DIE ERDE
Journal of the Geographical Society of Berlin

Vol. 149, No. 2-3 · Research article

Comparison of water consumption of three urban greening trees in a typical arid oasis city, northwest China

Maierdang Keyimu[1,2], Ümüt Halik[2], Zongshan Li[1], Abdulla Abliz[3], Martin Welp[4]

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085 Beijing, China, merdan@rcees.ac.cn, zsli_st@rcees.ac.cn

[2]Ministry of Education Key Laboratory of Oasis Ecology, College of Resources and Environmental Science, Xinjiang University, 830046 Urumqi, China, halik@xju.edu.cn (Ümüt Halik is corresponding author)

[3]College of Tourism, Xinjiang University, 830046 Urumqi, China, abdulla.abliz@xju.edu.cn

[4]Faculty of Forest and Environment, Eberswalde University for Sustainable Development, 16225 Eberswalde, Germany, martin.welp@hnee.de

Manuscript submitted: 10 April 2017 / Accepted for publication: 17 September 2017 / Published online: 27 September 2018

Abstract

In order to ensure sustainable development of arid oasis cities, close attention must be paid to the rational use of limited water resources. Since urban vegetation is one important user of water, urban greening activities should be adapted to local environmental conditions. In this study, one native (Morus alba L.) and two introduced urban greening tree species (Fraxinus sogdiana Bunge and Platanus acerifolia Willd.) were selected in Aksu – a typical oasis city in northwest China. Their stem sap flow velocity (SFV) was determined and diel water consumption was calculated. In the meantime, meteorological variables were recorded to analyze the water consumption strategy of these tree species. The results show that the average SFV of M. alba, F. sogdiana and P. acerifolia were 4.1±0.3 cm h^{-1}, 10.5±0.7 cm h^{-1} and 22.3±2.6 cm h^{-1}, respectively. SFV was positively correlated with solar radiation (Rs), air temperature (Ta), vapor pressure deficit (VPD) and wind speed (Ws), and negatively correlated with air humidity (RH). Stepwise analysis showed that VPD had the highest impact on SFV of F. sogdiana (R^2=0.987) and M. alba (R^2=0.887), while the impact of RH was highest on P. acerifolia (R^2=0.937). P. acerifolia had the highest sap flow daily accumulation (104±7 L $tree^{-1}$), F. sogdiana was second (52±4 L $tree^{-1}$), and third was M. alba (16±2 L $tree^{-1}$). The water use efficiency (WUE) was M. alba (3.61 mmol mol^{-1}) > F. sogdiana (3.33 mmol mol^{-1}) > P. acerifolia (2.90 mmol mol^{-1}). This study showed that native tree species developed certain adaptation strategies to the arid environment and thus consumed less water. Therefore, we recommend that in tree species selection by landscape planners as well as other decision makers, native tree species should be given priority in future urban greening projects.

Zusammenfassung

Um eine nachhaltige Entwicklung von Oasenstädten in Trockengebieten zu gewährleisten, muss der sparsamen Nutzung begrenzter Wasserressourcen eine besondere Aufmerksamkeit geschenkt werden. Da die Stadtvegetation zu den wichtigsten Wasserverbrauchern in der Stadt gehört, sollten Stadtbegrünungsaktivitäten (v. a. die Gehölzauswahl) an lokale Umweltbedingungen angepasst werden. In dieser Studie wurden die Saftflussgeschwin-

Maierdang Keyimu, Ümüt Halik, Zongshan Li, Abdulla Abliz, Martin Welp 2018: Comparison of water consumption of three urban greening trees in a typical arid oasis city, northwest China. – DIE ERDE **149** (2-3): 173-183

