ECOHYDROLOGY
Ecohydrol. **6**, 994–1000 (2013)
Published online 11 October 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/eco.1439

Sap flow and trunk maximum daily shrinkage (MDS) measurements for diagnosing water status of *Populus euphratica* in an inland river basin of Northwest China

Jian-Xin Ma, Xiang Huang, Wei-Hong Li* and Cheng-Gang Zhu
State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, China

ABSTRACT

Using sap flow flux density and trunk maximum daily shrinkage (MDS) as the main plant-based water stress indicators and combined with soil salinity parameters and plant population characteristics, water statuses of *Populus euphratica* were diagnosed. Based on these parameters, optimal groundwater depth for maintaining the development of natural *P. euphratica* were explored in middle and lower reaches of the Tarim River. When excluding the impact of soil salinity and climatic factors, our results demonstrated that sap flow flux density in *P. euphratica* decreases with increase groundwater depth and that such a negative correlation is significant. It also showed that MDS has a significant positive correlation with groundwater depth. When the water table depth reached 4.5–5.0 m, our study showed a significant reduction in sap flow flux density changes of *P. euphratica* apparent and increasing MDS, indicating that the growth of *P. euphratica* is under drying stress, and the plant adapts to the environment through reducing transpirational water consumption by self-regulation. When water table is in the range of 4–6 m, the populations characteristics (coverage, density and frequency) of *P. euphratica* under different groundwater depth reached the maximums. We conclude that groundwater depth between 4.5 and 5.0 m is the optimum restoring *P. euphratica* and its ecosystem in the middle and lower reaches of the Tarim River. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS groundwater depth; *P. euphratica*; sap flow flux density; trunk shrinkage; riparian forest

Received 12 August 2011; Revised 7 August 2013; Accepted 16 September 2013

INTRODUCTION

Climate aridity and scarcity of water resources are a historical and recurring characteristic in Northwest China. In arid and semi-arid ecosystems, water is the limiting resource for plant growth (Snyder and Williams, 2003). In inland river basins of Northwest China, riparian forests are occupied by drought-tolerant tree species that rely on shallow groundwater for establishment, growth and transpiration. Therefore, depth of groundwater can intuitively reflect the water conditions across the region and directly affect plant distribution, growth, population development, stability of ecosystem and even the survival of oasis. (Zhao *et al*., 2003; Chen *et al*., 2004; Liu *et al*., 2005; Chen *et al*., 2006; Liu *et al*., 2006; Ruan *et al*., 2007; Wang *et al*., 2007; Hao *et al*., 2009). Knowledge of how vegetation responds to the heterogeneity in water supply (heterogeneity in groundwater depth) is necessary for predicting the survival and growth of vegetation in varying environment (Carter and White, 2009). Information on how vegetation adapts to different groundwater depth is critical for predicting vegetation survival, growth and water use, which, in turn, has important impacts on site hydrology (Carter and White, 2009).

Riparian vegetation is sensitive to changes in hydrological regimes (Horton *et al*., 2001a). During the long process of evolution, adaptive mechanisms to changing groundwater conditions have evolved in desert plants. Although many scholars have studied the responses of the physiological characteristics of plants, such as plant water potential, proline, malondialdehyde, peroxidase, abscisic acid, photosynthesis and other physiological indicators, there are few studies on the changes of sap flow and maximum daily shrinkage (MDS) in response to groundwater depth changes, i.e. the depth of the water table. Previous studies indicated that plant transpiration correlates well with soil water conditions. When soil moisture changes, plant controls water loss through active regulation on transpiration. With an increase in water stress, plant transpiration rate decreases, and MDS increases (Ortuno *et al*., 2006; Conejero *et al*., 2007; Xie *et al*., 2008; Yuan *et al*., 2008). This is the physiological mechanism of self-regulation, through which plants adapt to the environment. Changes in plant transpiration are directly linked to the vital signs of plants, and the changes can reflect the plant status and

*Correspondence to: Wei-Hong Li, State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, China. E-mail: Liwh@ms.xjb.ac.cn

response to the water conditions. Measurements of sap flow and MDS are currently considered as the most accurate method to determine the status of plant transpiration (Wullschleger *et al*., 1998; Ortuno *et al*., 2004; Velez *et al*., 2007; Ortuno *et al*., 2010; Conejero *et al*., 2011) Therefore, the study on the characteristic sap flows and MDS in plants under different groundwater conditions can reflect the response and adaptation of transpiration in surface plants to changes in the water table depth.

