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Analysis of water use strategies of the desert riparian forest plant community in inland rivers of two arid regions in northwestern China

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Abstract

Studies of the water use of the desert riparian forest plant community in arid regions and analyses of the response and adaptive strategies of plants to environmental stress are of great significance to the formulation of effective ecological conservation and restoration strategies. Taking two inland rivers in the arid regions of northwestern China, downstream of the Tarim River and Heihe River Basin as the research target regions, this paper explored the stem water potential, sap flow, root hydraulic lift, and characteristics of plant water sources of the major constructive species in the desert riparian forest, *Populus euphratica* and *Tamarix ramosissima*. Specifically, this was accomplished by combining the monitoring of field physiological and ecological indicators, and the analysis of laboratory tests. Then, the water use differences of species in different ecological environments and their ecological significance were analyzed. This study indicated that: (1) in terms of water sources, *Populus euphratica* and *Tamarix ramosissima* mainly used deep subsoil water and underground water, but the plant root system in the downstream of the Tarim River was more diversified than that in the downstream of the Heihe River in water absorption, (2) in terms of water distribution, *Populus euphratica* root possessed hydraulic lift capacity, but *Populus euphratica* root in the downstream of the Tarim River presented stronger hydraulic lift capacity and more significant ecological effect of water redistribution, (3) in terms of water transport, the plants in the downstream of the Heihe River can adapt to the environment through the current limiting of branch xylem, while plants in the downstream of the Tarim River substantially increased the survival probability of the whole plant by sacrificing weak branches and improving the water acquisition capacity of dominant branches; and (4) in terms of water dissipation, the water use and consumption of *Populus euphratica* at night exhibited no significant difference, but the water use and consumption of *Populus euphratica* in the downstream of the Tarim River in the day was significantly higher than that in the downstream of the Heihe River, and the essential reason for this is the groundwater depth. The ecology in the downstream of the Heihe River has been in

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balance in the maintenance and development stage, while desert riparian forest plants in the downstream of the Tarim River are still in severe arid stress.

1 Introduction

Water is the most important limiting factor of plant distribution and growth; thus, plant water sources and use strategies are one of the major concerns of ecologists (Pausas and Austin, 2001; Cheng et al., 2006; Zhou et al., 2011). Most studies indicated that plant water sources and use strategies varied in different ecological environments. For example, in Utah's southern desert in the US, its annual and perennial succulent plants completely depend on summer rains, while herbaceous plants and perennial xylophyta simultaneously use summer rains and winter rains (Ehleringer et al., 1991). In the Mu-Us Desert in Northern China, it is easy for alien species, *Saliz matsudana*, to use underground water; whereas, native species, *Sabina vulgaris* and *Artemisia ordosica*, tend to store water (Ohte et al., 2003). Moreover, in southern Florida in the US, the tropical and sub-tropical hardwood species (e.g., *Coccoloba*) of coastal plants mainly use fresh water (rainfall and runoff), while salt-tolerance species (e.g., *Slicornia*) almost all use seawater. On the other hand, Redwood forest can use both of these kinds of water sources (Sternberg et al., 1987). In addition, the water use efficiency, sources, and means of plants also are closely correlated to the plant functional forms (Xu et al., 2005), plant growth stages (Sun et al., 2006), types of species (Duan et al., 2008), and seasonal variation (Ewe et al., 2002). Therefore, identifying plant water sources and use strategies are challenges and subjects of great interest in the ecological hydrology field, and of great significance to the comprehension of plants' drought-resistant mechanisms and survival strategies.

In the global terrestrial ecosystem, arid and semiarid ecosystems cover about 50 % of the earth's surface (Bailey, 1996). In China's terrestrial ecosystem, arid and semiarid ecosystems account for 52 % of the national land surface (Wang, 2007). Arid desert regions have rare rainfall; thus, water factor is a key limiting factor of plant growth and

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development. The exploration of plants' water use strategies in arid regions is extremely important to the conservation and restoration of the fragile ecosystems in the arid systems. At present, studies in China and globally have determined that the major means of water use methods and strategies in different habitat conditions include: stable isotope technology of ^{2}H, ^{18}O and ^{13}C (Drake et al., 2003; Duan et al., 2007; Zhou et al., 2011); trunk sap flow technology (Ma et al., 2013); water potential (Fu et al., 2012), etc. Typical studies have been conducted of tropical forest ecosystems (Meinzer et al., 1999), temperate forest ecosystems (White, 1985), riparian ecosystems (Snyder et al., 2000), coastal ecosystems (Dawson, 1998), desert ecosystems (Ohte et al., 2003), and semiarid areas (Willams and Ehleringer, 2000), and have successfully analyzed plants' water use efficiency and means in different environments. Furthermore, these studies provide important references for the studies of plant water use strategies in inland river basins. Combined with stable isotope technology, trunk sap flow technology, water potential, root water redistribution, etc., this paper comprehensively compared and analyzed the water use efficiency, source, distribution, and strategy of desert riparian forest plants in two typical arid regions, the downstream of the Tarim River and the Heihe River Basin, and explored the relation between the regional environment and plant water use strategy. The ultimate aim of our research is to perfect studies on plants' water physiological ecology and provide a scientific basis for the restoration and reestablishment of desert riparian forests of inland river basins in arid regions.

2 Study area

The Tarim River and Heihe River, respectively, are the largest and the second largest inland rivers, located in arid regions of northwestern China, and they are, respectively, 2179 and 821 km. The former goes through the Taklimakan Desert and Kuluke Desert in the Tarim Basin, and the latter is located in the transformation zone between the Alxa Plateau and Beishan Desert, both belonging to arid desert regions (Table 1). These two regions are both part of the Meso Cenozoic sedimentary basin, in which the earth's

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surface is deposited with alluvial-proluvial unconsolidated sediment hundreds of meters thick. The basically similar sedimentary texture and lithofacies determine similar aquifer distribution and groundwater runoff movement characteristics. Their soils are both composed of alleviation and lacustrine deposits, and their structures are relatively simple. Moreover, their soil-forming processes, structural compositions, and physico-chemical properties are similar. The salinization and wind desertion are severe (Liu et al., 2005; Zhao et al., 2010). Their climatic characteristics are similar, both belonging to typical warm temperate zone continental arid climate, with little rainfall and strong evaporation. They also both belong to a desert zone, and the underground water relies on river feeding. Due to the moistening of the draining water of the upper and middle stream, zonality and non-zonality vegetation is distributed. Among constructive species, arbor is *Populus euphratica,* shrub is *Tamarix ramosissima*, and herb is *Alhagi sparsifolia* and *Karelinia caspia*. Moreover, *Lycium ruthenicum*, *Phragmites communis*, and *glycyrrhiza* are distributed in blade. In the downstream of the Tarim River, there is *Apocynum venetum* and *Hexinia polydichotoma*, and the low-lying of the downstream of the Heihe River is also distributed sporadically with *Sacsaoul*, *Sophora alopecuroide*, and *Achnatherum splendens*.