DOI:10.12854/erde-2018-352

digkeit (SFV) und der Wasserverbrauch von einer einheimischen Baumart (*Morus alba* L.) und zwei eingeführten Baumarten (*Fraxinus sogdiana* Bunge und *Platanus acerifolia* Willd.) in Aksu – einer typischen Oasenstadt im Nordwesten Chinas – untersucht bzw. berechnet. Es wurden meteorologische Variablen erfasst, um die Wasserverbrauchsstrategie dieser Baumarten zu analysieren. Die Ergebnisse zeigen, dass das durchschnittliche SFV von *M. alba*, *F. sogdiana* und *P. acerifolia* 4,1±0,3 cm h^{-1}, 10,5±0,7 cm h^{-1} bzw. 22,3±2,6 cm h^{-1} beträgt. SFV korreliert positiv mit der Sonneneinstrahlung (Rs), der Lufttemperatur (Ta), dem Dampfdruckdefizit (VPD) und der Windgeschwindigkeit (Ws) und korreliert negativ mit der Luftfeuchtigkeit (RH). Eine weitere Analyse zeigt, dass VPD den größten Einfluss auf SFV von *F. sogdiana* (R^2=0,987) und *M. alba* (R^2=0,887) hat, während der Einfluss von RH auf *P. acerifolia* am höchsten ist (R^2=0,937). *P. acerifolia* hat die höchste Saftfluss-Tagesakkumulation (104±7 L), *F. sogdiana* hat die zweithöchste (52±4 L) und *M. alba* (16±2 L) die dritthöchste Akkumulation. Der einheimische Maulbeerbaum (*M. alba*) weist die höchste Wassernutzungseffizienz (WUE) mit 3,61 mmol mol^{-1} auf, während die WUE von den beiden exotischen Baumarten *F. sogdiana* (3,33 mmol mol^{-1}) und *P. acerifolia* (2,90 mmol mol^{-1}) niedriger sind. Diese Studie beweist, dass die einheimischen Gehölzearten bestimmte Anpassungsfähigkeiten an die trockenen Bedingungen haben und somit weniger Wasser verbrauchen. Daher empfehlen wir für die Baumauswahl durch Landschaftsplaner sowie andere Entscheidungsträger, einheimische Baumarten bei zukünftigen Stadtbegrünungsprojekten zu bevorzugen.

Keywords oasis cities, urban trees, sap flow velocity, water consumption, Southern Xinjiang

1. Introduction

Following climate change, rapid industrialization, as well as over-exploitation activities of humans, the contradiction between water supply and demand has become increasingly prominent in arid cities (*Halik* 2003). Water scarcity is one of the important regulating factors for the healthy and rapid development of urbanization in arid areas. Therefore, the scientific allocation and rational use of limited water resources is of importance to ensure the sustainable development of these regions. Since urban greenings represent the most significant consumption of water, when such activities are carried out in arid cities, the local environmental conditions must be considered, and the water consumption of the greening subject should be assessed (*Halik* and *Hamann* 1999; *Halik* 2003; *Zerbe* et al. 2005).

The tree water consumption through canopy transpiration can be determined by measuring tree stem sap flow (*Granier* 1987; *Vertessy* et al. 1997). There are a few methods in sap flow measurement (*Swanson* 1994; *Wullschleger* et al. 1998; *Lu* et al. 2004; *González-Altozano* et al. 2008; *Liu* et al. 2011; *Jansen* et al. 2015). Each method has its own favorable utilization condition and standard. The heat ratio method (HRM) is widely used in forest hydrological research due to the high accuracy of measurement and low impact on the measurement object (*Pfautsch* et al. 2011, 2015; *Van de Wal* et al. 2015). It was developed by the idea of tracking the stem flow rate by using heat transfer (*Bleby* et al. 2004). The HRM method measures the transfer velocity and amount of water through the stem under natural growth conditions of the vegetation. *Vertessy* et al. (1997) ran a sap flow measurement of a *Eucalyptus regnans* (F. J. Muell) forest in Yarra Ranges National Park, Australia, to estimate its water use. They used the HRM method, based on the correlation between Diameter at Breast Height (DBH), leaf area index of measurement object and water consumption, and validated it based on the actual water uptake by the trees from the nearby reservoir. *Buckley* et al. (2011) used the same measurement approach to determine the nocturnal water consumption of *Eucalyptus delegatensis* and *E. pauciflora* in southeastern Australia, by separating the transpiration and refilling component of tree sap flux, and suggested that the evaporative demand and soil moisture are the strong drivers of the nocturnal water usage process (*Buckley* et al. 2011). *Zhang* et al. (2005) and *Si* et al. (2004, 2005) measured the sap flow of *P. euphratica* and *Tamarix* spps in Ejina Poplar Nature Reserve at the middle reaches of Heihe River, China. They analyzed the sap flow diurnal variation process and the correlation between sap flow and DBH of vegetation, and calculated the diurnal water consumption of *P. euphratica* and *Tamarix* spp. *Li* et al. (2008) measured the sap flow of main urban greening trees (*Sophora japonica* Linn., *Ginkgo biloba* L., *Fraxinus chinensis* Roxb., *Eucommia ulmoides* Oliver., *Ailanthus altissima* (Mill.) Swingle) in the city of Beijing, and calculated their diurnal water consumption. Their study showed that water consumption of *S. japonica* was the largest compared to other tree species, while *F. chinensis* consumes the least water. *Ma* et al. (2010) determined the sap flow of typical arid land forest species (*Populus russkii* Jabl, *Populus euphratica* Oliv., *Ulmus pumila* L. and *Eleagnus angustifolia* Linn.). In the meantime, they used a climate station to record the meteorological factors simultaneously by establishing a correlation model between environmental factors and sap flow, and found that the above-mentioned tree species have a different sensitivity to environmental factors.