This study was performed by monitoring the sap flow and MDS in a major constructive species of desert riparian forests, *P. euphratica*, in the middle and lower reaches of the Tarim River. Water table depth, vegetation survey and data from an analysis of soil salinity were used to diagnose water status of *P. euphratica* in the inland river basin of Northwest China. Our objectives are (1) to examine the response of *P. euphratica* to groundwater depth using sap flow and MDS as water status indicators, (2) to evaluate the feasibility of obtaining baselines for these parameters for use in diagnosing water status and (3) to ascertain the optimal depth of water table for maintaining the growth and reproduction of natural *P. euphratica* in the middle and lower reaches of the Tarim River and to provide a scientific basis for the restoration and reconstruction of damaged ecosystems in the arid inland river basin.

MATERIALS AND METHODS

Site description

The study area is located in the middle and lower reaches of the Tarim River in China, from Yingbazha of Luntai County to Taitema Lake of Ruoqiang County, with a total length of 826 km, of which the middle part is from Yingbazha to Qiala, and the lower part is from Qiala to Taitema Lake (Figure 1). This area is an extremely arid region, with scarce precipitation and intensive evaporation. Mean annual precipitation is less than 50 mm, whereas the average annual evaporation is 2500–3000 mm. The existence and survival of ecosystems along the river and in the region depend on both river and groundwater. A continuous arbor, shrub and herb vegetation zone of varying width is formed along the river, where *P. euphratica* is the only tree species, *Tamarix spp*., *Lycium ruthenicum* and *Halimodendron halodendro* are the main shrubs, and *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Karelinia caspica* and *Glycyrrhiza inflata* are the major herbs. Due to extensive land and water development in the upstream of the Tarim River, there is only seasonal stream flow in the middle reach each year, and while the 321 km river course downstream from the Daxihaizi reservoir has been basically drying up since 1972 due to the gradually dwindling water supply, which resulted in an increased groundwater depth. Water table depth downstream of Yingsu dropped to 8–12 m (Chen *et al*., 2003b; Chen *et al*., 2011). Degeneration of the desert riparian forest with *P. euphratica* as the major constructive species has occurred since 1980s (Xu *et al*., 2004).

Experimental design

From Yingbazha to Taitema Lake, 14 plants ecological monitoring sections were set up along the aqueduct in the middle and lower reaches of the Tarim River. The monitoring sections were located at MA: Shajilike, MB: Shazihe, MC: Wusiman, MD: Aqik, ME: Tieyizi, LA: Akedun, LB: Yahepumahan, LC: Yingsu, LD: Abudale, LE: Kaerdayi, LF: Tugemailai, LG: Alagan, LH: Yiganbujima and LI: Kaogan (Figure 1). Four to six groundwater monitoring wells, which are with a certain distance apart according to the growth and distribution of the vegetation, were placed perpendicular to the river course at each section. A total of 74 groundwater monitoring wells were placed in the 14 sections, and 74 corresponding permanent vegetation survey plots were also established to monitor the change of water table depth and the response of surface vegetation to groundwater at both banks of the middle and lower reaches of the Tarim River.

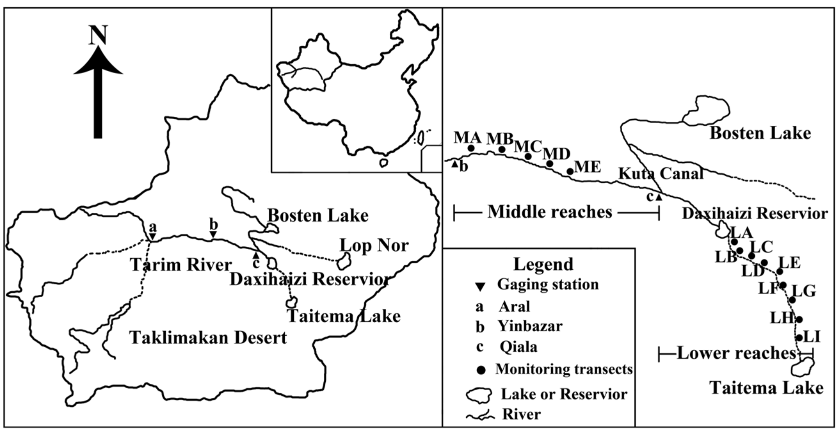

Figure 1. Study area and location of the monitoring sections in the middle and lower reaches of the Tarim River.