The common points between the Tarim River and Heihe River are as follows: (1) water resources form from the ice-snow melting water and rainfall. In the middle stream oasis region, the surface water is exploited in large quantity for agricultural irrigation. (2) The geological environment, soil-forming process, and rain conditions in the river downstream region are basically similar. Because the river downstream dried up for a long time and the underground water level falls, the desert riparian forest declines and even dies off in a large area, presenting desert landscape. (3) Since 2000, ecologic water transport has been applied in the downstream dried-up riverway, aiming at lifting the underground water level and saving increasingly declining desert riparian forest. The differences lie in that the mean underground water level of both sides of the downstream of the Tarim River is 6–8 m, and some sections reach over 10 m. In the past 13 years of the ecological water transport process, it mainly follows the down-

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stream river channel for linear water transport. Therefore, only the underground water level near both sides of the riverway is lifted (Chen et al., 2003). The mean underground water level of the Heihe River is 3–4 m. During this same time period, almost every year the waterhead reaches tail lake Dongjuyanhai Lake (Tang and Jiang, 2009), and when the water transfer quantity is huge, many overflows occur in the downstream.

3 Materials and methods

3.1 Layout of sections

This paper selected the Yingsu section of the downstream of the Tarim River and Ulan Tug section of the downstream of the Heihe River as the test site, and established 7 groundwater monitoring wells of different distances perpendicular to the riverway. Among them, the mean groundwater depth of the downstream of the Tarim River (Yingsu section) was 5.05 m, with the minimum buried depth of 3.59 m and the maximum buried depth of 8.68 m. The mean groundwater depth of the downstream of the Heihe River (Ulan Tug section) was 2.75 m, with the minimum buried depth of 3.96 m and the maximum buried depth of 1.05 m. Near each monitoring well, a 50 m × 50 m plant sample plot and soil moisture monitoring section were set. During July and September from 2010 to 2012, the monitoring of plant physiological ecology, and groundwater and soil sampling were made in the Yingsu section of the downstream of the Tarim River and Ulan Tug section of the downstream of the Heihe River.

3.2 Measurement of plant water potential

A portable water potential pressure chamber (3115, SEC Inc, USA) was adopted to measure the daily variation of stem water potential of the constructive species on the selected section, *Populus euphratica* and *Tamarix ramosissima*. For better comparability and scientificity, three plants similar in DBH (diameter at breast height) and plant height in each section were selected, and each plant selected 3–5 normally growing twigs to measure water potential at the direct solar radiation point. The monitoring time was from predawn (5:00–5:40 LT) to afternoon (18:00 LT). Monitoring was performed every three hours, and the measurements all were selected in sunny days.

3.3 Measure of plant water use and consumption

Three plants of *Populus euphratica* with similar stand structures and DBH were, respectively, selected in the Yingsu section and Ulan Tug section as sample trees. Sap flow meter (SFM1 Sap Flow Meter, ICT International Pty, Ltd., Australia) was adopted to monitor the daily variation of sap flow rate. Digital automatic meteorological station (ICT International Pty., Ltd., Australia) was adopted to simultaneously monitor environmental parameters, such as air temperature, relative air humidity, wind speed, and vapour pressure deficit (VPD).

3.4 Measurement of plant hydraulic conductivity

Three plants of mature, and disease and insect pest-free *Populus euphratica* and *Tamarix ramosissima* with similar DBH/crown breadth and height were, respectively, selected in the Yingsu section and Ulan Tug section as sample trees. A xylem conductivity and embolization measuring system (Xylem embolization meter, Bronkhorst, Montigny-les-cormeilles, France) was used to measure the root and branch xylem conductivity and embolization, with a diameter of $2\,\text{mm} \le d < 5\,\text{mm}$. The determination method was used as shown in the literature (Zhou et al., 2013).

3.5 Measurement of plant root hydraulic lift

Three plants of mature and healthy *Populus euphratica* with 10 m distance, 15–20 cm DBH, and 10–15 m height were, respectively, selected in the Yingsu section and Ulan Tug section as sample trees. HRM (Heat Ratio Method) and stem flow meter (ICT International, Australia) was used to measure the plant root stem flow. The determination method was used as shown in the literature (Hao et al., 2013). A CNC 100 neutron probe was used to real-time monitor the soil moisture in layer. The night increment of soil moisture in the study was viewed as night lifting water of plant root. The difference between the maximum and minimum soil moisture content within 24 h was viewed as plant transpiration water consumption (Warren et al., 2011).

3.6 Measurement of plant water sources

Samples were taken from the plant xylem. 3–5 disease and insect pest-free *Populus euphratica* and *Tamarix ramosissima* with proper crown breadth were selected. Branch xylem with 0.3–0.5 mm diameter and 3–5 cm were cut from stems of over two years old. The soil samples were collected from underground 0–10, 10–20, 20–30, 30–40, 40–50, 50–75 and 75–100 cm, until the soil saturated zone. Samples in each layer were collected twice, once for measuring water isotope and once for measuring soil moisture content. Regarding groundwater sampling, underground water was collected from the monitoring well.

δ^{18}O in different water bodies were measured with LGR (America LGR Company LWIA-V2[LDT-100]) liquid water isotope analyzer.

4 Results

4.1 Plant root water use

4.1.1 Plant water sources

In the downstream of the Heihe River, δ^{18}O at 0–50 cm soil surface fell between 9.8 and 3.5 ‰. With increasing depth, δ^{18}O decreased rapidly. Below the 200 cm soil layer, δ^{18}O basically maintained at −7.0 ‰ (Fig. 1a). In the downstream of the Tarim River, δ^{18}O at the soil surface was 14.9 ‰. With the further increase of soil depth, δ^{18}O presented a trend of fluctuating decrease. δ^{18}O of soil close to underground water was −8.6 ‰ (Fig. 1b). δ^{18}O in the underground of the downstream of the Heihe River and

Tarim River, respectively, were −6.9 and −7.7 ‰, which were similar to $\delta^{18}O$ at 200–250 and 375–550 cm (Fig. 1a and b). $\delta^{18}O$ of *Populus euphratica* in the downstream of the Heihe River and Tarim River, respectively, were −5.8 and −5.6 ‰, and there was no significant difference between them ($P > 0.05$). $\delta^{18}O$ of *Tamarix ramosissima* between both regions exhibited no significant difference ($P > 0.05$).

IsoSource software was utilized to estimate plant water sources, and results showed that in the downstream of the Heihe River, the mean water use of *Populus euphratica* at 0–20 and 0–75 cm, respectively, were 4.3 and 1 % (Fig. 2a). In the downstream of the Tarim River, the mean water use of *Populus euphratica* at 0–20 and 0–75 cm, respectively, were 3.9 and 4.3 % (Fig. 2b). These indicated whether or not mature *Populus euphratica* in the downstream of the Heihe River (with groundwater depth of 3.25 m) or mature *Populus euphratica* in the downstream of the Tarim River (with groundwater depth of 7.0 m) was partial to the use of the surface soil water. In the downstream of the Heihe River, the mean water use of *Populus euphratica* at 75–175 cm was 14.2 %, while the mean use proportion of soil water at 175–325 cm was 40.8 %, with a maximum of 94 %, and the mean use proportion of underground water was 39.8 %, with a maximum of 92 % (Fig. 2a). These indicated that mature *Populus euphratica* in the downstream of the Heihe River mainly absorbed soil water and underground water at 175–325 cm for transpiration. In the downstream of the Tarim River, the mean contribution rate of soil water at 75–175 cm to *Populus euphratica* was 9.3 %. The contribution rates at 175–375 and 375–700 cm, respectively, were 23.3 and 30.4 %, exhibiting a significant increase. Moreover, the mean use proportion of underground water of *Populus euphratica* was 28.8 %, with a maximum of 86 % (Fig. 2b), indicating that *Populus euphratica* mainly absorbed soil water and underground water at 375–700 cm.