In our study, we selected the following three common urban greening trees in oasis cities of southern Xinjiang, Northwest China:

(1) *Morus alba* L. (also known as white mulberry) is a fast-growing, deciduous tree species which is native to northern and northwestern China. Due to its broad ecological niche, it is also naturalized in many parts of the world. Mulberry has long cultivation history along ancient 'silk road', especially in southern Xinjiang (Kashgar, Hotan, and Aksu cities), northwest China (*Halik* 2003). Mulberry provides important ecosystem services. Its leaves are the preferred feedstock for silkworm in silk production, and it is also good wood material with a beautiful texture, often used for manufacturing furniture and musical instruments, bringing economic benefits. Besides, the fruit of the mulberry can be eaten, and it is used as medicine for treating headache, fever as well as diabetes (*Lin* et al. 2013). It is widely used in Uighur ethnic courtyard culture. Furthermore, it has a high capacity for dust retention and toxic gas absorption; therefore, it is regarded as the pioneer greening tree species (*Yu* et al. 2015).

(2) *Fraxinus sogdiana* Bunge (a central Asian ash species) originates from middle and southern China as well as northwest Xinjiang, where the climate conditions are rainy and warm. It grows naturally along riversides and wetlands at the edge of forests, often along with *Pterocarya stenoptera*, *Fraxinus rhynchophylla* (*Wu* et al. 2004).

(3) *Platanus acerifolia* Willd. (also known as London planetree) is a hybrid of *Platanus orientalis* and *Platanus occidentalis*, which are native to southeast Europe and western Asia. It is extensively cultivated and used as a roadside tree throughout the temperate regions of the world due to its many desirable characteristics, such as fast growth, broad crown, good tolerance to pruning and high resistance to environmental pollution as well as its aesthetically-pleasing appearance (*Halik* 2003; *Zhang* et al. 2014). *P. acerifolia* has a less-developed root system, and naturally grows in warm and humid regions, with 800-1200 mm of annual precipitation. In arid regions, it requires irrigation.

In our study, we hypothesized that the native tree species are more drought resistant and consume less amount of water compare to introduced tree species. We took samples of three main urban greening tree species *F. sogdiana* (introduced), *P. acerifolia* (introduced) and *M. alba* (native) along the Western main street (Xi Da Jie) of Aksu city, in northwest China, then run sap flow measurement, finally calculated stem sap flow velocity (SFV) and diurnal water consumption. Meanwhile, the meteorological factors were recorded as well to analyze the water consumption strategy of these tree species. The physiological parameters of these tree species were measured, and their water use efficiency was calculated. The aim of this research is thus to provide a scientific basis for the reasonable selection of urban greening tree species in arid cities considering their water consumption and environmental condition.