Measurements

Sap flow was measured throughout the experiment by the compensation heat-pulse technique (SF300, Greenspan technology Pty Ltd., Australia). According to the growth and distribution of *P. euphratica*, seven sampling sites were selected at five typical sections, including MA: Shajilike, MD: Aqike, LB: Yahepumahan, LC: Yingsu and LG: Alagan. Considering the long duration of river drying up and the severe drought stress at the downstream region, two monitoring sites with different distances from the main axis of the river course were set up in the downstream sections in LB: Yahapumahan and LG: Alagan. Unsheltered *P. euphratica* plants of the same age, similar diameter, similar canopy breadth and straight trunk were selected as the sampling subjects, and three trees at each of the sample sites were selected. In August 2008, during a sunny weather, sap flow was continuously monitored daily using three sets of four probes of SF300 heat-pulse sap flow metres (Greenspan technology Pty Ltd., Australia). Because total sap flow flux and sap flow rate vary with diameter at breast height (DBH) and crown width at different plots, they are unsuitable for comparison between trees. Instead, sap flow flux density ($L\,cm^{-2}\,h^{-1}$), which reflects the sap flow flux and sap flow rate per unit flux area, facilitate the comparison among trees with different DBHs. Therefore, sap flow flux density was used as an indicator in the present study to compare and analyse the sap flow of *P. euphratica* at different monitoring sections.

Micrometric trunk diameter fluctuations were measured throughout the experimental period in three trees per treatment, with a set of linear variable displacement transducers (Dendrometer DD, Ecomatik Ltd., Germany.) attached to the trunk, with a bracket made of Invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero. Measurements were taken every 30 min by a data logger. Trunk MDS was obtained from maximum and minimum daily trunk diameter.

Air temperature (Ta) (ATH-2, PhyTech Ltd., USA.), soil temperature (T_s,) (SMS-2M, PhyTech Ltd., USA.), leaf temperature(T_l) (LT-2M, PhyTech Ltd., USA.), relative humidity (RH) (ATH-2, PhyTech Ltd., USA.) and wind velocity (V_w) (010C-1, PhyTech Ltd., USA.) were simultaneously collected every 10 min using an automatic weather station (ICT International Pty. Ltd., Australia.).

Water level in the groundwater monitoring wells at each study section was recorded every other month using the conductivity method. Water table depth used in the present study was the average groundwater level collected from July to September, 2008.

Vegetation survey was performed in August 2008, during the same period of sap flow monitoring. 74 fixed vegetation plots at different sections through the middle and lower reaches of the Tarim River were surveyed for quantitative indices, such as the number of *P. euphratica* plants, plant height, crown width, DBH, and niche breadth. Niche breadth was estimated using the Levins index (Levins, 1968). Water table depth was divided into four gradients of 2–4, 4–6, 6–8 and 8–10 m. Trend of the changes corresponding to different groundwater depth gradients in the parameters of the *P. euphratica* population, such as coverage, frequency (the percentage of plant-appearing plots among the entire plots) and density, was analysed to better understand the impact of the water table depth on the growth of *P. euphratica*.

Soil profiles of 1.6 m, located 0.5 m from the sampling tree was exposed and divided into six layers of 0–5, 5–15, 15–30, 30–50, 50–80 and 80–120 cm. Soil samples from each layer were collected and brought into laboratory for measurements of total soluble salts after drying out. Meanwhile, distribution of *P. euphratica* root along the vertical direction of soil profile ranging from 0 to 140 cm was surveyed by sampling every 20 cm. Root morphological parameters, such as root surface area, diameter and length density, were measured using a WinRHIZO root scan analysis system (Regent, Canada).

RESULTS

Relationships among sap flow, maximum daily shrinkage and groundwater depth

Analysis of the changes of sap flow and MDS of *P. euphratica* at different groundwater depth indicates that the changes of the sap flow flux density and MDS in *P. euphratica* are significant related to groundwater depth in the middle and lower reaches of the Tarim River. Sap flow flux density decreases with the increase of groundwater depth and MDS diminution with the ascend of the groundwater depth (Figure 2), indicating the potent impact of the groundwater depth on the sap flow of *P. euphratica* in middle and lower reaches of the Tarim River.

Relationships among sap flow, maximum daily shrinkage and meteorological factors

We analysed the correlation of sap flow flux density and MDS of *P. euphratica* with the daily averages of a variety

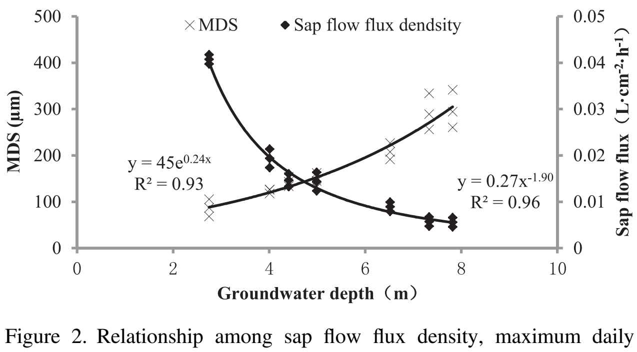

Figure 2. Relationship among sap flow flux density, maximum daily shrinkage of *P. euphratica* and groundwater depth in the middle and lower reaches of the Tarim River.

of environmental factors and the corresponding water table depths. Our results indicated that the sap flow flux density and MDS of *P. euphratica* are significantly correlated with water table depth, with correlation coefficient of −0.89 and 0.81, respectively, whereas the correlations with the meteorological factors are not significant (Table I).

