously published literature, suggest that this may be due to the soil being sandy and a high evaporation rate at the soil surface (Qiu et al. 2001; Chen et al. 2014). Among three soil profiles, the 10–30 and 30–50 cm depths had the highest mean moisture contents of 15.5 and 17.96 %, respectively, and the lowest CV values of them were 50.35 and 67.56 %, respectively, indicating a moderate amount of variation. The average amount of moisture in the soil profiles in order of lowest to highest was: 0–10 < 10–30 < 30–50 cm. Interestingly, the CV values were in an opposite order: 0–10 > 10–30 > 30–50 cm, which may be due to a decrease in evaporation and, thus, its influence on the moisture in the soil as the depth increased. Previous work has found that as soil depth increased, the effect of evaporation on soil moisture gradually decreased, which led to less variation in the amount of moisture in the soil profiles (Brocca et al. 2010).

For the soil sample obtained from 0 to 50 cm depth, the average EC value reached 2.71 ms/cm, which was significantly higher than the limitation of 650 µs/cm, indicating a high salt content in this area (Navarro-Pedreño et al. 2007; Griffin and Hollis 2013; Stadler et al. 2015). The EC

Table 1 Descriptive statistical analysis of properties of the soil and vegetation in sampling plots

Item	Soil layer (cm)	Mean	Min	Max	SD	Skewness	Kurtosis	CV (%)	Distribution type
Soil moisture (%)	0–10	8.10	0.2	26.8	8.06	0.29	−1.25	99.5	N
	10–30	15.5	0.29	40.71	10.47	0.56	0.59	67.56	N
	30–50	17.96	1.99	42.15	9.58	0.28	0.6	50.35	N
Soil electrical conductivity (ms/cm)	0–10	18.14	0.23	43.3	13.57	0.37	−1.24	91.69	N
	10–30	3.78	0.26	17.59	3.46	2.68	9.29	74.78	N
	30–50	2.71	0.37	8.85	1.83	1.38	2.94	67.70	N
Vegetation	Coverage (%)	44.11	10	75	12.77	−0.34	−1.23	28.95	N
	Height (m)	1.27	0.78	1.99	0.31	0.61	0.51	24.8	N
	Crown diameter (m^2)	0.05	0.02	0.11	0.02	0.73	0.24	41.92	N
	Density (individual/m^2)	43.84	20	72	13.55	−0.06	−1.04	30.9	N

N normal distribution

Table 2 Parameters and model of the semivariogram of soil moisture and vegetation properties

Item	Soil layer (cm)	Model	Nugget (C_0)	Sill ($C_0 + C$)	$C_0/(C_0 + C)$ (%)	Range (km)	D	R^2	RSS
Soil moisture (%)	0–10	G	62.27	70.54	82.87	0.012	1.921	0.894	0.277
	10–30	E	100.67	123.32	81.64	0.098	1.832	0.664	1.066
	30–50	G	92.06	92.06	100	0.094	1.93	0.848	1.048
EC (ms/cm)	0–10	E	0.016	1.412	1.1	0.011	1.903	0.534	0.375
	10–30	S	0.115	0.924	12.48	0.037	1.663	0.859	1.05
	30–50	G	0.115	0.924	12.48	0.036	1.951	0.861	1.05
Vegetation	Coverage (%)	G	0.071	0.083	15.06	0.098	1.851	0.827	1.073
	Height (m)	E	0.041	0.061	30.48	0.031	1.875	0.569	1.031
	Crown diameter (m^2)	S	0.139	0.214	34.96	0.098	1.797	0.849	1.101
	Density (individual/m^2)	G	0.077	0.676	88.58	0.098	1.913	0.686	1.048

S spherical, *G* Gaussian, *E* exponential, *D* fractal dimension, *RSS* residual sum of squares

values displayed a moderate variability (CV 67.7–91.69 %) for the soil samples obtained from 0 to 50 cm depth. The CV values of the EC increased as the mean EC value increased as the samples went from the deeper layer to more superficial layers. This suggests that the differences in spatial distribution of the CV values of the EC were attributable to a great deal of evaporation. The CV values of vegetation coverage, height, and crown diameter and density were 28.95, 24.8, 41.92, and 30.9 %, respectively. These all had moderate variation, and when considered with previously published work, they were influenced by relatively fewer factors (Corwin and Lesch 2005; Stadler et al. 2015).