2. Materials and methods

2.1 Study area

The city of Aksu (39°31′ - 42°41′ N, 78°02′ - 84°05′ E) is located in the southwest of Xinjiang Uighur Autonomous Region, China, on the northern edge of the Taklamakan Desert. The city is characterized by a temperate arid climate, with an average annual temperature, precipitation and evaporation of about 9.9-11.5 °C, 43.9-65.3 mm, and 1950-2600 mm respectively (*Han* et al. 2012; *Baidourela* 2015). Aksu is a typical oasis city in southern Xinjiang, the main urban greening trees are *Populus alba* var. *pyramidalis*, *Ulmus densa*, *Salix babylonica*, *Morus alba*, *Fraxinus sogdiana*, and *Platanus acerifolia* (*Halik* 2003; *Zerbe* et al. 2005; *Wumaier* et al. 2016).

2.2 Sample selection and measurement

Two sample trees of different species, with straight trunks, in good growth condition, and without pest affects were chosen along the Xida Jie in Aksu city based on the abundance and source of the species (*Table 1*). The density of the street trees was similar. A sap flow measurement was performed on each sample tree using a Sap Flow Meter (SFM1), which runs based on the heat ratio method (SFM1, ICT International, Australia) during 1 May to 20 May 2014.

The sapwood of three tree species in this study can be readily distinguished from heartwood. To calculate the sapwood area, we assume that the tree stem was circular, that the sapwood and the inner wood areas were in the shape of concentric circles, and the outer circle represents the sapwood area (*Fig. 1*).

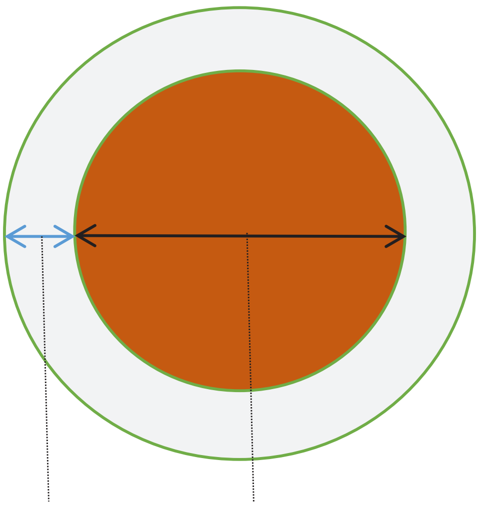

Fig. 1 Sapwood and heartwood of the tree stem (the grey colored part in the edge is the sapwood, the brown colored part in the center is the heartwood). Source: Own elaboration

The following equation is used for calculating the sapwood area (S_a):

$$S_a = \pi \times \left(\frac{DBH}{2}\right)^2 - \pi \times \left(\frac{DBH}{2} - x\right)^2 \qquad (1)$$

Here, S_a is sapwood area (cm^2), x is sapwood depth (cm), DBH is the diameter at breast height of tree (cm).

2.3 Sap flow measurement

Sap flow measurement was carried out simultaneously on different tree species in order to carry out comparative analysis on their water usage strategies. We used SFM1 sap flow sensors (Greenspan Technology, Australia) to measure the sap flow from 1 May to 20 May 2014. The installation and sensor design were identical to those used by *Pfautsch* et al. (2010) and *Keyimu* et al. (2017a, b). Initially, three tree species which were in a good state of health were selected. After removing the tree bark (10×10 cm^2) at breast height until the cambium was exposed, an installation guide was attached on the tree using four anchor pins to position and secure the guide on the tree. Then three holes were drilled perpendicularly and in parallel into the stem using a 1.3 mm drill bit. Probes were inserted after being coated with silicon gel to ensure thermal contact between the probe elements and sapwood. The measurement interval was set to 15 minutes and the data were saved on an SD card. The sensors were supplied by 12 V from an external battery. Finally, sensors were covered with waterproof plastic and aluminum cover to avoid physical damage and thermal influences. The working principle of SFM1 sap flow sensors was described by *Marshall* (1958) and *Barret* et al. (1996).