Relationship among sap flow, maximum daily shrinkage and soil salinity

The effect of soil salinity stress is primarily exerted on plant roots. Preliminary analysis of the vertical distribution of *P. euphratica* roots in this study indicates that fine roots are mainly distributed 60–100 cm below the surface (Figure 3), accounting for 63% of the total root length density of fine roots ($d \leq 5$ mm) in the soil layer ranging from 0 to 140 cm. Because fine roots are the major water-uptake roots to plant, we analysed the partial correlation between average soil salinity in the fine-root-enriched layer (50–120 cm) at each monitoring section and the corresponding sap flow and MDS of *P. euphratica* and the groundwater depth to determine the main factor that causes the changes in the sap flow flux density and MDS. Our correlation analysis indicated that both groundwater depth and soil salinity are significantly correlated with sap flow and MDS of *P. euphratica*. However, when water table depth was used as a control variable, our partial correlation analysis revealed that the correlation coefficient between soil salinity and sap flow or MDS are 0.31 ($P = 0.56$) and 0.43 ($P = 0.52$), respectively, indicating that salinity has a little effect on sap flow and MDS.

Relationship between goundwater depth and population characteristics of P. euphratica

The coverage, frequency and density of *P. euphratica* under different groundwater depth were calculated and analysed based on the survey data from 74 vegetation plots. Figure 4 shows certain trend of changes in the coverage, frequency and density of *P. euphratica* population with different water table depth at each monitoring section in the middle and lower reaches of the Tarim River. The coverage, frequency and density of *P. euphratica* population increase when groundwater depth is between 2–6 m, decrease rapidly when groundwater depth reaches 6–8 m, and slowly declines after the groundwater depth reaches 8–10 m. The coefficients of niche breadth at different groundwater table depths exhibit the same trend (Table II). The inflection point of *P. euphratica* population characteristics appears when water table depth reaches 4–6 m, indicating that growth of *P. euphratica* is under stress, which led to the corresponding changes in the population

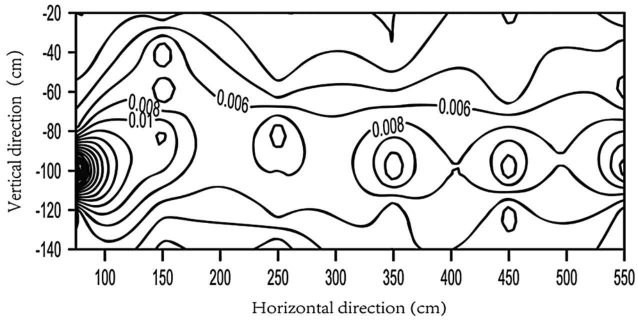

Figure 3. Vertical and horizontal distribution of fine root ($d \leq 5$ mm) length density (cm cm^{-3}) (mean ± SD, $n = 3$) of *P. euphratica*.

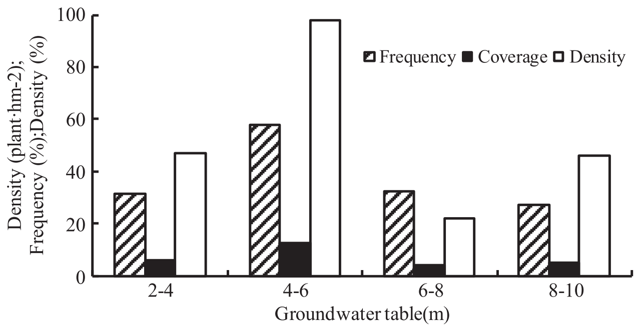

Figure 4. The relationship between population characteristics of *P. euphratica* (mean ± SD, $n = 10$)and groundwater depth in the middle and lower reaches of the Tarim River.

Table I. Pearson correlation among sap flow flux density, maximum daily shrinkage, and groundwater depth.

	Sap flow flux density	MDS	*V*w	*RH*	T_a	T_s	T_l
MDS	0.67*	—	—	—	—	—	—
Vw	−0.21	−0.34	—	—	—	—	—
RH	0.21	−0.42	−0.65	—	—	—	—
T_a	−0.14	0.35	0.69	−0.99**	—	—	—
T_s	−0.11	0.23	0.71	−0.92**	0.94**	—	—
T_l	0.28	0.31	0.74	−0.76*	0.83*	0.82*	—
Groundwater depth	−0.89**	0.81**	0.14	−0.34	0.27	0.27	−0.11

MDS, maximum daily shrinkage.
*$p < 0.05$.
**$p < 0.01$ (two-tailed).