In the downstream of the Heihe River, $\delta^{18}O$ of *Tamarix ramosissima* was similar to that in soil water at 125 cm. In the downstream of the Tarim River, $\delta^{18}O$ of *Tamarix ramosissima* was similar to that in soil water at 250–400 cm. In the downstream of the Heihe River, the mean use rate of soil water of *Tamarix ramosissima* at 20 cm surface was 5.5 %, and the mean use rate of soil water at 20–80 cm was only 11.0 %. It mainly used soil water (with a mean of 41.2 %) and underground water (with a mean of 42.4 %) below 80 cm. In the downstream of the Tarim River, the mean use rate of soil water of *Tamarix ramosissima* at 0–175 cm was no more than 6.7 %. It mainly used deep subsoil water (with a mean of 45.0 %) and underground water (with a mean of 34.0 %) at 375–700 cm.

4.1.2 Plant root hydraulic lift

Populus euphratica root at the Tarim River and Heihe River Basin generally exhibited the function of hydraulic lift (Fig. 3). However, root flow rate changes in different regions demonstrated a significant difference. In the downstream of the Tarim River, flow rates of the main root and lateral root differed substantially (Fig. 3a), and after the flow rate at 12:00 LT reached the peak, the flow rate could remain high for a long time. In contrast, in the downstream of the Heihe River, the flow rates of the main root and lateral root differed substantially (Fig. 3b), and after the flow rate at 12:00 LT reached the peak, the flow rate could not remain high for a long time. In the downstream of the Tarim River, the daily mean flow rate, minimum flow rate and night mean negative flow of *Populus euphratica* lateral root were 0.30, −2.65, and $-2.34\,\mathrm{cm\,h^{-1}}$, respectively. In the downstream of the Heihe River, the daily mean flow rate, minimum flow rate and night mean negative flow of *Populus euphratica* lateral root, were 3.82, −1.05, and $-0.80\,\mathrm{cm\,h^{-1}}$, respectively. These indicated that, at the simple root level, the hydraulic redistribution of *Populus euphratica* root in the downstream of the Tarim River was more significant.

The hydraulic lift of *Populus euphratica* root inevitably led to the obvious lift of soil moisture content in the corresponding soil layer. The analysis results indicated that the hydraulic lift of *Populus euphratica* root in the downstream of the Tarim River mainly occurred at the 10–110 cm soil layer, and the daily mean lift water at the whole soil layer of 0–110 cm was 0.41 mm. The root lift water in each soil layer from large to small, successively, were 10 cm > 30 cm > 110 cm > 70 cm > 90 cm > 50 cm (Fig. 4a). In the downstream of the Heihe River, the hydraulic lift of *Populus euphratica* root

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mainly occurred at the soil layer of 10–70 cm, and the daily mean lift water at the whole soil layer of 10–70 cm was 0.36 mm. The root lift water in each soil layer from large to small, successively, were 50 cm > 10 cm > 30 cm > 70 cm (Fig. 4b). Comparing the downstream of the Tarim River and the downstream of the Heihe River, the most differences of hydraulic lift of *Populus euphratica* root were amount of root lift water and depth of hydraulic lift happend. In the downstream of the Tarim River, the daily mean water consumption of transpiration was 1.30 mm, which was far smaller than that in the downstream of the Heihe River, i.e., 3.37 mm. The improvement of hydraulic lift of *Populus euphratica* root to the improvement soil moisture conditions in the downstream of the Tarim River (the lift water accounting for 32 % of the water consumption) should be significantly larger than that in the downstream of the Heihe River (the lift water accounting for 10 % of the water consumption). In other words, the ecological effect of the hydraulic lift of *Populus euphratica* root in the downstream of the Tarim River should be more significant.

4.2 Plant xylem hydraulic conductivity

In the downstream of the Tarim River, the initial hydraulic conductivity (K_{s0}) and maximum hydraulic conductivity (K_{smax}) of plant root and branch xylem were significantly lower than those of the downstream of the Heihe River ($P < 0.05$). Among them, the hydraulic conductivity of *Tamarix ramosissima* root xylem was the largest (Fig. 5), followed by *Tamarix ramosissima*. In terms of the conductivity of root xylem, K_{s0} and K_{smax} of *Tamarix ramosissima* root in the downstream of Tarim River were 1.59 and 17.65, respectively; K_{s0} and K_{smax} of *Tamarix ramosissima* root in the downstream of Heihe River were 20.63 and 35.03, respectively, increasing by 11.97 times and 0.98 times, respectively. K_{s0} and K_{smax} of *Populus euphratica* increased 6.74 times and 0.97 times, respectively. In terms of the conductivity of branch xylem, K_{s0} and K_{smax} of *Tamarix ramosissima* branch xylem in the downstream of the Heihe River increased by 9.48 times and 1.59 times, respectively, followed by those of *Populus euphratica*, increasing by 3.65 times and 1.18 times, respectively. The maximum conductivity (K_{smax}) of root

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and branch xylem indicated that both in the downstream of the Tarim River and the downstream of the Heihe River, the potential hydraulic conductivity of *Tamarix ramosissima* xylem was stronger than that of *Populus euphratica* xylem.

Natural embolization level (PLC) of xylem at the same part of the same plant exhibited a significant difference at different drought stress levels (Fig. 6). PLC of plant root and branch xylem in the downstream of the Tarim River were significantly higher than those in the downstream of the Heihe River ($P < 0.05$). These indicated that with increasing drought stress, the embolization level of plant root and branch xylem increased significantly, i.e., drought stress can significantly influence the water conductivity of the plant xylem. Under different drought stress levels, the stress level of plant root and branch xylem differed. The embolization level of plant branch xylem was significantly enhanced, i.e., plant branch xylem in the downstream of Heihe River was easier to be embolized. However, with increasing drought stress, the embolization level of plant root xylem in the downstream of the Tarim River would be significantly higher than that of branch xylem.

4.3 Plant transpiration water consumption

Plant sap flow can intuitively reflect the transpiration of plants. The experimental results indicated that the daily variation of the main trunk sap flow rate of *Populus euphratica* in the downstream of the Tarim River presented a wide front curve, and after 12:00 LT it showed a slight decrease. In contrast, the daily variation of the main trunk sap flow rate of *Populus euphratica* in the downstream of the Heihe River presented a unimodal distribution, and after 12:00 LT it reached the peak. The start of both sap flows basically was synchronous with sunrise and began to decrease quickly with sunset. At night, it maintained a relatively low speed (Fig. 7). Variance analysis demonstrated that the flow rates of *Populus euphratica* in both regions demonstrated a significant difference ($P < 0.01$).

