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Analysis of dominant factors influencing moisture change of broad-ovate leaves of *Populus euphratica* Oliv. in extremely arid region

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Abstract

We studied the dominant environmental factors that affect the gas-exchange characteristics and water potential (ψ) of broad-ovate leaves of *Populus euphratica* Oliv. in extreme arid area of Tarim River, China, and their correlation to water status of *P. euphratica* by analyzing on-field monitored meteorological data, soil moisture and salinity, *P. euphratica* leaf gas exchange and ψ, and revealed the indicative threshold of environmental factors for *P. euphratica* leaf water changes and growth. The results indicated that meteorological factors such as air relative humidity (RH), air temperature (T_{air}), *etc.* are the dominant factors. The threshold value of RH is (48.19 ± 1.06)% for *P. euphratica* growth, *i.e.* RH from 10.69% to 48.19% is suitable for *P. euphratica* growth in extremely arid region of Tarim River. This study provides a theoretical basis for reducing drought damage to *P. euphratica* and maintaining normal growth of *P. euphratica* by in-time watering.

Additional key words: environmental factors; extreme arid environment; gas exchange; *Populus euphratica* Oliv.; water potential.

Introduction

Tarim River Basin desert is one of the typical areas of natural *Populus euphratica* Oliv. forest in China. During the past 50 years, highly intensive human economic and social activities on development and utilization of water resources in Tarim River desert have dramatically changed its natural ecological processes, causing significant ecosystem degradation including dry rivers and lakes, greatly dropped groundwater level, declined vegetation and increased desertification. Therefore, restoration and reconstruction of severely degraded desert ecosystems are urgent scientific issues. Species selection is critical for restoring the ecosystem. In addition to consider the photosynthetic capacity, water utilization ability is particularly important. Leaf stomata control the exchange of water vapour and environmental CO_2. Stomatal conductance (g_s) is an important parameter to describe the flux exchange between vegetation and atmosphere (Nicolás and Philippe 2009, Hladnik *et al.* 2009, James 2004). The level of plant transpiration rate (E) can reflect plants' adaptive ability to the environment (Fung *et al.* 1998). If E is too high, the plant may be subjected to water stress. ψ reflects the combined effects of soil, vegetation, and atmospheric conditions on plant water availability *in vivo*. Its level indicates plants' ability to absorb moisture from the soil and ensures their normal physiological activities in extreme arid areas (Fu *et al.* 2008). Therefore, ψ can be used as a sensitive and useful indicator of water shortage of ecosystem (González and Ayerbe 2010, Ma *et al.* 2004).

Populus euphratica Oliv. is the oldest species of *P. euphratica* species (Si *et al.* 2008). It is distinct from other species by its resistance to high temperature and salinity, plays important roles in maintenance of ecological balance in arid and semiarid regions, protection of agricultural production in oasis and is a good timber source for residents. Its water status and growth rate are affected by multiple environmental factors. Su *et al.* (2003) reported that the effect of light on g_s and E of *P. euphratica* is more obvious at low CO_2 concentration than that at high CO_2 concentration. Zhou *et al.* (2008)

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Abbreviations: E – transpiration rate; g_s – stomatal conductance; P_N – net photosynthetic rate; PAR – photosynthetically active radiation; RH – air relative humidity; T_{air} – air temperature; T_l – leaf temperature; T_s – soil temperature; SVP – saturation vapour pressure; WUE – water use efficiency; ψ – the water potential; $ψ_l$ – leaf water potential; $ψ_s$ – soil water potential.

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believed that the net photosynthetic rate (P_N) of *P. euphratica* is mainly affected by atmospheric CO_2 concentration and photosynthetically active radiation (PAR). Chen *et al*. (2011) reported that the groundwater depth is the dominant factor influencing the gas-exchange characteristics of *P. euphratica*. Jiang (1991) suggested that *P. euphratica* adjusts its leaf temperature (T_l) to adapt to the environmental changes and air temperature (T_{air}) can affect its ψ in discrepancy with the opinion of foreign scholars (Lang and Nobel 1982). Li *et al*. (2006) believed that the optimum temperature for its seed germination is between 15–35°C. They believed that the order of external factors that affect ψ is light> RH> T_{air}. RH significantly influences stomatal diffusion resistance and leaf transpiration of *P. euphratica* (Jiang *et al*. 1991). Among those internal and external factors that affect leaf transpiration of *P. euphratica*, stomatal diffusion resistance is the main factor, followed by RH and T_{air} (Jiang *et al*. 1991). T_{air} and irradiance have negative effect on ψ of *P. euphratica*, whereas RH has positive effect (Si *et al*. 2005), suggesting that water status of *P. euphratica* is significantly and positively correlated with soil moisture. Study on the correlation of desert plants' ψ with environmental factors has shown that (Song *et al*. 2005) ψ of *Haloxylon*, *P. euphratica* and *Tamarix* are deeply correlated with deep soil water potential (ψ_s), whereas that of *Sophora* has good correlation with the shallow soil ψ_s. ψ of *P. euphratica* has high relevance to RH, whereas these of *Haloxylon* and *Tamarix* have poor correlation with RH. ψ *of* these four species have very poor association with T_{air}. Zhang *et al*. (2004a) reported that the callus' relative growth rate reaches a maximum in the presence of 50 mmol NaCl and growth is inhibited with increasing NaCl concentration. However, these studies only considered the effects of single or limited numbers of environmental factors on water status of *P. euphratica* in arid and semi-arid areas. Most of the studies only did single factor correlation analysis rather than a comprehensive and systematic analysis of the effects of environmental factors on *P. euphratica* in arid region, not to mention the dominant environmental factors and their threshold values.

In this paper, we studied the dominant environmental factors that affect the gas exchange and ψ of *P. euphratica* leaves and their thresholds, and accurately evaluated the drought stress intensity by monitoring environmental factors. This research could provide theoretical basis for reducing drought-caused damages to *P. euphratica* and maintaining its normal growth.

Materials and methods

Study area: The study area is in the Yinsu and Alagan sections in the lower reaches of Tarim River (39°38'–41°45'N, 85°42–89°17'E), the longest inland river (321 km) located at north edge of Taklimakan Desert in China and one of the well-known inland rivers in the world, and surrounded by Taklimakan Desert, Kuluk Desert, Daxihaizi Reservoir and Taitema Lake (Fig. 1). Tarim River has been dry completely since 1970. The lakes Luobupo and Taitema in the end area of the river have been run dry since 1970 and 1972, respectively. The groundwater level has dropped so dramatically that the natural vegetation supported by groundwater degenerates extremely, leading to the wither of its main components herbs such as *Phragmites communis* Trin., *Apocynum venetum* Linn. and *Alhagi sparsifolia* Shap. and arbors or shrubs like *Populus euphratica* Oliv. and *Tamarix ramosissima* Ledeb. Meanwhile, wind erosion and land desertification accelerated. The weather of lower reaches of Tarim River is continental warm temperate and extremely arid desert climate: little rainfall and much sand-wind, with mean annual precipitation of 17.4–42.0 mm and evaporation capacity of 2,500–3,000 mm. Monthly mean temperature ranges from 20°C to 30°C in July and –20°C to –10°C in January. The highest and lowest temperature is 43.6°C and –27.5°C, respectively. The accumulative year temperature >10°C ranges from 4,100°C year to 4,300°C year.

Riverbank vegetation provides a natural defense against the wind by obstructing sand movement. The famous Green Corridor plays an important role in keeping National Highway No. 218 free of sands. The flora of the region consists of 14 families, 24 genera, and about 40 species of vascular plants. The major plant species include *Populus euphratica* Oliv., *Tamarix ramosissima* Ledeb., *T. hispida* Willd., *Lycium ruthenicum* Murr., *Phragmites communis* Trin., *Alhagi sparsifolia* Shap., *Apocynum venetum* Linn., *Karelinia caspica* Less. and *Glycyrrhiza inflata* Batal. The natural vegetation such as the shrub-grass vegetation, is dominated by *T. chinensis* Lour., *Halimodendron halodendron* Voss., *Phragmites communis* Trin., *Apocynum venetum* Linn., *etc*., and the forest is dominated by *P. euphratica*. Both shrub-grass and forest rely on groundwater for their survival and growth, and have been seriously degenerated. The sand dunes of the sand region between the forests have become unstable.