Table II. Coefficients of niche breadth at different groundwater depth.

Species	Coefficients of the niche breadth					
	0–2	2–4 m	4–6 m	6–8 m	8–10 m	>10 m
Populus euphratica	1	9.74	14.58	6.79	3.77	—

characteristics. These data are consistent with the results from Liu *et al.* (2006) and Hao *et al.* (2009).

Significant changes of sap flow flux density and maximum daily shrinkage in P. euphratica

Analysis of sap flow flux density and MDS in *P. euphratica* at different water table depth indicated that in this extremely arid desert environment, the rate of change in sap flux density in *P. euphratica* varied with groundwater depth. Figure 5 shows that the changes of sap flow flux density are large when water table depth is in the ranges of 2.75–4.01 m and 4.01–4.41 m. A drastic decline in sap flow flux density was observed when groundwater depth is in the 4.41–4.99 m range. Although sap flow flux density slightly rebounded at ranges of 4.99–6.52 m and 6.52–7.33 m, the extent of this change is small, and the change is even small when groundwater depth is in the range of 7.33–7.82 m. Overall, when water table depth is greater than 4.41 m, the rate of changes in sap flow flux density of *P. euphratica* becomes smaller. When groundwater depth is greater than 4.99 m, stem maximum daily amount of shrinkage has a considerable increase. Significant changes in the density and MDS of *P. euphratica* within a specific ranges of groundwater depth, to a certain extent, reflect the level of drought stress.

DISCUSSION

Although many studies indicated significant effects of meteorological factors on plant sap flow and MDS, most of these conclusions were drawn under same-site conditions and without considering the effect of groundwater depth (Zhang *et al.*, 2004; Chang *et al.*, 2006; Ortuno *et al.*, 2006; He *et al.*, 2007; Duan *et al.*, 2008; Zhou *et al.*, 2008b; Liu *et al.*, 2009). In the present study, each monitoring site had a sunny weather during the study period, and the difference in daily average temperature and intensity of solar radiation at each study section exhibiting similar is relatively small. Therefore, the effect of meteorological factors on sap flow and MDS of *P. euphratica* can be basically ruled out, which was also confirmed by the correlation analyses of both sap flow flux density and MDS of *P. euphratica* with water table depth and daily environmental factors (Table I). Sap flow flux density and MDS of *P. euphratica* are significantly correlated with water table depth ($P < 0.01$). A possible explanation for this correlation is that under the same site condition, plant sap flow and MDS are strongly influenced by meteorological factors, whereas for *P. euphratica* grown under different water table depths, the sap flow flux density and MDS are mainly controlled by groundwater depth, with a relatively small impact from the meteorological factors.

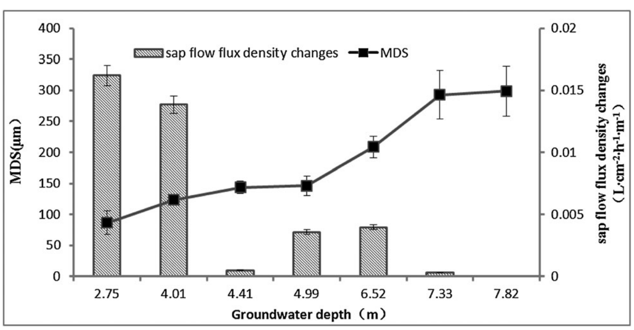

Figure 5. Relationship among sap flow density changes, maximum daily shrinkage and groundwater depth in the middle and lower reaches of the Tarim River. (mean ± SD, $n = 3$).

Salinity also exerts physiological stress onto plants, and increased salinity often leads to a decrease in net photosynthetic rate, transpiration rate and stomatal conductance in plants, and thus affecting sap flow rate (Chen *et al.*, 2003a; Qiu *et al.*, 2006; Zhang *et al.*, 2008; Ke *et al.*, 2009). Fine roots of a plant are the mainly roots that absorb water, and soil salt exerts its effect only after entering the plant in soluble form with water through its root system. Therefore, it is reasonable to use salinity data collected from the soil layers rich in fine roots to analyse the effect of salinity on the change in the sap flow and MDS of *P. euphratica*. When water table depth was used as the control variable, the correlations between soil salinity and *P. euphratica* sap flow flux density and MDS were found insignificant. However, when soil salinity was used as the control variable, the correlation between the water table depth and both sap flow flux density and MDS of *P. euphratica* became significant ($P < 0.01$). *P. euphratica* has been shown as one of the salt-tolerant plants, and it can grow normally in soil that has 1% salt content in the plough layer (Liu *et al.*, 2008). In this study, the highest total salt content in the soil layer the range of 50–120 cm is only 5.39 g kg^{-1}, i.e. far short of 1%, and thus exerts no stress effect on the growth of *P. euphratica*, although soil salinity does elevate with the increase of groundwater depth. Therefore, the effect of soil salinity on *P. euphratica* sap flow and MDS can be ruled out, i.e. the most important factor affecting sap flow and MDS of *P. euphratica* in middle and lower reaches of Tarim River is ground water depth.