Sap flow rates of *Populus euphratica* in the downstream of the Tarim River and Heihe River were correlated significantly with meteorological factor ($P < 0.01$), but it varied in different habitats (Fig. 8). According to the trend, the analysis of extremum showed that the sap flow rates of *Populus euphratica* in the downstream of the Tarim River and Heihe River decreased with the increase of RH. When RH were 43 and 58 %, respectively, the sap flow rates of *Populus euphratica* tended to flatly decrease with the increase of RH. When the wind speeds were lower than 7.7 and 4.2 km h^{-1}, respectively, the sap flow rates of *Populus euphratica* in the downstream of the Tarim River and Heihe River increased with the increase of wind speed. In contrast, when the wind speeds were respectively larger than those two values, the sap flow rates of *Populus euphratica* tended to decrease with the increase of wind speed. When vapor pressure deficits (VPD) were lower than 6.1 and 5 kPa, respectively, the sap flow rates of *Populus euphratica* in the downstream of the Tarim River and Heihe River increased with the increase of VPD. When VPDs were larger than 6.1 and 5.0 kPa, respectively, the sap flow rates of *Populus euphratica* tended to decrease with the increase of VPD. The analysis revealed that, due to the difference between the two experimental sections in the downstream of the Tarim River and Heihe River in terms of environmental factor, the response of transpiration of *Populus euphratica* in both regions to meteorological factors differed, reflecting the adaptation of the same plant to different long-term habitats.

4.4 Variation of plant water potential

Through the analysis of daily variation of stem water potential of *Populus euphratica* and *Tamarix ramosissima* (Fig. 9), it can be found that from predawn to 18:00 LT, the daily variation of stem water potential of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Heihe River presented a unimodal distribution. At predawn, the water potential was the maximum −0.44 and −0.67 MPa, respectively. With the increase of temperature, the water potential began to decrease. At 12:00 LT, the water potential was the minimum −2.19 and −2.63 MPa, respectively. After 12:00 LT, with the decrease of temperature, the water potential began to increase slowly. The daily variation of stem water potential of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Tarim River presented a slowly decreasing unimodal distribution. At predawn, the water potential was the maximum −4.53 and −2.50 MPa, respectively. Later, with the increase of temperature, the stem water potential of *Populus euphratica* decreased quickly to −6.69 MPa at 9:00 LT. At 12:00 LT, the stem water potential of *Tamarix ramosissima* decreased to −4.00 MPa. After 12:00 LT, with the decrease of temperature, the water potential increased shortly, but later the water potential decreased, and at 18:00 LT the stem water potential decreased to −8.08 and −5.23 MPa, respectively.

In the past 10 years, ecologic water transport projects were implemented in the downstream of the Tarim River and Heihe River. However, after water transport, the ecological effects varied. The groundwater depth in the downstream of the Tarim River was still deep, and the shallowest place was over 3 m; over 600 m from the riverway, it even reached over 8 m. During the water transport in the downstream of the Heihe River, there were many occurrences of overflows, and the groundwater depth near the riverway was shallow, with a mean depth of less than 3 m. Through the analysis of the stem water potential variation characteristics of *Populus euphratica* and *Tamarix ramosissima* at predawn and 12:00 LT at different groundwater depths, it can be found that (Fig. 10) in the downstream of the Tarim River, with the increase of groundwater depth, the water potential of *Populus euphratica* and *Tamarix ramosissima* at predawn both decreased firstly and then increased. However, the stem water potential of *Populus euphratica* at 12:00 LT gradually decreased, while stem water potential of *Tamarix ramosissima* at 12:00 LT gradually increased. In the downstream of the Heihe River, with the increase of groundwater depth, the water potential of *Populus euphratica* at predawn exhibited no significant increase or decrease; whereas, the water potential of *Tamarix ramosissima* at predawn increased instead of decreased. The possible reason for this may lie in measuring error and requires further analysis. However, the water potential of *Populus euphratica* at 12:00 LT increased, while the water potential of *Tamarix ramosissima* at 12:00 LT decreased.

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5 Discussion and conclusions

Both natural and artificial ecosystems, such as terrestrial, ocean, forest, grassland, lake and pond, are important objects in biogeoscience studies, for which the biogeochemical effects play a key role in their evolution processes, for example, the formation and depletion of atmosphere, formation and degradation of soil, changes and deterioration of water resources and water quality, and climate change. (Geng et al., 2001). Therefore, biogeoscience studies are very important for providing scientific basis for sustainable development of the biosphere, environmental protection, and global change prediction.

The desert riparian forest in arid area is an essential component of of the terrestrial ecosystem in the world. It is a very complex system because of human activities and climate change, and is an important object of the biogeoscience study. Heihe River Basin and Tarim River Basin are two important river system in arid Northwestern China. Both river basins are rich in natural resources, but the ecological environment are extremely vulnerable because of limited water resources (Chen et al., 2007). Over the past several decades, both natural ecological processes and hydrological cycle in the two basins have been deeply modified by human activities and climate change (Xu et al., 2010). As a result, the downstream of the Heihe River and Tarim River had dried up one after another in 1960s and 1970s, respectively. Consequently, the groundwater table dropped significantlyleding to a serious decline in the desert riparian forest vegetation in the affected area. Large patches of herbaceous plants, such as *Phragmites communis* Trirn, *Apocynum venetum L.*, and *Alhagi sparsifolia*, died. The *Populus euphratica* and *Tamarix ramosissima* plant communities also degenerated in the region (Li et al., 2010). The lower reaches of the Tarim River and Heihe River have been experiencing the most serious ecological problems from over exploitation and utilization of water resources in western China.

The groundwater table in most of the area declined to below 6 m, and even reached over 10 m in the lower reaches of the two rivers (Chen et al., 2004). To save the desert

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riparian forest, China implemented ecological emergency water transfer projects in the downstream of the Heihe River and Tarim River in 1999 and 2000. Each year, water was transferred from upstream of the river in order to lift the downstream underground water level, and to provide water for the growth and development of riparian vegetation. From 2000 to 2009, the downstream of the Heihe River received $100.03 \times 10^8\,m^3$ water from upstream. In the growing season of each year, a fixed amount of surface water was supplied to underground water, and the downstream water level of the Heihe River was lifted constantly. The groundwater depth of the Ejin Oasis basically maintained around 3 m, with a small inter-annual fluctuation (Jiang and Liu, 2009). However, the downstream of the Tarim River received only $22.3 \times 10^8\,m^3$ water from 2000 to 2009, while the transferring time and quantity were not fixed. The groundwater depth of the Yahepumahan section was around 5–6 m after water supply, with a large inter-annual fluctuation (Chen et al., 2011). After the implementation of ecological water transfer project, the monitoring results of groundwater depth in both regions indicated that the mean groundwater depth in the downstream of the Heihe River had recovered to around 3 m, and the maximum water content in the shallow soil layer (within 1 m) reached 29 % (Fu et al., 2014). However, the mean groundwater depth in the downstream of the Tarim River still maintained around 6–8 m, and the maximum water content in the shallow soil layer within 2 m was only 15 % (Halik et al., 2008). A number of research results (Fu et al., 2006; Chen et al., 2006; Hao et al., 2010; Zhou et al., 2010; Li et al., 2013) have shown that rational groundwater depth of *Populus euphratica* is 2–4 m, and the critical groundwater depth is 4 m. If the groundwater depth is over 4 m, *Populus euphratica* will face water stress. the rational groundwater depth of *Tamarix ramosissima* is 4–6 m, and the critical groundwater depth is 6 m. If it is over 6 m, *Tamarix ramosissima* will face water stress. Therefore, the downstream of the Heihe River has satisfied the rational survival water level of desert riparian forest, whereas the downstream of the Tarim River is still at the stress water level for the desert riparian forest. Correspondingly, the desert riparian forest, mainly include *Populus euphratica* and *Tamarix ramosissima,* in the Heihe River and Tarim River developed different survival and adaptive strategies due to the long-term and particular evolution of water resources.