Gas-exchange characteristics: The leaves of twelve 35–50 years old *P. euphratica* trees (8–10 m high) without any diseases within 1 km in radius around each section were randomly selected. During May to September of 2006–2008, their gas-exchange characteristics including P_N, E, g_s, and environmental factors including PAR and SVP were measured with a portable gas-exchange system (*Li 6400*, *LiCOR*, Lincoln, NE, USA) at noon (14:00 h of Beijing times is the noon at Xinjiang due to time differences between Beijing and Xinjiang) every day except rainy, windy, and sandy days. WUE = P_N/E. The

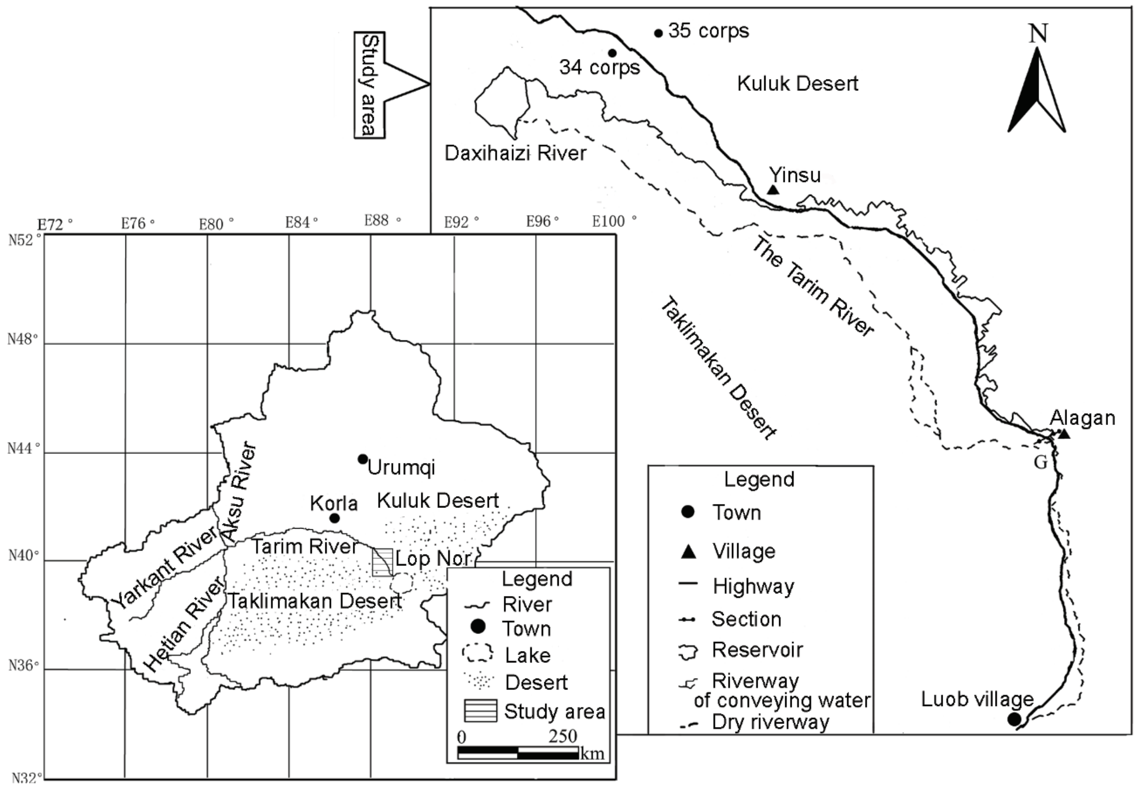

Fig. 1. The distribution map of Yinsu and Alagan sections in the lower reaches of the Tarim River, Xinjiang, China.

highest PAR was 2,000 μmol m^{-2} s^{-1}, the ambient concentration of CO_2 was 375 μmol mol^{-1}, air temperature was 40°C, and RH was 12% in the chamber. The fully expanded, healthy and mature leaves in the middle part of crown were closed in chamber (2 × 3 cm) for measurements. The leaf surface was held perpendicularly to the radiation direction. The photosynthetic curve was in the light-saturation region. Every measurement had three replications.

Leaf water potential (ψ_l): The ψ of the broad-ovate leaves of *P. euphratica* was determined using *HR–33T* Dew Point Microvolt-meter (*WESCOR Company*, Logan, USA). Six healthy leaves whose gas-exchange characteristics had been measured were picked at noon (14:00 h of Beijing time) and immediately put into sealed polyethylene plastic bag. Then an area of 5 mm in diameter in each leaf was collected by avoiding leaf veins and placed in six *C–52* sample chambers of Dew Point Microvolt-meter to measure ψ_l. Plant samples with epidermis and cuticle were allowed to equilibrate with chamber air in the *C–52* sample chambers for 4 h. After achieving equilibration, according to the temperature of the sample chamber and the sensor model, an appropriate coefficient of refrigeration (Πv) value was chosen and dew-point value [μV] was measured. ψ_l [MPa] was calculated from (dew-point value)/–7.5. An average ψ_l of the six leaves was considered as the final value.

Environmental factors: The environmental factors T_{air}, T_l, T_s, and RH at the moment when the gas-exchange characteristics and ψ were measured were monitored using the Soil-Plant-Atmosphere Continuum (SPAC) ecological environment monitoring system [*In Circuit Tester (ICT) Company*, Australia]. Based on the characteristics of that system, T_{air} was measured at 1 m above the surface, T_l of leaves at the sun irradiation position was measured at 1.5 m above the surface, T_s was measured at 20 cm below the surface, and RH was measured at 1.5 m above the surface.

Soil salinity and moisture: Fresh soil samples were collected every morning during the experimental period at underground sites with depth of 80–100 cm, where the roots of *P. euphratica* were most concentrated (Hao *et al.* 2011), in the area with 2–3 m distance to the *P. euphratica* selected above. Each sample is a mixture of soils collected from five different sites in the same layer. In order to measure soil moisture content, extra samples were collected in an aluminum box and weighed at the time of sampling, and later oven-dried at 105°C. Soil samples were air-dried after removal of roots passed through a 2-mm sieve, and subsequently analyzed in the laboratory for pH (water:soil ratio 1:5) and soil salinity (drying method after extracted with 5-fold volume of deionized water).

Sample numbers: Data of the same category obtained from samples collected at the same day were averaged and considered as one data point. Therefore, the total data points for each measurement from May to September were 153, same as the total experiment days.

Data analysis: Pearson correlation analysis was used to analyze the relativity of nine environmental factors using *SPSS13.0* software [*International Business Machines (IBM) Company*, USA]. *t*-test was used to test the significance of the correlation of nine environmental factors. The formula is:

$$t = \frac{\sqrt{n-2}\,r}{\sqrt{1-r^2}}$$

In the formula, r is correlation coefficient, n is sampling observational number, n–2 is a degree of freedom. If the probability (p) of *t*-test is less than 0.05, the correlation between two variables is significant, which signed by * above the probability value; if p<0.01, the correlation is extremely significant, which signed by ** above the probability value; if p>0.05, the correlation is nonsignificant.

The impact factor of each environmental factor on ψ_l and gas exchange characteristics of *P. euphratica* were sorted using detrended canonical correspondence analysis (DCCA) in standard program of *CANOC*O (v*ersion 4.5*, *Ter Braak*, Netherlands) package and analyzed with its associated *CANODRAW3.0* mapping software. Multiple stepwise regression analysis was used to analyze the impacts of environmental factors (RH, T_{air}, T_l, T_s, soil salinity, PAR and SVP) on ψ_l and gas-exchange characteristics. The differences of P_N, g_s, E, WUE, and ψ_l were compared among the different RH by *ANOVA* and least significant difference (LSD), respectively (p<0.05) using *SPSS13.0* software. *F*-test was used to test the significant of differences of P_N, g_s, E, WUE, and ψ_l among the different RH. The formula is: $F = t^2$.