Physiological water-related characteristics, such as water potential, stomatal conductance, transpiration rate and net photosynthetic rate, of desert plants are responsive to water table depth (Horton *et al*., 2001b; Horton *et al*., 2001a; Zhao and Liu, 2006). Those studies demonstrated that with the increase in the water table depth, the growth and survival rates of the dominant species in a desert riparian forest decrease significantly, whereas the rate of canopy death increases; when the water table depth is over 3 m, the degenerations progress rapidly. Kranjcec *et al*. (1998) reported that both the growth rate of new branches and plant transpiration rate elevate with the increase in water table depth. The branch water potential of *P. euphratica* is closely related to water table depth in the middle and lower reaches of the Tarim River. When water table depth is over 4 m, the effect of groundwater on the survival of *P. euphratica* weakened gradually, and the branch water potential of *P. euphratica* elevated with the increase in groundwater depth. However, when water table depth is over 8 m, the branch water potential of *P. euphratica* showed no significant correlation with groundwater depth (Fu *et al*., 2004), indicating that 4 m is the inflection point for water table depth having an effect on the branch water potential in *P. euphratica*. Zhou *et al*. (2008a) demonstrated that the transpiration and net photosynthetic rates changed in *P. euphratica* in the middle and lower reaches of the Tarim River when the water table depth is over 4 m. PRO and ABA contents reflect stress level in plants. Chen *et al*. (2003b, 2004) observed that there are significant accumulations of PRO and ABA in *P. euphratica* leaves when water table depth is approximately 4 m.

The changes of sap flow flux density and MDS with the increase in the depth of shallow groundwater are physiological response of *P. euphratica* to water deficit. Tang *et al*. (2005) showed that under the condition of declining soil moisture, plants use ABA as a signalling substance to transmit the water stress signal to the leaves, and thereby regulate the stomatal conductance and reduce the transpirational water loss. These observations indicate that plants can physiologically sense external environment and actively adjust to it. Greater changes in sap flow flux density and MDS in *P. euphratica* were observed when water table depth was in the range of 2.75–4.41 m, reflecting the self-regulation and adaptation of plants to external water conditions. Under these conditions, leaf transpiration and net photosynthetic rates of *P. euphratica* are primarily regulated by stomatal limitation. However, when water table depth is greater than 4.41 m, leaf transpiration rate and net photosynthetic rate of *P. euphratica* are mainly regulated by non-stomatal limitation. Sap flow flux density significantly reduces and then tends to be stable, indicating that water and drought stresses are beyond the limit of stomatal adjustment, resulting in the insensitivity of sap flow to the depth of water table. *P. euphratica* prevents water loss by reducing sap flow to ensure its survival under drought conditions, which is evidenced by the fact that during drought environment in middle and lower reaches of the Tarim River, sap flow flux density of *P. euphratica* reduced with the increase of the depth of shallow groundwater and the increase of drought level. The change of sap flow flux density in *P. euphratica* was significantly attenuated when groundwater table depth dropped to 4.41–4.99 m, which reflected both the changes of plant physiological characteristics and the level of stress. Coverage, frequency and density of plant population are the basic quantitative indices directly reflecting the changes of vegetation growth (Liu *et al*., 2006). During the process of environmental degeneration, the effect of water stress on plants was manifested as a gradual reduction in those indices. The relationship between water table depth and the population characteristics of *P. euphratica* indicated that a water table depth of 4–6 m is the inflection point that led to the changes of population quantitative characteristics (coverage, frequency and density) of *P. euphratica*.

CONCLUSION

Our results demonstrated that significant correlations among sap flow, MDS and groundwater depth could be used as indicators to diagnose *P. euphratica* water status in the middle and lower reaches of the Tarim River, and to guide water management practices in the region. This study demonstrated that 4.5–5.0 m is the optimal groundwater depth for maintaining the development of natural *P. euphratica* in middle and lower reaches of the Tarim River, and the growth of *P. euphratica* is under stress when water table depth is greater than 5 m.

ACKNOWLEDGEMENT

This work was financially supported by the National Natural Science Foundation of China (Grant No: 91025025, 41101102, 41101533).

REFERENCES

Carter JL, White DA. 2009. Plasticity in the Huber value contributes to homeostasis in leaf water relations of a mallee Eucalypt with variation to groundwater depth. *Tree Physiology* **29**: 1407–1418.