Semivariance analysis of soil and vegetation properties

Spatial–temporal gradients of salt ions and moisture in the soil have traditionally been considered the strongest influences on plant distribution, including plants such as *Halostachys caspica* and *P. australis* (Li and Reynolds 1995; Brocca et al. 2010; Oliver and Webster 2014). To further examine the spatial variation of soil and vegetation properties, a semivariogram was created for each data set (Table 2; Figs. 2, 3). Frequency distributions and K–S test indicate that all of these properties were normally distributed (Table 1, $P > 0.05$). Therefore, the optimal theoretical models for analyzing these samples were the spherical (S), Gaussian (G) and exponential (E) models. The determination coefficients (R^2) ranged from 0.534 to 0.894, and the residual sum of squares (RSS) was small, suggesting that the models used accurately reflect the spatial characteristics of the samples in surface soil and vegetation within the study area.

The nugget to sill [$C_0/(C_0 + C)$] ratio represents the spatial autocorrelation, and values of <25, 25–50, and >75 % indicate great, moderate and weak spatial autocorrelation, respectively (Karlen et al. 2014; Liu et al. 2014). The EC and vegetation coverage sill ratios were less than 25 % (Table 2) suggesting a strong spatial

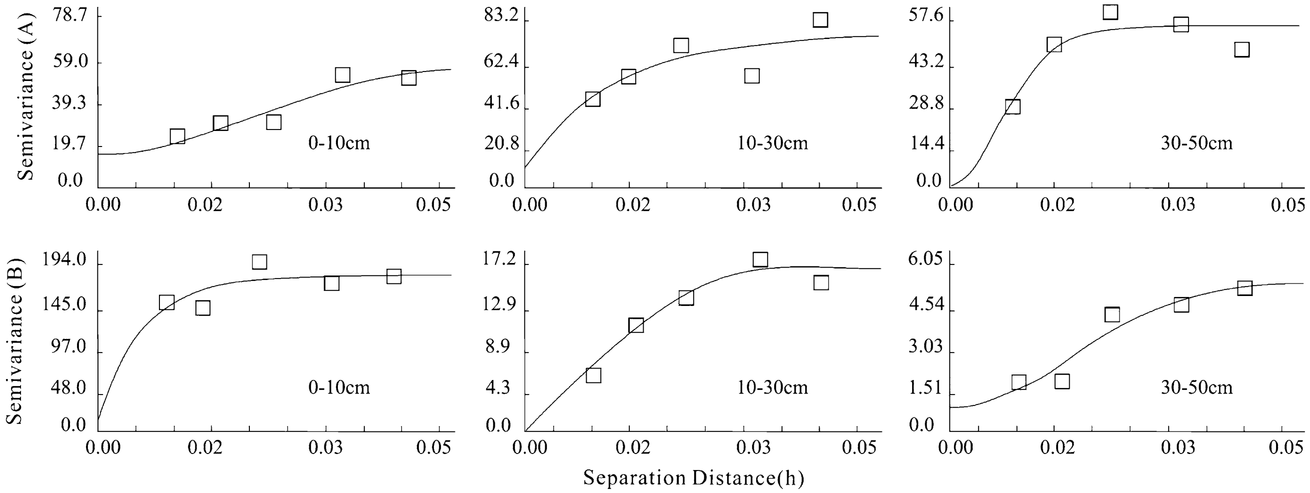

Fig. 2 The semi variance of the soil water content (**a**) and electric conductivity (**b**)