First of all, the water absorption patterns of plant root are different (Fig. 1). In an environment with limited water, the evaporation demand is more than the amount of rainfall, and the water in the soil layer is difficult to obtain; thus, plants may use deep roots to absorb soil water or underground water (Nie et al., 2011). According to stable $\delta^{18}O$ composition in the water of the xylem, it can be known that in the downstream of the Heihe River and the downstream of the Tarim River, both *Populus euphratica* and *Tamarix ramosissima* took deep subsoil water and underground water as the main water source, and did not mainly rely on the surface soil water (Figs. 1 and 2). This use of the deep soil layer and permanent water (e.g., underground water) can allow the plants to survive in the long-time rainless period and ever grow further (Zencich et al., 2002). *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Tarim River and Heihe River may obtain a stable water source by developing their deep roots to adapt to, or avoid, drought. Combining $\delta^{18}O$ contents in soil and underground water, it can be known that below 175 cm of the downstream of the Heihe River $\delta^{18}O$ content in the soil layer is similar to $\delta^{18}O$ content in the underground water, and below 375 cm of the downstream of Tarim River $\delta^{18}O$ content in the soil layer is similar to $\delta^{18}O$ content in the underground water (Fig. 1). These indicate that deep soil water mainly came from the supply of underground water. Therefore, it can be seen that *Populus euphratica* and *Tamarix ramosissima*, the major plant community of desert riparian forests in the downstream of the Heihe River and Tarim River, actually use underground water, which is consistent with the research conclusion regarding plant water used in the downstream of the Tarim River and Heihe River in the study of Chen et al. (2006) and Zhao et al. (2008). This may be relevant to the deep root distribution of *Populus euphratica* and *Tamarix ramosissima* (Fu et al., 2014). However, both differed in the use patterns of soil water and underground water. The use ratio of underground water of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Tarim River is smaller than that in the downstream of the Heihe River with adequate water,

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and its use of soil water is relatively larger than that in the downstream of the Heihe River, and its use of the soil depth layer is also wider. In other words, under long-term water stress, the water absorption of *Populus euphratica* and *Tamarix ramosissima*'s roots becomes diversified.

In addition, the water redistributions of plant roots are different (Figs. 5 and 6). As the active adaptation strategy to drought stress, the hydraulic lift of plants may play a key role in the riparian forest vegetation in the inland river basins of arid regions. On the individual plant scale, the hydraulic lift is equal to the improvement of water absorption efficiency of deep roots, carbon yield of plants, availability of nutrient substance in the shallow soil, etc. (Horton and Hart, 1998; Querejeta et al., 2007). Research results (Warren et al., 2005; Brooks et al., 2006; Munoza et al., 2008) indicate that hydraulic lift can extend the available period of water, which is beneficial to the maintenance of physiological activity and hydraulic conductivity of plant tissue, and postpones the time of critical water potential of root embolization caused by the decrease of soil water potential. The hydraulic lift capacity of plant roots depends on the influences of plants, meteorological conditions, the environment, and other factors (Emerman and Dawson, 1996; McMichael and Lascano, 2010; Warren et al., 2011). In the downstream of the Heihe River, the single hydraulic lift capacity of *Populus euphratica* is relatively weak, and the hydraulic lift of the root occurs at the 10–50 cm shallow soil layer, and its capacity is usually small (0.36 mm d^{-1}), accounting for about 10 % of water consumption. In the downstream of the Tarim River, *Populus euphratica* root at night tends to release the soil water at mid-depth (10–110 cm) to the shallow layer, and the content is large (0.41 mm d^{-1}), accounting for about 32 % of water consumption.

Simultaneously, the xylem water transport patterns of plant are different. Xylem water transport of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Heihe River is significantly higher than that in the downstream of the Tarim River. Moreover, the branch xylem in the downstream of the Heihe River is easier to embolize, indicating that in the downstream of the Heihe River, the embolization of the root xylem of desert plants is little, and the root water absorbing capacity is strong. However, the water transport capacity of branch xylem is weaker than that of root. In this way, the strong flow resistance in the branch xylem not only can effectively reduce the water desorption of branch, but can also be beneficial to the uniform distribution of water from root in branch. In this way, adequate water in the plant is maintained to coordinate the normal growth and development of the whole plant. In other words, desert riparian forest plants in the downstream of the Heihe River adapt to mild drought stress by the flow limiting in the branch xylem. However, in the downstream of the Tarim River, the embolization of root xylem of *Populus euphratica* and *Tamarix ramosissima* is obviously larger than that of branch, indicating that the water resistance of desert plants mainly lies in root, and the root water absorbing capacity is substantially limited. To maintain survival, the water absorption resistance must be actively reduced to compete for the extremely limited water supply and enable the water to rapidly transmit to blades. However, due to the limit of water, some branches with weak competition are doomed to wither due to water shortage. It is common to see a small part of branches of *Populus euphratica* and *Tamarix ramosissima* growing well, while the remaining branches wither to death in the downstream of the Tarim River (Fig. 11). Therefore, desert riparian forest plants in the downstream of the Tarim River mainly guarantee the survival of the whole plant by sacrificing weak branches and improving dominant branches with a strong ability to compete. To a certain level, this verified the findings of Zhou and colleagues, who proposed that when the water is adequate, the plant water transport conforms to the xylem flow limiting hypothesis; thus, when the water is not adequate, the plant water transport conforms to the branch limiting hypothesis (Zhou et al., 2013).

Furthermore, plant evapotranspiration characteristics are different. Through the comparison and analysis of root and stem sap flow of *Populus euphratica* in the downstream of the Heihe River and Tarim River, it is found that root and stem sap flow of *Populus euphratica* in both regions at night are similar, with a non-significant difference ($P > 0.05$); whereas, the sap flow of *Populus euphratica* in the downstream of the Heihe River in the daytime is significantly smaller than that in the downstream of the Tarim River ($P < 0.05$). In other words, daytime water consumption of *Populus euphratica* in

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the downstream of the Tarim River is significantly higher than that in the downstream of the Heihe River. In the downstream of the Heihe River, the sap flow of the main root and lateral root of *Populus euphratica* in the daytime is fairly large, and both main root and lateral root bear the transport of evapotranspiration of *Populus euphratica*. In the downstream of the Tarim River, the shallow soil water is not adequate, and *Populus euphratica* in the daytime mainly transports water, depending on developed deep main root. At night, plant evapotranspiration reduces, and to make up for the huge loss of shallow soil water in the daytime, the lateral sap flow begins to flow negatively. Water in the plant xylem releases in the shallow soil to supply the soil water and improve the water environment of shallow root system plants, which is beneficial to the succession development of the plant community.