Chang XX, Zhao WZ, Zhang ZH, Su YZ. 2006. Sap flow and tree conductance of shelter-belt in and region of China. *Agricultural and Forest Meteorology* **138**: 132–141.

Chen SL, Li JK, Wang TH, Wang SS, Andrea POLLE, Aloys HÜETEPMANN. 2003a. Gas exchange, xylem ions and abscisic acid response to Na^+ salts and Cl^{-1} salts in *Populus euphratica*. *Acta Botanica Sinica* **45**: 561–566.

Chen YN, Chen YP, Li WH, Zhang HF. 2003b. Response of ABA content of *Populus euphratica* to groundwater depth changes in lower Tarim River. *Chinese Science Bullet* **48**: 958–961.

Chen YN, Li WH, Chen YP, Zhang HF. 2004. Physiological response of natural plants to the change of groundwater level in the lower reaches of Tarim River, Xinjiang. *Progress in Natural Science* **14**: 975–983.

Chen YN, Zilliacus H, Li WH, Zhang HF, Chen YP. 2006. Groundwater lever affects plant species diversity along the lower reaches of the Tarim river. *Journal of Arid Environments* **66**: 231–246.

Chen YN, Ye ZX, Shen YJ. 2011 Desiccation of the Tarim River, Xinjiang, China, and Mitigation Strategy. *Quaternary International* **244**: 264–271.

Conejero W, Alarcon JJ, Garcia-Orellana Y, Abrisqueta JM, Torrecillas A. 2007 Daily sap flow and maximum daily trunk shrinkage measurements for diagnosing water stress in early maturing peach trees during the post-harvest period. *Tree Physiology* **27**: 81–88.

Conejero W, Mellisho CD, Ortuno MF, Galindo A, Perez-Sarmiento F, Torrecillas A. 2011. Establishing maximum daily trunk shrinkage and midday stem water potential reference equations for irrigation scheduling of early maturing peach trees. *Irrigation Science* **29**: 299–309.

Duan YX, Qin J, He KN, Zhang JH, Zhao K, Sun Y. 2008. A comparative study on the sap flow patterns of *Ulmus pumila* and *Populus alba* and their responses in Hedong sandy land. *Journal of Desert Research* **28**: 1136–1144.

Fu AH, Chen YN, Li WH, Liu JZ, Xue Y. 2004. Analysis on the changes of stems water potential of *Populus euphratica* in different groundwater level in lower reaches of Tarim River in Xinjiang. *Arid Land Geography* **27**: 207–211.

Hao XM, Chen YN, Li WH. 2009. Indicating appropriate groundwater tables for desert river-bank forest at the Tarim River, Xinjiang, China. *Environment Monitor Assess* **152**: 167–177.

He B, Li WH, Chen YJ, Xu CC, Yuan SF. 2007. Variation of sap flow and stem diameter of *Populus euphratica* under drought stress – a case study along Yingsu section. *Acta Botanica Boreali-Occidentalia Sinica* **27**: 315–320.

Horton JL, Kolb TE, Hart SC. 2001a. Responses of riparian trees to interannual variation in ground water depth in a semi-arid driver basin. *Plant, Cell and Environment* **24**: 293–304.

Horton JL, Thoums EK, Stephen CH. 2001b. Physiological response to ground water depth varies among species and with river flow regulation. *Ecological Applications* **11**: 1046–1059.

Ke YZ, Zhou JX, Lu N, Zhang XD, Sun QX. 2009. Effects of salinity on photosynthetic physiology and chlorophyll fluorescence characteristics of mulberry (*Morus alba*)seedlings. *Forest Research* **22**: 200–206.

Kranjcec J, Mahoney JM, Root SB. 1998. The responses of three riparian cotton wood species to water table decline. *Forest Ecology and Management* **110**: 77–87.

Levins R. 1968. *Evolution in Changing Environments: Some Theoretical Explorations*. Princeton University Press: USA.

Liu JZ, Chen YN, Chen YJ, Zhang N, Li WH. 2005. Degradation of *Populus euphratica* community in the lower reaches of the Tarim River, Xinjiang, China. *Journal of environmental sciences* **17**: 740–747.

Liu JZ, Chen YN, Li WH, Chen YJ. 2006. The process and mechanism of degradation of desert riparian vegetation. *Acta Geographica Sinica* **61**: 946–956.

Liu HP, Zhao SZ, Bai YZ, Wang YJ, Jian YW. 2008. *Populus euphratica* planting technology in Alkaline soil. *Inner Mongolia Forestry* **4**: 15.