Results

The relationship among environmental factors: The maximum values of the nine environmental factors measured in the Yinsu and Alagan sections in the lower reaches of Tarim River were normalized and their correlation to T_{air}, T_l and T_s were analyzed. As listed in Table 1, RH is negatively correlated to T_{air}, T_l and T_s with correlation coefficients of –0.920, –0.759, and –0.546, respectively, and is positively correlated to SVP, pH and soil salinity with correlation coefficients of 0.584, 0.261, and 0.511, respectively. Soil salinity is significantly correlated to T_{air}, T_l, T_s, SVP, pH and soil moisture with correlation coefficient of –0.499, –0.461, –0.258, 0.514, 0.737, and 0.378, respectively. Soil moisture is significantly correlated with soil salinity with a correlation coefficient of 0.378. These data indicate that meteorological factor RH is a main environmental factor affecting soil moisture and salinity in the shallow surface of Yinsu and Alagan sections. With RH increasing, T_{air}, T_l and T_s decrease, and soil salinity and moisture increase. In Alagan section T_{air}, T_l and T_s are significantly correlated to each other with the correlation coefficients of 0.931, 0.307, and 0.219, respectively. RH and T_s are

Table 1. Correlation coefficients between the environmental variables in Yinsu and Alagan sections of the lower reaches of Tarim River (only values significant at p<0.01 are shown).). RH – air relative humidity; T_{air} – air temperature; T_l – leaf temperature; T_s – soil temperature; PAR – photosynthetic active radiation; SVP – saturation vapor pressure

Environmental factors	Sections	RH [%]	T_{air} [°C]	T_l [°C]	T_s [°C]	PAR [μmol m^{-2}s^{-1}]	SVP [kPa]	pH	Soil salinity [%]
T_{air}[°C]	Yinsu	–0.920							
	Alagan	-							
T_l[°C]	Yinsu	–0.759	0.808						
	Alagan	-	0.931						
T_s[°C]	Yinsu	–0.546	0.627	0.259					
	Alagan	–0.747	0.307	0.219					
PAR [μmol m^{-2} s^{-1}]	Yinsu	-	-	-	-				
	Alagan	-	-	–0.336	-				
SVP [kPa]	Yinsu	0.584	–0.502	–0.468	–0.256	0.406			
	Alagan	-	0.753	–0.802	-	-			
pH	Yinsu	0.261	–0.212	–0.271	-	-	0.461		
	Alagan	-	-	-	-	-	0.260		
Soil salinity[%]	Yinsu	0.511	–0.499	–0.461	–0.258	-	0.514	0.737	
	Alagan	-	-	-	-	-	-	0.821	
Soil moisture[%]	Yinsu	-	-	-	-	-	0.356	0.678	0.378
	Alagan	-	-	-	-	-	0.251	-	0.544

Table 2. The standardized original data of water potential and gas-exchange characteristics of *Populus euphratica* and nine environmental factors. Note: "-" means the missing data, which were not measured because of machine failures. P_N – net photosynthetic rate; g_s – stomatal conductance; E – transpiration rate; WUE – water-use efficiency; ψ_l – leaf water potential; RH – air relative humidity; T_{air} – air temperature; T_l – leaf temperature; T_s – soil temperature; PAR – photosynthetically active radiation; SVP – saturated water vapour pressure.

Serial number	ψ_l	P_N	g_s	E	WUE	RH	T_{air}	T_l	T_s	PAR	SVP	pH	Soil salinity	Soil moisture
1	–0.813	–1.707	–0.627	–1.646	–0.367	1.932	–1.723	–0.634	–1.979	–1.240	–0.587	0.511	–0.493	–0.321
2	–0.648	0.603	–0.049	–0.631	0.711	0.008	–0.080	–0.499	–0.024	0.356	–0.257	0.516	–0.490	–0.295
3	–0.648	0.141	–0.458	0.164	–0.241	–0.359	0.289	–0.502	0.994	0.951	–0.339	0.590	–0.525	–0.180
4	–1.201	–1.415	–1.652	–0.869	–0.730	–0.591	0.758	–0.474	1.355	0.878	–0.614	0.596	–0.526	–0.006
5	–1.345	–0.354	0.274	0.800	–0.739	–0.759	1.061	–0.364	1.689	–0.623	–1.055	0.596	–0.522	0.753
6	–0.664	0.355	–0.396	0.133	–0.105	–0.841	1.135	–0.199	1.873	0.460	0.018	0.596	–0.529	0.450
7	–0.807	–1.580	–0.319	–0.331	–1.070	–0.778	0.869	–0.027	1.262	–1.212	–0.202	0.511	–0.493	0.189
8	–0.829	–0.766	0.190	–1.384	0.538	1.848	–1.804	–1.223	–2.081	–1.114	0.183	0.516	–0.490	–0.356
9	–0.930	0.421	1.115	–0.027	0.031	1.215	–1.376	–1.187	–1.129	–0.595	0.403	0.590	–0.525	1.037
10	–1.159	–0.140	–0.203	0.721	–0.612	0.597	–0.724	–1.123	–0.234	–0.585	0.348	0.596	–0.526	–0.201
11	–0.893	–0.041	0.074	1.304	–0.739	0.321	–0.468	–0.902	–0.119	0.882	–0.697	0.596	–0.522	5.162
12	–1.180	–0.852	0.876	0.960	–0.989	0.103	–0.137	–0.596	0.044	–0.956	–1.110	0.596	–0.529	2.441
13	–1.116	–1.047	–1.136	–0.443	–0.666	–0.114	0.012	–0.306	0.476	–0.970	–0.559	0.511	–0.493	–0.024
14	–1.042	–1.557	–1.490	–1.209	–0.639	–0.012	–0.063	–0.134	0.082	–1.511	–0.614	0.516	–0.490	–0.081
15	–0.861	–0.766	–1.575	–1.914	2.513	1.785	–1.767	–1.367	–1.733	0.221	1.916	0.508	–0.417	–0.346
16	–1.090	0.949	–0.334	–0.822	1.290	0.349	–0.627	–1.221	0.563	0.987	1.944	0.488	–0.444	–0.291
17	–0.786	–0.999	–1.506	–1.060	–0.186	–0.311	0.201	–0.880	1.628	–0.194	1.779	0.498	–0.459	–0.321
18	–0.573	–0.173	–1.228	–0.451	–0.041	–0.330	0.381	–0.412	0.872	1.324	0.403	0.503	–0.362	–0.297
19	–1.090	0.157	–0.835	–0.114	–0.068	–0.416	0.385	0.073	0.379	1.171	0.128	0.513	–0.472	–0.231
20	–0.877	0.091	–0.959	–0.194	–0.059	–0.351	0.363	0.295	0.321	0.735	–0.257	0.531	–0.479	–0.259
21	–0.999	–0.856	–1.622	–1.161	0.086	–0.225	0.162	0.300	0.024	–0.625	–0.422	0.601	–0.373	–0.276
22	–0.232	–0.222	0.051	–1.355	1.163	1.932	–1.723	–0.634	–1.979	–0.842	0.651	0.714	–0.202	–0.321
23	–0.366	0.949	1.354	0.694	–0.105	0.008	–0.080	–0.499	–0.024	0.412	0.898	0.675	–0.480	–0.295
24	–0.536	1.032	1.438	1.331	–0.340	–0.359	0.289	–0.502	0.994	1.020	0.733	0.773	–0.499	–0.180
25	–0.477	–0.321	–0.512	0.350	–0.567	–0.591	0.758	–0.474	1.355	–0.671	0.403	0.781	–0.501	–0.006
26	–0.579	0.355	–0.034	1.225	–0.567	–0.759	1.061	–0.364	1.689	0.656	0.018	0.711	–0.471	0.753
27	–0.680	0.405	–0.134	1.145	–0.521	–0.841	1.135	–0.199	1.873	0.186	–0.257	0.724	–0.497	0.450
28	–1.074	–0.857	–1.067	–0.459	–0.521	–0.778	0.869	–0.027	1.262	–0.875	–0.339	0.760	–0.494	0.189
29	–0.488	0.042	0.475	–1.042	0.828	1.848	–1.804	–1.223	–2.081	–0.844	0.678	0.727	1.422	–0.356
30	–0.541	0.817	1.739	0.933	–0.277	1.215	–1.376	–1.187	–1.129	0.609	0.898	0.711	2.454	1.037
31	–0.893	1.131	1.777	1.569	–0.385	0.597	–0.724	–1.123	–0.234	0.995	1.394	0.773	1.649	–0.201
32	–1.004	0.372	0.945	1.410	–0.612	0.321	–0.468	–0.902	–0.119	–0.051	1.008	0.837	1.066	5.162
33	–0.680	0.504	1.192	1.755	–0.657	0.103	–0.137	–0.596	0.044	–0.169	–0.064	0.757	0.480	2.441
34	–0.946	–0.074	0.012	1.119	–0.712	–0.114	0.012	–0.306	0.476	–0.021	0.431	0.953	–0.390	–0.024
35	–0.451	–0.684	0.251	0.535	–0.812	–0.012	–0.063	–0.134	0.082	–1.295	–0.367	0.840	–0.427	–0.081
36	–0.520	-	-	-	-	1.785	–1.767	–1.367	–1.733	-	-	0.737	1.942	–0.346
37	–0.839	-	-	-	-	0.349	–0.627	–1.221	0.563	-	-	0.760	3.358	–0.291
38	–0.626	-	-	-	-	–0.311	0.201	–0.880	1.628	-	-	0.781	1.604	–0.321
39	–0.536	-	-	-	-	–0.330	0.381	–0.412	0.872	-	-	0.783	0.122	–0.297