Plant evapotranspiration can reflect the water status of habitat (Ma et al., 2013). Sap flow is an intuitive reflection of plant evapotranspiration (Wullschleger et al., 1998). Under normal conditions, for the same plant, its evapotranspiration rate in water stress will be lower than that in adequate water. In the downstream of the Tarim River and Heihe River, the sap flow rate of *Populus euphratica* exhibits a significant difference ($P < 0.01$), indicating that both regions may differ in water status. In drought stress, especially during the strongest evapotranspiration period at 12:00 LT, the leaf stomata reduces its opening to decrease water consumption and further reduce the evapotranspiration rate. Thus, there is a break at 12:00 LT, which is an adaption mechanism of plants to water shortage. Daily variation of sap flow rate of *Populus euphratica* in the Tarim River will have a slight decrease, which is a presentation of this mechanism. This indicates that in the downstream of the Tarim River, *Populus euphratica* is in water stress. In contrast, the sap flow rate of *Populus euphratica* in the downstream of the Heihe River presents a unimodal curve, indicating that its water status is good. The data of branch water potential also confirm this point. In rivers, the water potentials of *Populus euphratica* and *Tamarix ramosissima* obviously increase after 12:00 LT. Furthermore, when the groundwater depth varies within 3 m, the water potentials of *Populus euphratica* and *Tamarix ramosissima* at predawn have no significant differ-

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ence, and neither does the soil water. Thus, it can be proven that *Populus euphratica* and *Tamarix ramosissima* do not suffer water stress. In the downstream of the Tarim River, the water potentials of *Populus euphratica* and *Tamarix ramosissima* at 18:00 LT are low and have no sign of lift, indicating that with the decrease of temperature, the weakening of evapotranspiration, and untimely water supply of soil to blade, the water potential of blade manifests as low. In addition, with the increase of groundwater depth, the water potentials of *Populus euphratica* and *Tamarix ramosissima* at predawn decrease obviously, and the water stress of soil is extremely serious. Thus, this indicates that *Populus euphratica* and *Tamarix ramosissima* are suffering serious water stress. From the daily variation of water potential, the daily variation of stem water potential of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Heihe River conforms to water potential characteristics in adequate water. In contrast, the daily variation of the stem water potential of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Tarim River conforms to water potential characteristics in water stress (Song et al., 2005). This is consistent with the conclusions in the study of Fu et al. (2006, 2014) that in the downstream of the Heihe River, neither *Populus euphratica* nor *Tamarix ramosissima* suffered from serious arid stress. The geological environment and soil-forming process in the downstream of the Heihe River and Tarim River are basically similar, and annual average rainfall is below 40 mm and annual average evaporation capacity is above 2500 mm, with little rainfall and strong evaporation (Zhou et al., 2013). Regarding the downstream of the Heihe and Tarim River with serious vegetation degradation, the influences of surface runoff, precipitation, and condensation water on desert plants are insignificant (Bai et al., 2008). When the plant root depth can reach the lifting height of capillary water, the plant can grow normally by absorbing the continuous supply of capillary water; otherwise, the plant root will wither and even die without enough water (Gong et al., 2006). In the downstream of the Tarim River and Heihe River, underground water is the main supply source of soil water in the aeration zone. *Populus euphratica* and *Tamarix ramosissima* both take underground water as the main water source. Therefore, this is the essential reason for the water use difference of *Populus euphratica* in both regions.

Plant physiological and ecological changes are the results of long-term adaptation to survive in a particular environment. Through changes of water use indexes of the major plant community in the desert riparian forests in the downstream of the Heihe River and Tarim River, including water source, water distribution, water transport, water transpiration and water potential, we found that there were significant differences in plants' water use strategies and survival modes under different evolutions of water resources environments in arid areas. These findings are helpful for study on the succession and evolution of desert vegetation in arid area, and to provide scientific basis for restoring and reconstructing desert riparian forests in Northwestern China.

Author contributions. Y. N. Chen and W. H. Li designed the experiments and H. H. Zhou carried out the experiment of plant xylem hydraulic conductivity, Y. P. Chen carried out the experiment of plant water sources, X. M. Hao carried out the experiment of plant root hydraulic lift, A. H. Fu carried out the experiment of plant water potential; J. X. Ma carried out the experiment of plant sap flow. H. H. Zhou prepared the manuscript with contributions from all co-authors.

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Table 1. Elevation and climatic variables in the lower reaches of the Tarim River and Heihe River.

Area	Elevation	Average precipitation	Average evaporation	Average temperature	Relative humidity
Lower reaches of the Tarim River	800–940 m	33.6 mm	2671.4 mm	10.7 °C	24.2 %
Lower reaches of the Heihe River	900–1127 m	39.8 mm	3537.0 mm	8.2 °C	50.16 %

Note: data of the Tarim River come from Fu et al. (2006); data of the Heihe River come from Yao et al. (2006); data of relative humidity come from Zhou et al. (2013).

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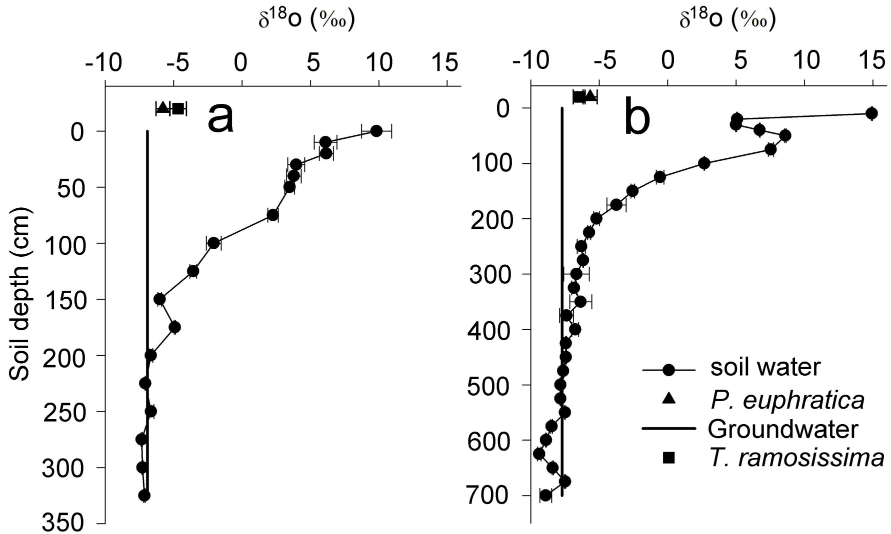

Figure 1. Changes of soil, plant, and underground $\delta^{18}O$ at the downstream of the Heihe River **(a)** and the Tarim River **(b)**.

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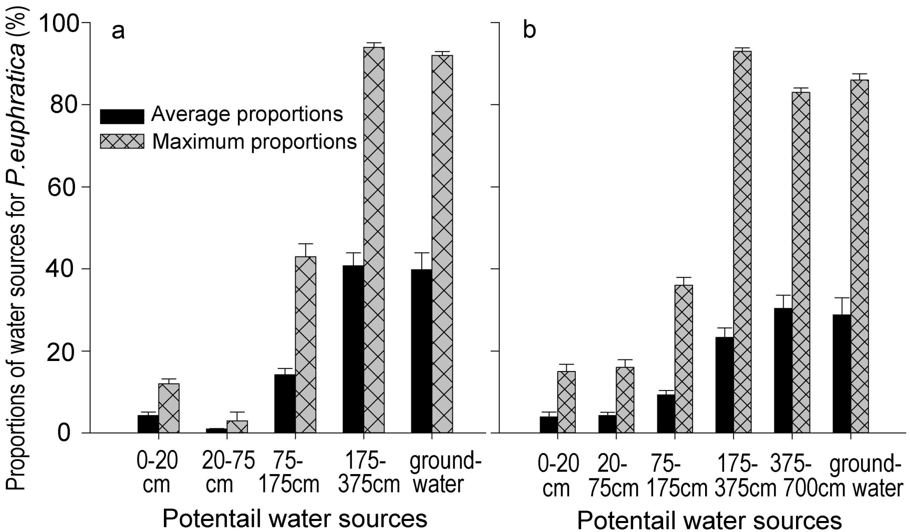

Figure 2. Use proportion of *Populus euphratica* in the downstream of the Heihe River **(a)** and Tarim River **(b)** to potential water.