Liu XJ, Zhao P, Cai XA, Rao XQ, Zeng XP. 2009. Variations of whole tree transpiration at different diameter classes in *Acacia mangium* during dry and wet seasons. *Acta Ecologica Sincia* **29**: 619–626.

Ortuno MF, Alarcon JJ, Nicolas E, Torrecillas A. 2004. Interpreting trunk diameter changes in young lemon trees under deficit irrigation. *Plant Science* **167**: 275–280.

Ortuno MF, Garcia-Orellana Y, Conejero W, Ruiz-Sanchez MC, Alarcon JJ, Torrecillas A. 2006. Stem and leaf water potentials, gas exchange, sap flow, and trunk diameter fluctuations for detecting water stress in lemon trees. *Trees-Structure and Function* **20**: 1–8.

Ortuno MF, Conejero W, Moreno F, Moriana A, Intrigliolo DS, Biel C, Mellisho CD, Perez-Pastor A, Domingo R, Ruiz-Sanchez MC. Casadesus J, Bonany J, Torrecillas A. \2010. Could trunk diameter sensors be used in woody crops for irrigation scheduling? A review of current knowledge and future perspectives. *Agricultural Water Management* **97**: 1–11.

Qiu LZ, Huang YJ, Huang JQ, Xia GH, Gong N. 2006. Comparative study on vegetal and physiological characteristics of different salt-tolerant plants under salt stress. *Journal of Zhejiang University (Agriculture & Life Sciences)* **32**: 420–427.

Ruan X, Wang Q, Chen YN, Li WH. 2007. Physiological response of riparian plants to watering in hyper-arid areas of Tarim River, China. *Front Biology China* **2**: 54–61.

Snyder KA, Williams DG. 2003. Defoliation alters water uptake by deep and shallow roots of Prosopis velutina (Velvet Mesquite). *Functional Ecology* **17**: 363–374.

Tang LS, Zhang JL, Li Y, Zhou B. 2005. Response of plants to the change of soil moisture content and the controlled alternative partial root-zone irrigation. *Arid Zone Research* **22**: 90–93.

Velez JE, Intrigliolo DS, Castel JR. 2007. Scheduling deficit irrigation of citrus trees with maximum daily trunk shrinkage. *Agricultural Water Management* **90**: 197–204.

Wang H, Zhao WZ, Chang XX. 2007. Spatial variability of soil moisture and vegetation in desert oasis ecotone in the middle reaches of Heihe River Basin. *Acta Ecologica Sincia* **27**: 1731–1739.

Wullschleger SD, Meinzer FC, Vertssy RA. 1998. A review of whole-plant water use studies in trees. *Tree Physiology* **18**: 499–517.

Xie TT, Zhang XM, Liang SM, Shan LS, Yang XL, Hua YH. 2008. Effects of different irrigations on the water physiological characteristics of *Haloxylon ammodendron* in Taklimakan Desert hinterland. *Chinese Journal of Applied Ecology* **19**: 711–716.

Xu HL, Song YD, Wang Q, A Mti. 2004. The effect of groundwater lever on vegetation in the middle and lower reaches of the Tarim River, Xinjiang, China. *Acta Phytoecologica Sinica* **28**: 400–405.

Yuan XH, Wu JY, Sun L, Duan LS, Wang JZ. 2008. Evapotranspiration of *Dianthus chinensis* at different irrigation levels. *Journal of Beijing Forestry University* **30**: 77–81.

Zhang XY, Gong JD, Zhou MX, Si JH. 2004. Spatial and temporal characteristics of stem sap flow of *Populus euphratica*. *Journal of Desert Research* **24**: 489–492.

Zhang YX, Shi Y, Wang RG, Chen SL, Li NY, Shao J, Zhang H, Li J, Sun J. 2008. Effects of ABA and CaM on leaf gas exchange of *Populus euphratica* in the process of initial salinity. *Scientia Silvae Sinicae* **44**: 57–64.

Zhao WZ, Liu H. 2006. Recent advances in desert vegetation response to groundwater table changes. *Acta Ecologica Sincia* **26**: 2702–2708.

Zhao M, Guo ZZ, Wang YL, Li AD, Zhang DK, Jia BQ. 2003. Study on the transpiration characteristics of 10 species of plants under the different depths of groundwater level. *Arid Zone Research* **20**: 286–291.

Zhou HH, Chen YN, Li WH, Chen YP. 2008a. Characterization of photosynthesis of *Populus euphratica* Oliv and its microclimate explanation in lower Tarim River. *Journal of Desert Research* **28**: 665–672.

Zhou XM, Chen YN, Li WH, He B, Hao XM. 2008b. Study of sap flow in stem of *Populus euphratica* in lower reaches of Tarim River. *Journal of Desert Research* **28**: 673–678.