Table 1 Descriptive statistics of sampling trees (Mean±SD). Source: Own elaboration

Sample trees	DBH cm	Sapwood diameter cm	Wound diameter mm	Sapwood area cm^2	Crown diameter m	Average leaf size* cm^2
M. alba	24.2±0.4	2.1±0.2	1.70	173±12	5.2±0.5	100±7
F. sogdiana	25.6±0.3	2.7±0.2	1.70	454±18	6.8±0.9	36±3
P. acerifolia	24.5±0.4	2.8±0.2	1.70	426±16	6.5±0.8	150±13

DBH: Diameter at Breast Height; **Baidourela* (2015)

Nocturnal water refill is the accumulation of sap flow when *Rs* (solar radiation) is zero (*Wang* et al. 2007).

$$\text{Nocturnal water refill} = \sum Js \times A \times t \qquad (2)$$

where *Js* is the sap flux density, *A* is the sapwood area, and *t* is the measurement interval. *Js* was obtained using following equation:

$$Js = \frac{F}{A \times t} \qquad (3)$$

where *F* is sap flow rate, *A* is sapwood area, and *t* is sap flow measurement interval.

2.4 Meteorological data

Meteorological variables, such as *Rs* (solar radiation), *Ta* (air temperature), *RH* (humidity), and *Ws* (wind speed) were collected from the corresponding sensors (Watchdog 2900ET weather station, Spectrum, Co. Ltd., USA). The variables were recorded by the internal data logger at 1 h intervals, and data read out was completed using Spec ware software. VPD (vapor pressure deficit) was calculated using the following equation:

$$VPD = \left(1 - \frac{RH}{100}\right) \times ea^* \qquad (4)$$

where *RH* is air humidity and ea^* is actual vapor pressure. ea^* is obtained using following equation (*Campbell* and *Norman* 1998):

$$ea^* = a \times \exp\left(b \times \frac{Ta}{Ta + c}\right) \qquad (5)$$

where *Ta* is air temperature, value of parameters *a*, *b*, *c* are 0.611 kPa, 17.502, 237.3 °C, respectively.

2.5 Measurement of plant physiological parameters and calculation of water use efficiency

Three to five tree leaves of *M. alba*, *F. sogdiana* and *P. acerifolia* were chosen during the sap flow measurement, and the physiological parameters of the net photosynthetic rate (*Pn*) and transpiration rate (*E*) were measured using the Li-6400 photosynthetic system (LI-COR, Lincoln, NE, USA) from 6:30–18:30 (UTC+6) in two-hour intervals on 3rd, 5th, and 7th day of sap flow measurement. The water use efficiency (WUE) was calculated by applying a gas exchange method (*Richards* et al. 2003):

$$WUE = Pn/E \qquad (6)$$

where *Pn* is the net photosynthetic rate, *E* is transpiration rate.

2.6 Data processing

Using the sap flow tool (ICT International, Australia), the sap flow data of sample trees were processed, and SFV as well as sap flow daily accumulation were calculated. The sapwood area calculation was carried out with Microsoft Excel 2015 using Eq. (1). Pearson correlation analysis was run between the meteorological variables and sap flow velocities of three tree species to reveal their relationship. Regression models between sap flow and meteorological variables were achieved (results at $p \leq 0.05$ significance level) using SPSS statistics 20.0 (IBM, USA). A stepwise eliminative regression method was used to select the best regression model between the sap flow velocity and environmental variables. The 95% confidence interval was used as the criterion for the elimination of an independent variable to establish the optimal regression equation. Akaike Information Criterion (AIC) of each regression model was calculated to determine the best model. The plotting was performed with Sigmaplot 12.5 (SYSTAT, USA) and Microsoft Excel 2015 (Microsoft, USA).

3. Results and analysis

3.1 Daily sap flow process

Diel dynamics of SFV of all tree species during sunny days were compared. The SFV of each tree species showed a significant circadian rhythm, it remained stable at night, though at a lower velocity. However, there were certain differences on the sap flow process of each tree species.