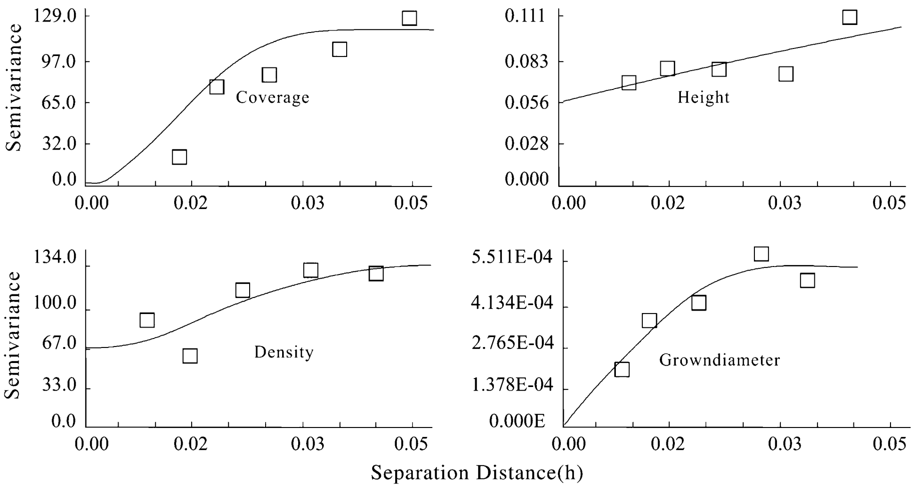

Fig. 3 The semi variance of vegetation coverage, height, density and crown diameter

dependency of each variable. This can be explained that structural factors including soil parent material, soil type and climate have certain impacts on the spatial variation (Shi et al. 2007). In this study, the vegetation height and crown diameter sill ratio values were 25–75 %, suggesting a moderate spatial autocorrelation, and their spatial variations were affected simultaneously by both random factors, such as farming measures and cultivation systems, and structural factors, such as climate, soil parent material, root distribution, groundwater, and soil type. The sill ratio values of soil moisture and vegetation density were more than 75 %, indicating a relatively weak spatial dependency at the present sampling resolution, and suggesting that random factors, such as fertilization, farming measures and cultivation systems, played a leading role in spatial variation. The range was considered to be the distance beyond which the observations were not spatially dependent. The points within the range were considered to be autocorrelated, while the points beyond the range were considered to be spatially independent (Brocca et al. 2010). The use of geostatistics was considered to be appropriate when the semivariogram lag distance was within the range (Kardanpour et al. 2014). In this study, the soil moisture and EC of different soil layers ranged from 0.011 to 0.098 km and the vegetation properties ranged from 0.038 to 0.098 km. Furthermore, the soil point (size = 1 m × 1 m) and the neighboring soil points were within these ranges (Table 2). This distribution pattern was caused by spatial nonstationarity. The fractal dimension (D) value is indicative of the curve rate of the variogram curve. At smaller *D* values, the spatial pattern is unambiguous. The D value of the EC for the soil samples from the depth of 10–30 cm and crown diameter of the vegetation were 1.663 and 1.797, respectively, delineating a clear spatial pattern. The *D* values for the moisture in the soil and EC for the soil samples from the depths of 0–10 cm and 30–50 cm were 1.921 and 1.93, and 1.903 and 1.951, respectively. Also, the density of the vegetation of the plot was 1.913, and therefore, had only weak spatial patterns. The principal structural parameters of the soil may be a consequence of differences in geology, topography and hydrography. The geostatistical methods applied, which were based on the geographical location of individual observations, offered a method of quantifying the spatial variability in the soil properties.

Soil–vegetation relationship

Previously published work has concluded that the EC and moisture in the soil are major factors that influence the distribution of vegetation, especially in arid and semi-arid regions (Maestre et al. 2003; Massaccesi et al. 2015; Morzaria-Luna and Zedler 2014; Zhao et al. 2014). The close relationship between these two properties has also been demonstrated in saline environments in numerous studies (Zhang et al. 2013; Badreldin et al. 2014). In this study, the measured soil and vegetation parameters were correlated to establish a relationship between soil and vegetation, and the data showed that the soil parameters influenced plant growth (Tables 2, 3).