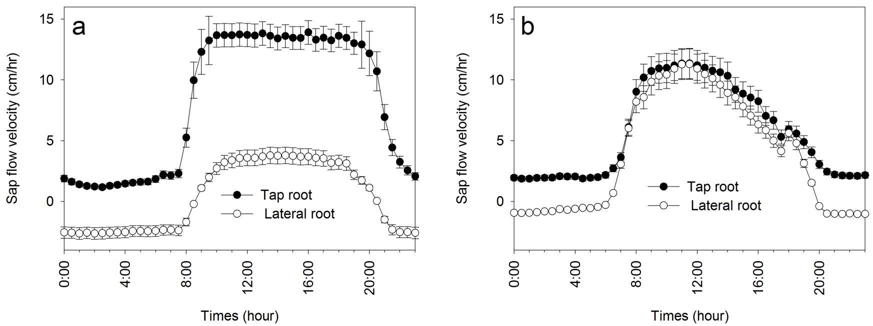

Figure 3. Daily change of sap flow rate of *Populus euphratica* root (**a** the downstream of the Tarim River; **b** the downstream of the Heihe River).

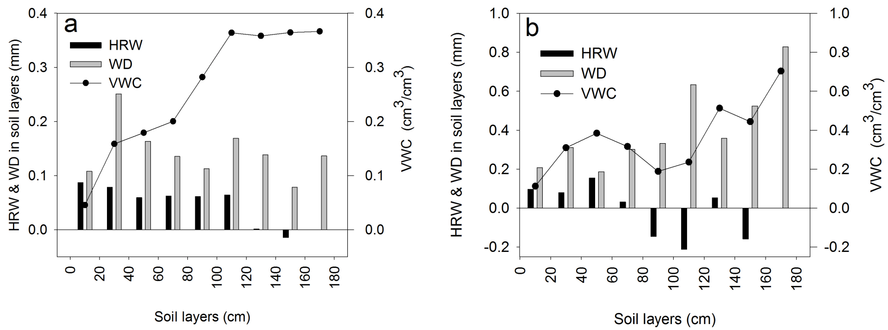

Figure 4. Comparisons of mean volumetric soil water content (VWC), hydraulic redistributed water (HRW) and soil water depletion by transpiration (WD) between different soil layers (**a** the downstream of the Tarim River; **b** the downstream of Heihe River).

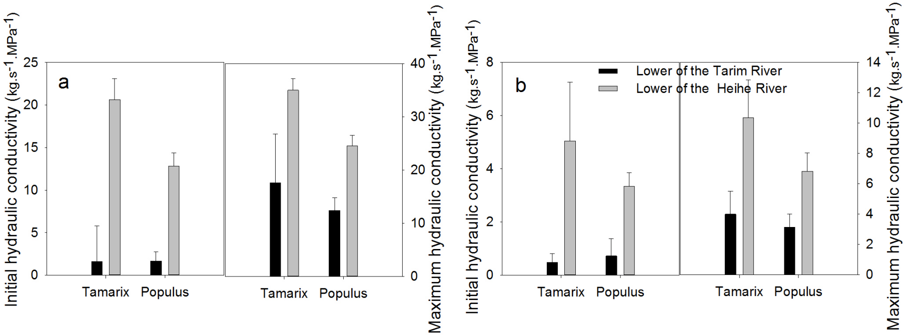

Figure 5. Conductivity characteristics of plant root **(a)** and stem **(b)** in the desert riparian forest.

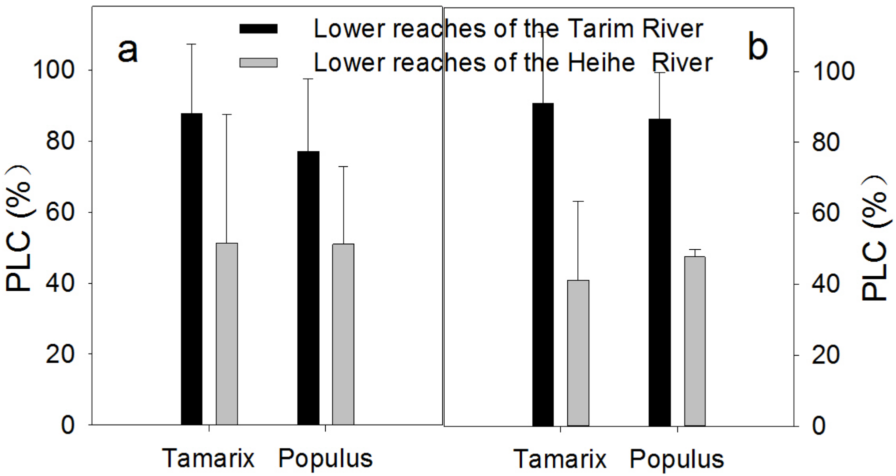

Figure 6. Comparison of xylem embolization between plant stem **(a)** and root **(b)**.

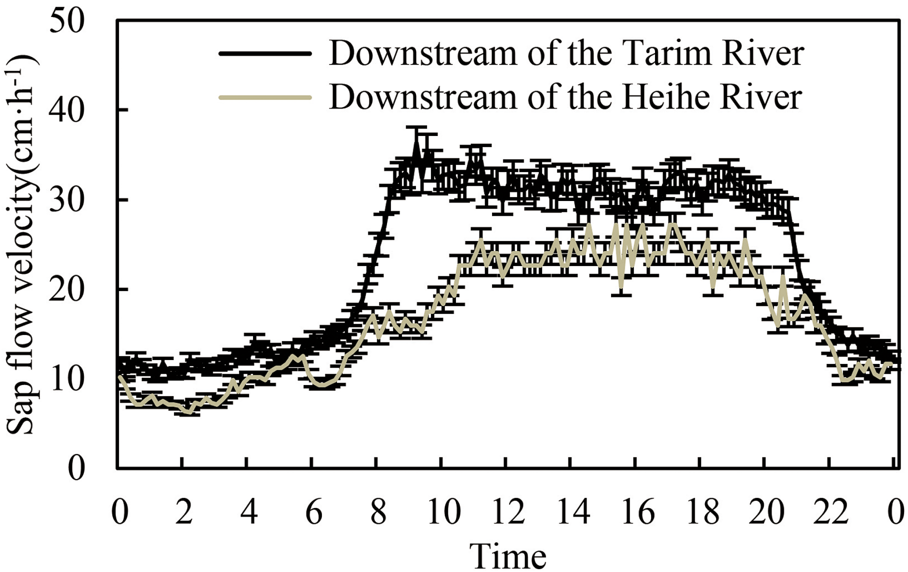

Figure 7. Daily variation of flow rate of *Populus euphratica* in the downstream of Tarim River and Heihe River.