Table 2 continued

Serial number	ψ_l	P_N	g_s	E	WUE	RH	T_{air}	T_l	T_s	PAR	SVP	pH	Soil salinity	Soil moisture
40	–0.488	-	-	-	-	–0.416	0.385	0.073	0.379	-	-	0.865	–0.357	–0.231
41	–0.728	-	-	-	-	–0.351	0.363	0.295	0.321	-	-	0.845	–0.458	–0.259
42	–0.701	-	-	-	-	–0.225	0.162	0.300	0.024	-	-	0.791	–0.438	–0.276
43	–0.648	-	-	-	-	2.922	–2.185	–1.249	–1.736	-	-	0.737	1.942	–0.346
44	–2.261	-	-	-	-	1.487	–1.411	–1.106	–0.866	-	-	0.760	3.358	–0.291
45	–0.770	-	-	-	-	0.407	–0.806	–1.044	0.237	-	-	0.781	1.604	–0.321
46	–0.728	-	-	-	-	0.010	–0.344	–0.985	0.036	-	-	0.783	0.122	–0.297
47	–0.749	-	-	-	-	–0.064	–0.307	–0.875	–0.108	-	-	0.865	–0.357	–0.231
48	–0.946	-	-	-	-	0.208	–0.394	–0.727	–0.181	-	-	0.845	–0.458	–0.259
49	–0.861	-	-	-	-	0.241	–0.493	–0.604	–0.438	-	-	0.791	–0.438	–0.276
50	0.039	–0.602	–0.620	–1.731	1.834	1.741	–1.370	–0.579	–1.516	–1.028	1.036	0.714	–0.202	–0.321
51	–0.536	0.850	0.883	–0.594	0.855	0.589	–0.431	–0.396	–0.091	0.506	1.201	0.675	–0.480	–0.295
52	–0.605	0.784	0.837	0.774	–0.222	0.057	0.290	–0.372	0.749	0.875	1.559	0.773	–0.499	–0.180
53	–0.605	0.999	1.238	0.721	–0.105	–0.267	0.696	–0.324	1.377	1.234	0.816	0.781	–0.501	–0.006
54	–0.520	0.768	0.113	0.800	–0.250	–0.681	1.039	–0.207	1.816	1.332	0.486	0.711	–0.471	0.753
55	–0.382	1.114	0.991	1.516	–0.367	–0.716	1.072	–0.046	2.206	1.072	0.238	0.724	–0.497	0.450
56	–0.366	0.256	0.860	0.482	–0.331	–0.752	0.905	0.107	1.528	–0.613	0.238	0.760	–0.494	0.189
57	–0.083	–0.618	–0.882	–1.731	1.816	3.150	–1.856	–0.686	–1.933	–0.851	1.063	0.727	1.422	–0.356
58	–0.259	1.312	0.906	–0.225	0.747	1.217	–0.642	–0.506	–0.292	–0.716	1.394	0.711	2.454	1.037
59	0.151	1.527	1.677	1.357	–0.159	0.774	–0.259	–0.353	0.053	0.093	1.366	0.773	1.649	–0.201
60	–0.382	0.933	2.024	1.331	–0.376	0.154	0.332	–0.134	0.614	0.476	0.843	0.837	1.066	5.162
61	–0.153	1.230	1.731	1.596	–0.349	–0.104	0.777	0.275	1.632	1.308	0.458	0.757	0.480	2.441
62	–0.435	0.289	0.775	1.596	–0.693	–0.273	0.951	0.628	1.712	–0.370	0.403	0.953	–0.390	–0.024
63	–0.749	0.009	0.167	0.138	–0.304	–0.058	0.574	0.898	1.167	–1.108	0.348	0.840	–0.427	–0.081
64	–0.536	0.108	–0.550	–0.938	0.720	0.352	–0.897	–0.336	–0.691	–0.570	0.073	0.737	1.942	–0.346
65	–0.680	0.768	–0.111	0.048	0.176	0.509	–0.026	0.066	0.290	1.447	0.018	0.760	3.358	–0.291
66	–1.265	0.042	–1.059	–0.143	–0.123	–0.080	0.664	0.379	1.191	0.716	–0.037	0.781	1.604	–0.321
67	–0.893	0.850	0.221	1.013	–0.304	–0.574	0.879	0.808	1.448	1.409	1.724	0.783	0.122	–0.297
68	–1.159	0.537	–0.072	1.198	–0.485	–0.660	1.050	1.157	1.665	1.301	1.366	0.865	–0.357	–0.231
69	–1.265	–0.173	–0.851	0.456	–0.539	–0.752	1.095	1.368	1.574	–0.341	–0.945	0.845	–0.458	–0.259
70	–0.893	0.025	–0.635	0.270	–0.358	–0.805	1.055	1.411	1.736	–0.388	–1.027	0.791	–0.438	–0.276
71	1.083	–1.773	–1.691	–2.258	2.386	3.727	–2.162	–1.864	–1.012	–1.499	1.063	0.714	–0.202	–0.321
72	1.024	0.784	0.475	–1.280	2.187	2.513	–1.478	–0.713	–0.866	0.533	1.228	0.675	–0.480	–0.295
73	0.928	0.586	0.544	0.138	0.013	1.709	–0.913	–0.324	–0.841	1.186	1.256	0.773	–0.499	–0.180
74	0.651	0.883	1.253	0.125	0.185	1.036	–0.500	–0.099	–0.772	1.352	0.953	0.781	–0.501	–0.006
75	0.614	0.949	1.030	0.535	–0.041	0.837	–0.147	0.204	–0.664	1.091	0.513	0.711	–0.471	0.753
76	0.577	0.883	0.976	0.615	–0.105	0.099	0.066	0.259	–0.467	0.630	0.128	0.724	–0.497	0.450
77	0.683	–1.329	–0.304	–0.822	–0.675	0.344	–0.221	0.007	–0.215	–1.170	0.046	0.760	–0.494	0.189
78	1.077	–1.758	–1.352	–2.221	1.960	2.290	–2.539	–2.461	–1.917	–0.592	1.063	0.727	1.422	–0.356
79	0.896	1.065	0.621	–1.201	2.268	1.001	–1.203	–0.113	–1.906	0.216	0.403	0.711	2.454	1.037