From this analysis, a significant correlation ($P < 0.01$) was found between the vegetation coverage, height, crown diameter and density, and soil moisture at the depth of 10–30 and 30–50 cm. The vegetation cover and density, and soil moisture at the soil depth of 0–10 cm were also significantly correlated ($P < 0.05$). When these data were combined with the field surveys, it was determined that the capillary root of *P. australis* was primarily distributed at soil depth of 0–50 cm, rendering the effect of surface soil moisture on vegetation growth unclear. However, an increase in the moisture in the soil will eventually lead to a number of issues, such as the production of a large number of Tillering strains, an increase in vegetation density, intraspecific competition and a decrease in plant height. Also, there was only a low correlation between each of the characteristics of the vegetation and the EC of the soil at the depth of 0–50 cm, while there was a higher correlation between vegetation height, crown diameter and density and moisture in the soil at 30–50 cm depth ($P < 0.05$). A previous study found a positive correlation between the salt ions and EC of the soil profile (Wahap et al. 2006), and that a change in these properties accurately reflected a change in soil salt content; our work is consistent with these conclusions. Also, it was observed that as the soil depth increased; there was no clear impact of soil EC on the growth of *P. australis*; however, soil moisture had a positive impact on the growth of *P. australis*.

Conclusions

The following conclusions have been drawn from this study:

(1) Analysis using classical statistics demonstrated that soil moisture at depth of 0–10 cm varied greatly, while the soil moisture at depth of 10–50 cm, EC at depth of 0–50 cm, and the measured vegetation properties varied only moderately. A K–S test demonstrated that the distribution of the sampling data of the measured properties of soil and vegetation had a normal distribution.

(2) The spatial distribution of the samples was characterized by geostatistical analyses. It was found that the EC at depth of 0–50 cm, and vegetation coverage had a strong spatial autocorrelation. Meanwhile, the soil moisture at depth of 0–50 cm, and vegetation density had a lower spatial autocorrelation. Also, the EC at depth of 10–30 cm and the vegetation crown diameter showed a clear spatial pattern. Overall, these results indicate that a strong spatial autorelationship is the cause of the heterogeneity of the soil EC and vegetation coverage.

(3) Significant correlations between the measured soil and vegetation properties were observed. A positive correlation was found between the vegetation characteristics and the soil moisture at depth of 0–50 cm, indicating that an increase in soil moisture can promote the growth of *P. australis*. A low negative correlation was found between the vegetation

Table 3 Correlation coefficients between measured parameters of the soil and vegetation samples

Item	Soil layer (cm)	Soil moisture (%)			EC (ms/cm)		
		0–10	10–30	30–50	0–10	10–30	30–50
Vegetation	Coverage (%)	0.426*	0.619**	0.545**	−0.116	−0.146	−0.31
	Height (m)	0.363	0.624**	0.605**	−0.123	−0.175	−0.408
	Crown diameter (m^2)	0.377	0.765**	0.649**	−0.085	−0.091	−0.445
	Density (individual/m^2)	0.485*	0.735**	0.657**	−0.022	−0.344	−0.472

* Correlation <0.05 (two-tailed)

** Correlation <0.01 (two-tailed)

characteristics and EC at the soil depth of 30–50 cm, suggesting that an increase in soil EC can inhibit the growth of *P. australis*. However, as the soil depth increased, the salt content had less impact on the coverage of *P. australis*. Most of the vegetation in the study area was deep-rooted; therefore, the impact of surface soil water–salt on the vegetation was unclear. Based on the obtained results, we conclude that the soil moisture and EC at soil depth of 0–50 cm are not major influencing factors on the vegetation patterns in the study area. Thus, to understand the vegetation distribution, further investigations into the role of groundwater in vegetation growth need to be done. By extending this work, the relationship between soil and vegetation can be well delineated, which would be helpful when working to maintain the ecological balance within this region.

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