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Interactive Discussion

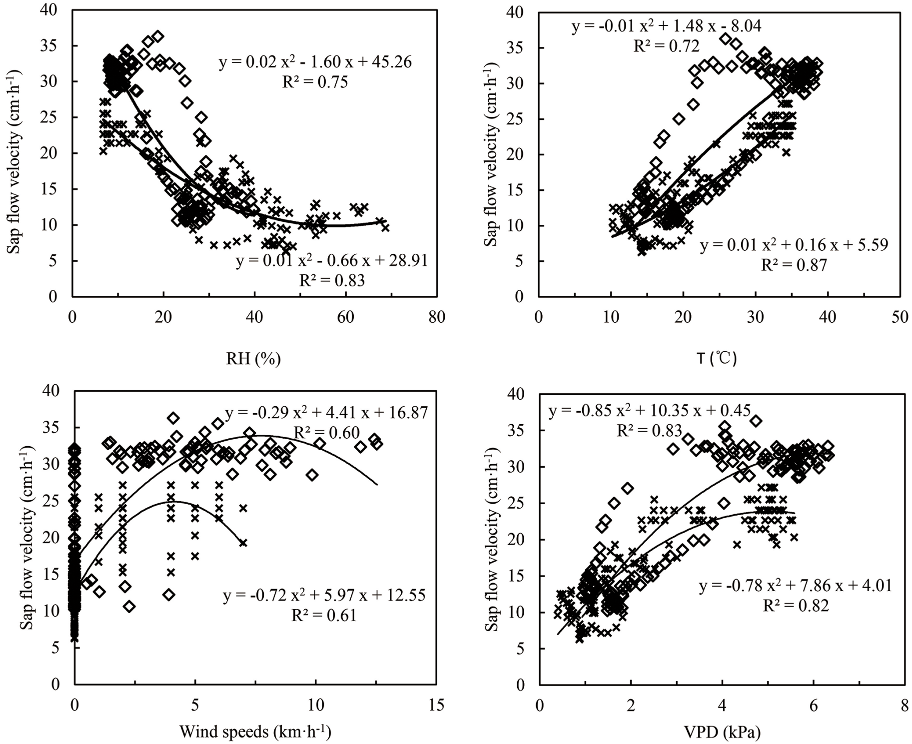

Figure 8. Response of sap flow velocity of *P. euphratica euphratica* in the downstream of the Tarim River (◇) and Heihe River (×) to meteorological factors.

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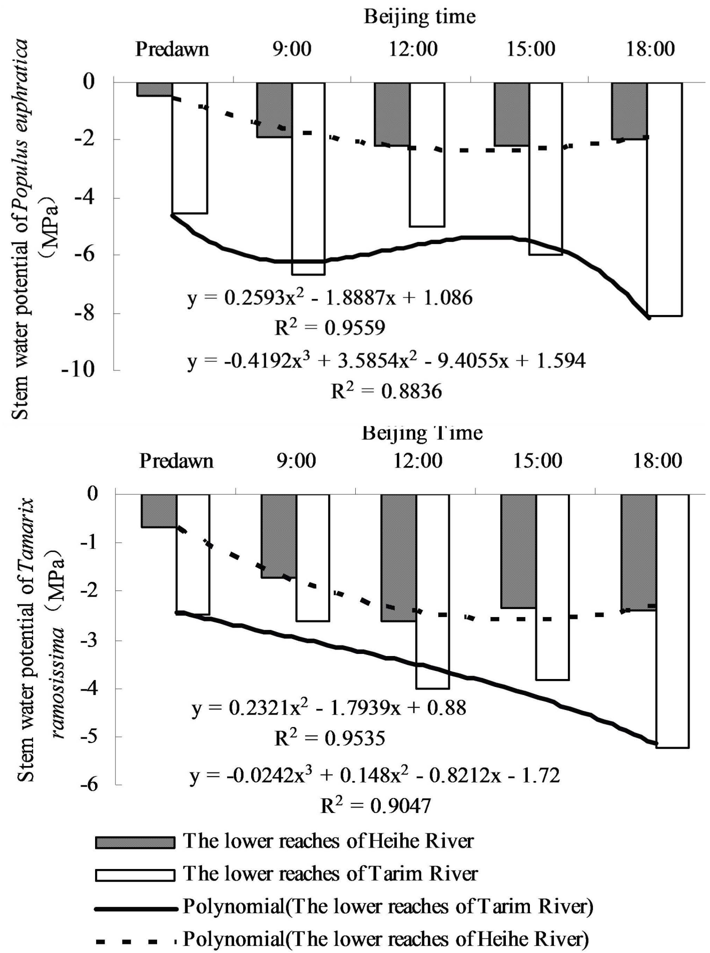

Figure 9. Stem water potential of *Populus euphratica* and *Tamarix ramosissima* in the downstream of the Heihe River and Tarim River.

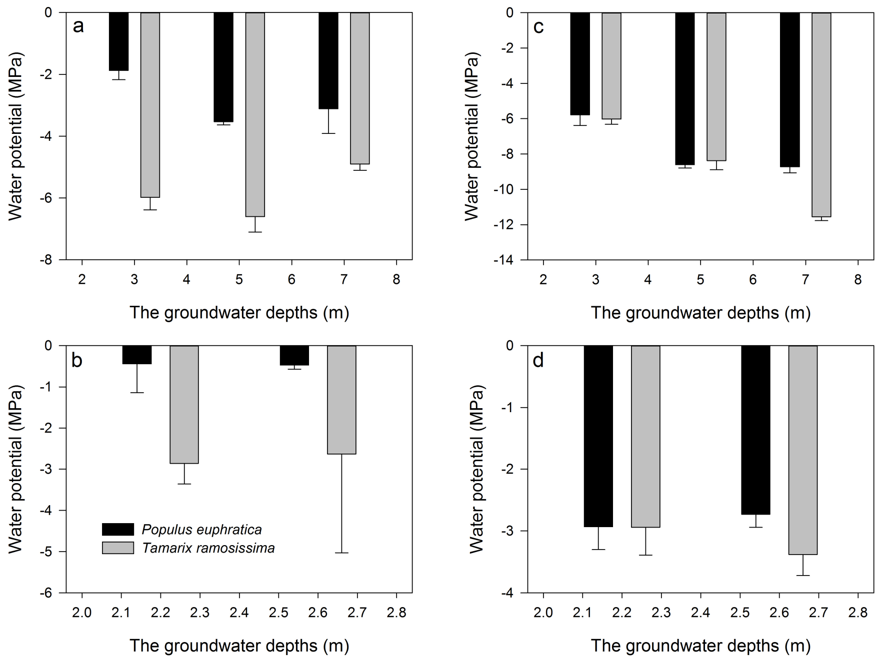

Figure 10. Stem water potential proportion of *Populus euphratica* and *Tamarix ramosissima* at predawn and 12:00 LT in the downstream of the Tarim River (**a** and **c**) and Heihe River (**b** and **d**).

Figure 11. Survival state of Populus euphratica in the downstream of the Heihe River (left) and the downstream of Tarim River (right).

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