Table 2 continued

Serial number	ψ_l	P_N	g_s	E	WUE	RH	T_{air}	T_l	T_s	PAR	SVP	pH	Soil salinity	Soil moisture
80	0.934	0.949	2.132	0.376	0.058	–0.649	0.292	1.199	–1.802	0.805	0.458	0.773	1.649	–0.201
81	0.577	0.817	2.209	0.403	–0.032	–0.479	0.503	1.531	–1.567	1.402	0.183	0.837	1.066	5.162
82	0.630	0.999	1.754	0.880	–0.177	–0.710	0.670	1.300	–1.193	0.985	0.431	0.757	0.480	2.441
83	0.651	0.405	2.070	0.880	–0.431	–0.935	0.752	0.929	–0.967	–0.211	0.101	0.953	–0.390	–0.024
84	0.678	–0.783	0.506	–0.490	–0.449	–0.250	0.198	0.019	–0.817	–1.266	0.018	0.840	–0.427	–0.081
85	1.125	–0.519	–1.174	–1.970	3.582	1.578	–1.736	–1.987	–1.091	–0.953	0.431	0.737	1.942	–0.346
86	0.769	1.098	0.236	–0.612	1.064	0.205	–1.016	–0.711	–1.032	1.093	0.431	0.760	3.358	–0.291
87	0.651	0.438	–0.612	–0.249	0.212	–0.382	–0.208	0.107	–0.921	1.350	0.348	0.781	1.604	–0.321
88	0.587	0.834	0.259	0.747	–0.186	–0.694	0.385	1.205	–0.837	1.063	–0.064	0.783	0.122	–0.297
89	0.486	0.174	–0.805	0.482	–0.376	–0.694	0.696	1.222	–0.728	0.741	0.073	0.865	–0.357	–0.231
90	0.534	–1.755	–1.205	–0.936	–1.000	–0.870	0.798	0.785	–0.535	–1.266	–0.697	0.845	–0.458	–0.259
91	0.641	–1.713	–1.144	–0.899	–0.979	–0.774	0.573	0.462	–0.438	-	-	0.791	–0.438	–0.276
92	1.045	–0.288	–0.858	–1.858	3.210	2.496	–2.515	–1.133	–2.657	–1.079	0.458	0.737	1.942	–0.346
93	0.758	1.015	1.153	–0.363	0.692	0.674	–1.153	–0.996	–0.504	0.993	0.431	0.760	3.358	–0.291
94	0.556	0.834	0.105	0.138	0.140	–0.052	–0.125	–0.953	0.279	1.392	0.348	0.781	1.604	–0.321
95	0.444	–0.107	–1.097	–0.313	–0.105	–0.669	0.283	–0.770	0.622	1.326	–0.037	0.783	0.122	–0.297
96	0.529	–0.486	–0.542	0.668	–0.757	–0.821	0.351	–0.497	0.727	0.263	0.046	0.865	–0.357	–0.231
97	0.556	–1.649	–1.645	–1.283	–0.684	–0.937	0.323	–0.328	0.554	–1.109	–0.697	0.845	–0.458	–0.259
98	0.699	-	-	-	-	–0.784	0.085	–0.235	–0.037	-	-	0.791	–0.438	–0.276
99	1.849	-	-	-	-	0.418	–0.905	–1.020	–0.451	–1.516	–0.477	–0.764	–0.450	–0.405
100	2.110	–0.536	2.086	0.029	–0.558	–0.355	0.049	0.219	–0.602	–0.072	–0.587	–1.245	–0.508	–0.405
101	1.951	–0.305	1.315	1.039	–0.779	–0.587	0.593	0.582	–0.511	–0.924	–0.835	–1.463	–0.529	–0.404
102	1.951	4.513	0.036	0.827	1.390	–0.703	0.721	0.704	–0.261	–1.201	–1.220	–1.507	–0.531	–0.405
103	1.738	-	-	-	-	–0.479	0.548	0.309	–0.049	–1.322	–1.055	–0.548	–0.435	–0.404
104	1.887	-	-	-	-	1.259	–1.223	–1.168	–0.642	–1.455	–1.055	–0.345	–0.403	–0.404
105	1.780	2.154	0.621	–0.586	1.834	–0.483	0.375	0.379	–0.649	-	-	–0.962	–0.493	–0.404
106	1.466	3.242	–0.566	–0.353	2.187	–0.478	1.045	0.822	–0.569	–1.089	–0.614	–1.494	–0.528	–0.404
107	1.322	–0.057	–0.103	0.130	–0.340	–0.437	1.201	0.830	–0.392	–0.906	0.046	–1.530	–0.532	–0.402
108	1.498	-	-	-	-	–0.489	0.842	0.340	–0.234	–1.094	–0.394	–1.530	–0.533	–0.402
109	1.833	-	-	-	-	0.568	–1.978	–1.585	–0.801	-	-	–1.029	–0.466	–0.405
110	1.679	0.669	0.143	0.217	0.004	–0.975	0.165	–0.437	0.483	0.486	–0.422	–1.052	–0.484	–0.405
111	1.535	0.091	–0.920	–0.281	0.013	–1.148	0.979	–0.367	1.384	0.491	–0.532	–1.121	–0.501	–0.404
112	1.706	-	-	-	-	–1.045	1.107	–0.176	1.083	–1.364	–0.862	–1.106	–0.496	–0.404
113	1.780	-	-	-	-	–0.828	0.667	0.582	–0.040	–1.516	–1.137	–1.191	–0.505	–0.404
114	2.094	-	-	-	-	0.696	–1.499	–0.823	–0.580	-	-	–1.445	–0.526	–0.402
115	1.253	–0.123	0.182	0.026	–0.322	–0.213	0.420	1.034	–0.496	–1.553	–0.752	–1.484	–0.528	–0.404
116	1.280	0.471	–0.627	0.061	–0.005	–1.074	1.280	1.723	–0.513	–1.424	–1.000	–1.517	–0.531	–0.399
117	1.541	0.108	0.151	1.145	–0.639	–1.171	1.302	1.712	–0.522	–1.456	–1.357	–1.499	–0.530	–0.393
118	1.562	-	-	-	-	–1.167	1.171	1.427	–0.493	–1.513	–1.632	–1.481	–0.528	–0.387
119	1.407	–1.192	0.090	–1.280	–0.150	0.437	–1.530	–1.309	–0.467	–1.120	–1.797	–0.764	–0.450	–0.405

Table 2 continued

Serial number	ψ_l	P_N	g_s	E	WUE	RH	T_{air}	T_l	T_s	PAR	SVP	pH	Soil salinity	Soil moisture
120	0.343	0.075	–0.550	–0.315	0.022	–0.398	0.025	0.236	–0.401	0.184	–1.770	–1.245	–0.508	–0.405
121	0.103	0.042	–0.635	0.456	–0.440	–0.783	0.931	1.312	–0.297	–1.371	–1.880	–1.463	–0.529	–0.404
122	–0.041	–0.585	–1.121	0.641	–0.800	–1.037	1.238	1.510	0.011	1.231	–2.182	–1.507	–0.531	–0.405
123	–0.147	–0.156	0.097	1.410	–0.807	–1.078	1.333	1.498	0.262	1.226	–0.009	–1.522	–0.532	–0.404
124	–0.174	–0.618	–1.090	0.217	–0.675	–1.061	1.161	1.239	0.357	0.670	–0.284	–1.530	–0.533	–0.404
125	–0.131	–1.077	–0.897	–0.414	–0.702	–0.971	1.033	1.042	0.383	–1.146	–0.394	–1.530	–0.533	–0.404
126	1.210	–1.421	–1.008	–1.786	0.704	0.568	–1.482	–1.277	–0.350	-	-	–1.532	–0.533	–0.404
127	0.747	0.166	0.220	–0.669	0.413	–0.134	–0.292	0.109	0.002	-	-	–1.530	–0.533	–0.402
128	–0.456	0.475	0.101	0.379	–0.187	–0.628	0.559	0.972	0.067	-	-	–1.525	–0.532	–0.402
129	–0.435	–0.890	–0.983	–0.094	–0.711	–0.828	1.052	1.696	0.228	-	-	–1.527	–0.533	–0.402
130	–1.393	–0.337	–0.265	0.334	–0.586	–0.943	1.140	1.326	0.492	-	-	–1.525	–0.532	–0.402
131	–0.536	0.336	–0.490	0.045	–0.065	–0.913	1.030	1.039	0.751	-	-	–1.522	–0.531	–0.401
132	–1.430	–1.298	–0.675	–0.542	–0.766	–0.854	0.842	0.971	0.917	-	-	–1.530	–0.531	–0.402
133	0.981	–1.705	–1.406	–1.911	0.203	0.063	–0.894	–0.714	–0.170	–1.485	–0.807	–0.548	–0.435	–0.405
134	–0.264	0.537	1.176	0.021	0.067	–0.247	–0.051	0.521	0.111	0.335	–0.697	–0.345	–0.403	–0.405
135	–1.004	–0.074	–0.273	0.403	–0.467	–0.679	0.633	1.431	0.184	0.953	–0.752	–0.962	–0.493	–0.404
136	–0.680	0.042	0.513	1.410	–0.739	–0.861	1.013	1.918	0.361	0.898	–1.082	–1.494	–0.528	–0.405
137	–1.713	–1.283	–1.552	–0.151	–0.932	–0.971	1.058	2.003	0.700	0.875	–1.495	–1.530	–0.532	–0.390
138	–0.062	–0.239	0.382	1.463	–0.852	–1.037	1.211	2.231	1.067	0.593	–1.852	–1.525	–0.531	–0.405
139	0.364	–1.897	–2.051	–1.606	–0.730	–0.946	0.942	1.176	1.327	–1.067	–2.045	–1.481	–0.529	–0.404
140	–0.083	–2.048	–1.198	–1.906	–0.630	1.188	–2.021	–1.590	0.461	–1.295	–0.752	–1.520	–0.531	–0.404
141	–0.861	–0.008	0.483	–0.125	–0.168	–0.143	–0.352	0.038	0.379	0.685	–0.697	–1.486	–0.527	–0.402
142	–0.664	–0.057	0.490	0.774	–0.594	–0.723	0.712	1.489	0.297	–0.229	–0.752	–1.527	–0.532	–0.399
143	–1.729	–0.879	–0.566	0.827	–0.972	–0.957	1.248	1.882	0.348	0.948	–1.110	–1.535	–0.532	–0.402
144	–0.690	–0.305	0.429	2.020	–0.971	–1.030	1.291	2.879	0.556	0.989	–1.522	–1.532	–0.532	–0.402
145	–1.004	–0.668	–0.342	0.986	–0.913	–1.012	1.269	2.237	0.835	0.553	–1.825	–1.517	–0.531	–0.402
146	–1.430	–1.695	–1.051	–0.435	–1.121	–0.983	0.984	1.283	1.074	–1.054	–2.017	–1.499	–0.529	–0.402
147	1.951	–0.651	–1.306	–2.115	5.031	3.279	–2.912	–2.557	–1.317	–0.580	2.274	–1.029	–0.466	–0.399
148	1.189	0.223	1.169	–0.215	0.049	0.517	–1.161	–0.381	–0.943	1.103	2.246	–1.052	–0.484	–0.405
149	0.401	0.487	1.107	0.270	–0.123	–0.173	–0.485	–0.106	–0.845	1.425	2.109	–1.121	–0.501	–0.405
150	1.013	0.306	0.706	0.482	–0.313	–0.267	–0.057	0.531	–0.726	1.496	1.751	–1.106	–0.496	–0.404
151	0.508	0.570	0.968	0.641	–0.268	–0.199	0.017	0.197	–0.531	1.571	1.311	–1.191	–0.505	–0.404
152	0.981	0.570	1.222	0.721	–0.295	–0.340	0.014	0.168	–0.288	0.932	1.036	–1.445	–0.526	–0.404
153	1.003	–0.453	–0.180	–0.395	–0.277	–0.151	–0.069	0.064	–0.080	–0.403	0.843	–1.484	–0.528	–0.402

significantly and negatively correlated with a correlation coefficient of –0.747; T_l is negatively correlated with PAR with correlation coefficient of –0.336; SVP is significantly correlated with T_l, soil moisture and pH with correlation coefficients of -0.802, 0.251, and 0.260, respectively; soil salinity and soil moisture are positively correlated with correlation coefficient of 0.544. These data indicate that the higher the RH is, the lower the T_s and T_l are and the higher the soil moisture and salinity are. Thus, RH, SVP and PAR are the meteorological factors affecting soil moisture and salinity of the shallow surface in the extremely arid region.

Relationship between environmental factors and ψ_l and gas-exchange characteristics: The maximum values of all environmental factors obtained were normalized and used as environmental data source (*.env) in *CANOCO*. ψ_l and gas-exchange characteristics were used as the data source (*.spe) in CANOCO (Table 2). These two data sources composed a data matrix. The responses of ψ_l and gas exchange to environmental factors were sorted using DCCA method. The obtained two-dimensional DCCA ordination diagrams are shown in Figs. 2 and 3. In the ordination diagram, the environmental factors are indicated with arrows, the length of the arrow shows the extent of the relationship of environmental factors with ψ_l and gas-exchange characteristics of *P. euphratica*. The angle of the arrow and axes indicates the extent of the relationship of the environmental factor to the axes. The direction of the arrow indicates the trend of environmental factors. The point of intersections of the perpendicular lines of the environmental factor with ψ and gas-exchange characteristics are used to indicate the extent of the correlation between the environmental factor and gas exchange characteristics. The closer the point to the arrow is, the greater the correlation is. If the point is in the opposite direction of the arrow, the greater the absolute distance is, the greater the negative correlation is (Zhang *et al*. 2004b).

The arrows of the ψ_l and gas-exchange characteristics and environmental factors reflect the change of leaf water properties along the gradient of each environmental factor. As shown in Fig. 2, Monte-Carlo test of Yinsu section shows that all the ordination axes are highly significant (p=0.001). The first shaft is significantly and negatively correlated with PAR, SVP, T_l, and T_{air} with correlation coefficients of –0.3511, –0.4544, –0.1793 and –0.1575, respectively; the second shaft is significantly and positively correlated with soil salinity and RH with correlation coefficients of 0.2989 and 0.5185, respectively, and negatively correlated with T_{air}, T_s and T_l with correlation coefficients of –0.5165, –0.4885 and –0.3719, respectively. All four shafts were not correlated with soil moisture and pH. These data indicate that the order of the dominant impact factors in Yinsu section for leaf moisture is RH>T_{air}> T_s>SVP>T_l>PAR>soil salinity.

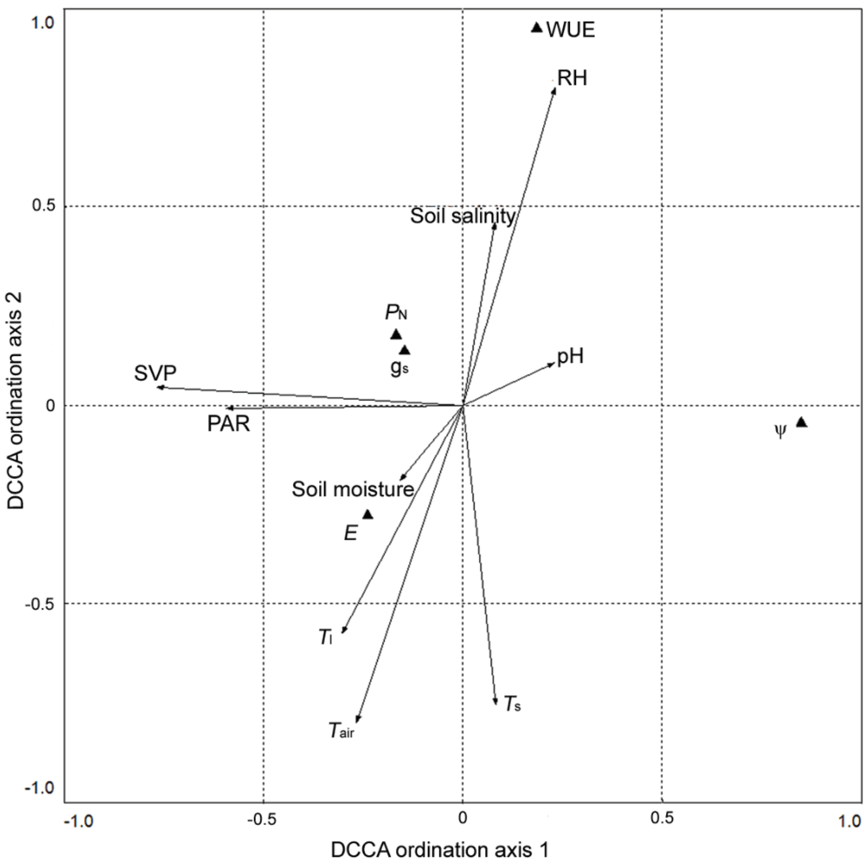

Fig. 2. Two-dimensional DCCA ordination diagram on the impact of environmental factors on water characteristics of *Populus euphratica* leaf in Yinsu section. E – transpiration rate; g_s – stomatal conductance; P_N – net photosynthetic rate; PAR – photosynthetic active radiation; RH – air relative humidity; T_{air} – air temperature; T_l – leaf temperature; T_s – soil temperature; SVP – saturation vapour pressure; WUE – water-use efficiency; ψ – water potential.

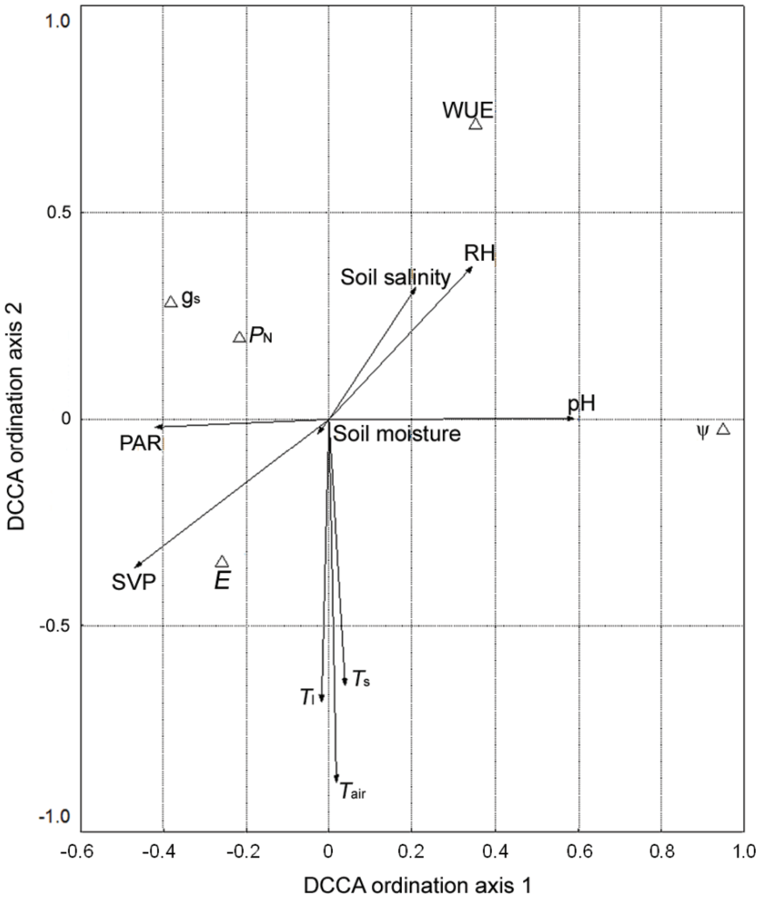

Fig. 3. Two-dimensional DCCA ordination diagram on the impact of environmental factors on water characteristics of *Populus euphratica* leaf in Alagan section. E – transpiration rate; g_s – stomatal conductance; P_N – net photosynthetic rate; PAR – photosynthetic active radiation; RH – air relative humidity; T_{air} – air temperature; T_l – leaf temperature; T_s – soil temperature; SVP – saturation vapour pressure; WUE – water-use efficiency; ψ – water potential.

In Alagan section, as shown in Fig. 3, Monte-Carlo test shows all the ordination axes are highly significant (p=0.001). The first shaft shows a significant negative correlation to PAR and SVP with coefficients of –0.2154 and –0.1746, respectively, and positive correlation to pH and RH with coefficients of 0.2214 and 0.1592, respectively. The second shaft shows significant negative correlation to T_{air}, T_l and T_s with coefficients of –0.3589, –0.2837, and –0.2673, respectively, and positive correlation to RH with coefficient of 0.1816. Four axes had no correlation to soil salinity and moisture. The order of the dominant impact factors in Alagan section for leaf moisture is T_{air}>T_l>T_s>pH>PAR>SVP>RH. Taking together, DCCA analyses indicate that environmental factors RH and T_{air} are the dominant meteorological factors that have the greatest impact on the leaf water characteristics in the extremely arid region.

Figs. 2 and 3 show WUE is in the first quadrant. When RH is larger and the T_{air}, T_l, and T_s are smaller, WUE increases with RH increasing. ψ_l is in the fourth quadrant, that means PAR and SVP are relative small, and the weaker the radiation and the smaller the SVP are, the higher ψ_l is. This is because weaker radiation causes less water loss through transpiration. Therefore, absorbing small amount of water from soil would meet the demand of leaves for transpiration, leading to a higher ψ. E is in the third quadrant, at this time, the RH is smaller, and T_{air} and T_l are higher in Yinsu section (Fig. 2). Alagan section has the similar environmental conditions of Yinsu section, but their PAR and SVP are higher (Fig. 3), indicating that as the radiation, T_{air} and SVP increases, RH decreases and leaf transpiration intensity increases. P_N and g_s are in the first quadrant, suggesting that when all the environmental factors in Yinsu section are at medium level, values of P_N and g_s are higher (Fig. 2); on the other hand in Alagan section, when PAR and SVP are greater, the pH is smaller and the P_N and g_s are greater (Fig. 3), indicating that in the extreme arid and acidic soil, the more the radiation and SVP increases, the better *P. euphratica* grows.

The quantitative relationship between leaf water characteristics and environmental factors: Multiple stepwise regression analysis was used to analyze the impacts of environmental factors (RH, T_{air}, T_l, T_s, soil salinity, PAR, and SVP) on ψ_l and gas-exchange characteristics. The results show that among those environmental factors in Yinsu and Alagan sections of Tarim River, ψ_l, P_N, g_s and E of *P. euphratica* are closely related to RH (p<0.001), T_l (p<0.001), T_s (p<0.001), T_{air} (p<0.05), PAR (p<0.05) and SVP (p<0.05). The stepwise regression equations are as follows:

ψ: $Y_1 = 2.155 - 0.039$ RH $- 0.046\ T_l - 0.195\ T_s + 0.012$ SVP, $r^2 = 0.205$

P_N: $Y_2 = 20.943 - 0.102$ RH $- 0.210\ T_l + 0.002$ PAR, $r^2 = 0.088$

g_s: $Y_3 = 0.660 - 0.003$ RH $- 0.005\ T_l - 0.007\ T_s - 0.00004$ PAR, $r^2 = 0.147$

E: $Y_4 = 5.857 - 0.078$ RH $+ 0.078\ T_{air} + 0.001$ PAR $+ 0.024$ SVP, $r^2 = 0.213$

WUE: $Y_5 = 0.418 - 0.007\ T_l$, $r^2 = 0.158$

These equations indicate that ψ_l, P_N, g_s, and WUE all are closely related to T_l. In particular, WUE shows significantly linear relationship with T_l. ψ_l, P_N, g_s and E are subject to the impact of RH although WUE changes with T_l closely. Since T_l is influenced by T_{air} and RH, it can be inferred that WUE is also indirectly influenced by RH. PAR affects leaf P_N, g_s and E, *i.e.* the growth. ψ_l is not only influenced by meteorological factors such as RH and SVP, but also constrained by T_s and T_l along with the increase of RH and T_s and the decrease of T_l and ψ_l.

Thresholds of environmental factors that reflect leaf water changes: Since RH has stronger influences on ψ_l, P_N, g_s, E, and WUE, it is feasible using changes in RH to show the comprehensive impact of environmental factors on water utilization and to determine the environmental threshold to show water status.

The RH values of the 153 sample points were assigned into 13 levels in ascending order as (10.69 ± 0.21)%, (16.43 ± 1.75)%, (19.11 ± 1.18)%, (23.06 ± 1.45)%, (28.09 ± 1.57)%, (33.12 ± 1.43)%, (38.23 ± 1.82)%, (43.34 ± 1.53)%, (48.19 ± 1.06)%, (53.55 ± 1.45)%, (62.82 ± 1.62)%, (71.71 ± 3.11)% and (80.40 ± 1.20)%. So did ψ_l, P_N, E, g_s, and WUE of *P. euphratica*. The values were analyzed by *SPSS13.0* software using method "analysis of variances with single variable and multiple factors in general linear model" and the results are listed in Table 3. As shown, when RH increased to (80.40 ± 1.20)%, P_N, g_s and E changed significantly compared with those at previous eight levels ($p<0.05$). When RH increased from (10.69 ± 0.21)% to (48.19 ± 1.06)%, gas-exchange characteristics did not change significantly compared with that at later four levels, indicating that RH value of (48.19 ± 1.06)% is the critical threshold, at which RH begins to affect P_N, g_s, and E of *P. euphratica* leaves. Table 3 shows that P_N, g_s, and E were significantly descended when RH increased from (10.69 ± 0.21)% to (48.19 ± 1.06)%**,** and there was no significant change of gas-exchange characteristics when RH increased from (48.19 ± 1.06) % to (80.40 ± 1.20)%. We show that (48.19 ± 1.06) % was the maximal RH affecting the change of gas-exchange. Because ψ_l and WUE are not evidently different among 13 RH levels, RH of (48.19 ± 1.06)% can only be used as an indicator for growth conditions, not as an indicator for changes in leaf water content.

Discussion and conclusion

Si *et al*. (2005) have reported that the daily change of ψ_l of *P. euphratica* is significantly correlated to T_{air}, RH, PAR and soil moisture when soil water is abundant. In other words, a small change of soil moisture can significantly affect the content of plant water when soil water is abundant. However, whether soil moisture has effect on ψ_l of *P. euphratica* at the extreme arid soil has not been investigated. It is believed that in arid areas, soil moisture plays a key role in *P. euphratica* growth and development. However, this research presents different conclusions that RH and meteorological factors such as T_{air} are the dominant environmental factors affecting changes of *P. euphratica* leaf water content. Because, in the extremely arid areas, the groundwater level is generally deeper than 5 m, the moisture content in the shallow surface soil is very low and has weaker impact on changes in *P. euphratica* leaf water content. In the condition of strong drought stress, meteorological factors have the dominant effects on the water status of *P. euphratica* leaves.

In terms of the factors that affect leaf gas-exchange characteristics, this paper concludes that in extremely arid environments, PAR affects P_N, g_s, and E of *P. euphratica* leaves, i.e. affects the growth. This is in agreement with a previous study conducted by Zhou *et al*. (2008), showing that in the lower reaches of Tarim River, PAR becomes a major factor that controls g_s and E of *P. euphratica* with underground water level decreasing. Si *et al*. (2008) have reported that g_s of *P. euphratica* is significantly correlated with T_{air} and RH. Other studies also have shown that under relative stable T_{air} and light intensity conditions, leaf transpiration has significant negative correlation with RH (Jiang 1991). Previous studies have also shown that T_{air}, and RH strongly influenced the gas-exchange characteristics of *P. euphratica* leaf. Similar to that, we also found that both high T_{air} and longtime low T_{air} restrained g_s of *P. euphratica* (Si *et al*. 2008). However, the effect of T_{air} on g_s of *P. euphratica* depends on PAR. Therefore, PAR is the dominant factor influencing the gas-exchange characteristics of *P. euphratica* leaf in the extremely arid zone.

This study suggests that RH, SVP, T_s, and T_l have impacts on changes in ψ_l of *P. euphratica*. Previous research has shown that the effect of T_{air} on the water status is reflected by its effect on ψ, i.e., with the T_{air} rising, water situation of *P. euphratica* deteriorates, resulting in decreased ψ (Jiang 1991). Previous study (Lang and Nobel 1982) has also shown that the order of factors that have most dramatic influences on ψ is light > RH > T_{air}, consistent with our results that the environ-

Table 3. *ANOVA* and least significant difference (LSD) analysis of ψ_l and the gas-exchange characteristics of *P. euphratica* under the different range of RH. *Note:* Mean difference (I-J) represents the mean difference of P_N, g_s, E, WUE and ψ_l between RH (I) and RH (J),Standard error represents the standard error of P_N, g_s, E, WUE, and ψ_l between RH (I) and RH (J),The significant level represents the significant level of P_N, g_s, E, WUE and ψ_l between RH (I) and RH (J). RH – air relative humidity; P_N – net photosynthetic rate; g_s – stomatal conductance; E – transpiration rate; WUE – water-use efficiency; ψ_l – leaf water potential.

Variables	(I) RH [%]	(J) RH [%]	Mean difference (I–J)	Standard error	Significance level
P_N [μmol(CO_2) m^{-2} s^{-1}]	80.40 ± 1.20	10.69 ± 0.21	–12.8147	4.9381	0.010
		16.43 ± 1.75	–13.0043	4.6542	0.006
		19.11 ± 1.18	–12.5020	4.7479	0.009
		23.06 ± 1.45	–13.5091	4.7053	0.004
		28.09 ± 1.57	–13.8951	4.7848	0.004
		33.12 ± 1.43	–12.2698	4.8458	0.012
		38.23 ± 1.82	–14.1567	5.4394	0.010
		43.34 ± 1.53	–12.8872	5.0823	0.012
		48.19 ± 1.06	–13.2231	5.6303	0.020
		53.55 ± 1.45	–8.4125	5.1397	0.103
		62.82 ± 1.62	–8.1086	5.2126	0.121
		71.71 ± 3.11	–3.4500	5.6303	0.541
g_s [mmol(H_2O) m^{-2} s^{-1}]	80.40 ± 1.20	10.69 ± 0.21	–0.2018	0.090	0.035
		16.43 ± 1.75	–0.2211	0.089	0.014
		19.11 ± 1.18	–0.2329	0.092	0.012
		23.06 ± 1.45	–0.2718	0.091	0.003
		28.09 ± 1.57	–0.2680	0.092	0.004
		33.12 ± 1.43	–0.2199	0.093	0.019
		38.23 ± 1.82	–0.2657	0.1049	0.012
		43.34 ± 1.53	–0.2956	0.099	0.003
		48.19 ± 1.06	–0.1298	0.1086	0.233
		53.55 ± 1.45	–0.1908	0.099	0.055
		62.82 ± 1.62	0.1380	0.1005	0.171
		71.71 ± 3.11	–0.0420	0.1086	0.702
E [mmol(H_2O) m^{-2} s^{-1}]	80.40 ± 1.20	10.69 ± 0.21	–9.0795	2.7416	0.001
		16.43 ± 1.75	–8.1947	2.5840	0.002
		19.11 ± 1.18	–7.3681	2.6360	0.006
		23.06 ± 1.45	–8.2595	2.6124	0.002
		28.09 ± 1.57	–8.7926	2.6566	0.001
		33.12 ± 1.43	–6.8592	2.6904	0.011
		38.23 ± 1.82	–7.7150	3.0200	0.011
		43.34 ± 1.53	–7.0892	2.8217	0.013
		48.19 ± 1.06	–5.8283	3.1260	0.064
		53.55 ± 1.45	–3.1154	2.8536	0.276
		62.82 ± 1.62	–3.3068	2.8041	0.242
		71.71 ± 3.11	–0.5453	3.1260	0.862
WUE [μmol $mmol^{-1}$]	80.40 ± 1.20	10.69 ± 0.21	0.050	0.092	0.588
		16.43 ± 1.75	0.029	0.087	0.735
		19.11 ± 1.18	0.058	0.088	0.512
		23.06 ± 1.45	0.044	0.088	0.621
		28.09 ± 1.57	0.045	0.089	0.616
		33.12 ± 1.43	0.031	0.091	0.736
		38.23 ± 1.82	0.068	0.1017	0.503
		43.34 ± 1.53	0.045	0.095	0.636
		48.19 ± 1.06	–0.024	0.1052	0.823
		53.55 ± 1.45	–0.028	0.096	0.775
		62.82 ± 1.62	–0.016	0.097	0.867
		71.71 ± 3.11	–0.057	0.1052	0.587

Table 3 continues on the next page

Table 3 continued

Variables	(I) RH [%]	(J) RH [%]	Mean difference (I–J)	Standard error	Significance level
ψ_l [MPa]	80.40 ± 1.20	10.69 ± 0.21	0.9800	1.3976	0.484
		16.43 ± 1.75	0.7995	1.3172	0.544
		19.11 ± 1.18	0.4730	1.3437	0.725
		23.06 ± 1.45	0.6229	1.3317	0.640
		28.09 ± 1.57	1.0817	1.3542	0.425
		33.12 ± 1.43	0.7150	1.3714	0.603
		38.23 ± 1.82	–0.1640	1.5394	0.915
		43.34 ± 1.53	–0.2944	1.4384	0.838
		48.19 ± 1.06	0.6575	1.5935	0.680
		53.55 ± 1.45	0.7575	1.4546	0.603
		62.82 ± 1.62	0.2043	1.4753	0.890
		71.71 ± 3.11	–0.2450	1.5935	0.878

mental factors that affect ψ are the meteorological factors rather than soil water content.

In extremely dry regions of the lower reaches of Tarim River, P_N, E, and g_s of *P. euphratica* leaf are subject to PAR, SVP and T_{air}. Along with these environmental factors increasing, the gas exchange rate also increases, resulting in accelerated growth under the limited environmental conditions. To keep *P. euphratica* grow normally, lowering RH, and increasing PAR and SVP are necessary. Under this condition, transpiration tension, absorptive capacity for soil moisture, and ψ_l can be enhanced to meet the demand of leaf for water to keep strong transpiration.

Our study shows that (48.19 ± 1.06)% of RH can be used to indicate whether growth of *P. euphratica* is normal, but not to reflect the changes in Tarim River leaf water status. Because P_N, E and g_s of *P. euphratica* leaf have significant negative correlation with RH (that is to say, the lower the RH, the higher the frequency of leaf gas exchange, and the faster the *P. euphratica* growth). In extremely arid region of Tarim River, RH between (10.69 ± 0.21)% and (48.19 ± 1.06)% is favourable for leaf gas exchange and growth of *P. euphratica*. Si *et al*. (2008) have deduced the similar conclusion that g_s of *P. euphratica* leaf increases to certain level and then decreases with RH increasing. Because g_s under the cloudy sky with higher RH, less SVP, and weaker light is smaller than that under shinny sky with lower RH, threshold value of RH can be used to predict the gas-exchange characteristics of *P. euphratica* leaf.

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