SFV of *F. sogdiana* started to rise at 8:00 a.m. in the morning (6.7±0.5 cm h^{-1}) until it reached the maximum value of 18.1±3.2 cm h^{-1} at 2:30 p.m (*Fig. 2a*). Afterward, it started to decrease, and reached its lower value of 8.9±0.7 cm h^{-1} at 8:30 p.m. The minimum value of SFV during the measurement day appeared at 3:00 a.m., which was 6.0±0.5 cm h^{-1}. The average daily SFV was 10.5±1.7 cm h^{-1}. The diel consumed water amount was 51.6±4.4 L $tree^{-1}$ d^{-1}. The amount of water refilled at night was 12.5±1.6 L $tree^{-1}$ d^{-1}, which accounted for 24.2% of total daily water consumption.

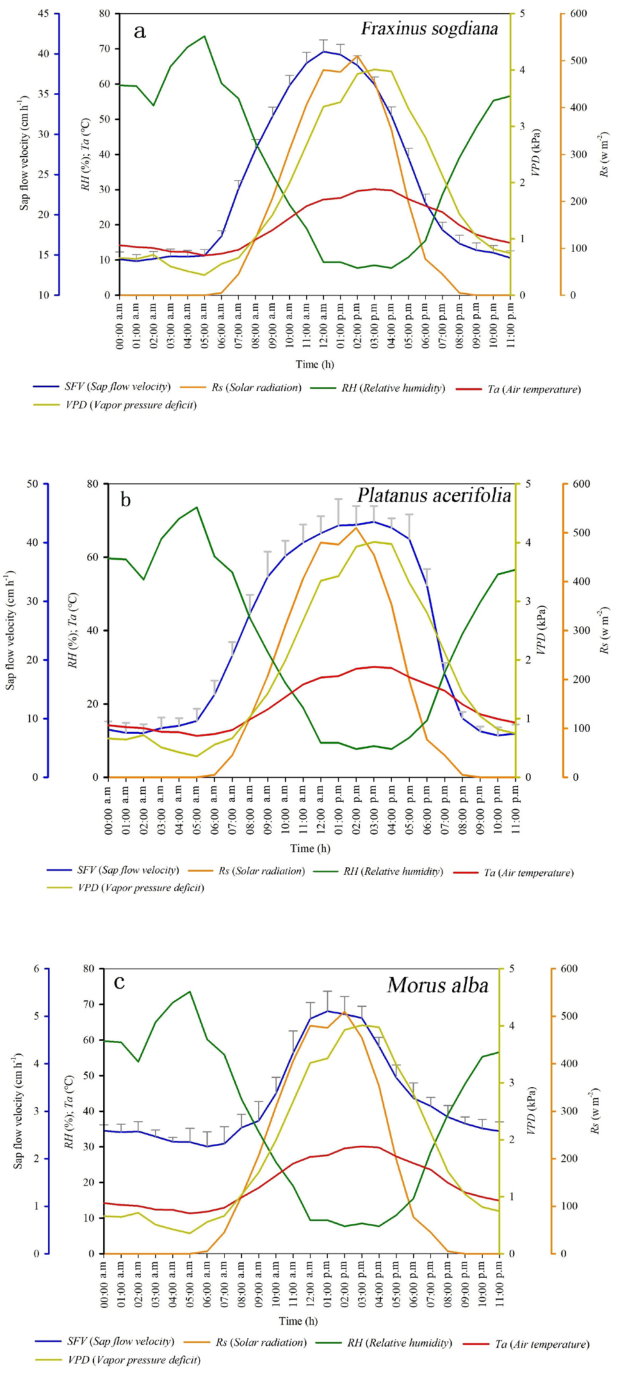

Fig. 2 Diel variation of sap flow velocity of three tree species and environmental variables. Source: Own elaboration

SFV of *P. acerifolia* started to rise at 7:00 a.m. (10.1±1.6 cm h^{-1}), which was earlier than that of *F. sogdiana*, until it reached a value of 36.3±3.6 cm h^{-1} at 11:00 a.m. Afterward, it continued to rise at a lower rate (*Fig. 2b*). The maximum value of SFV was observed at 03:45 p.m. (43.7±4.5 cm h^{-1}). From 6:00 p.m. on, the sap flow started to decline sharply, and reached its lower value of 11.9±2.3 cm h^{-1} at 9:30 p.m. The lowest value of SFV was observed at 3:00 a.m. (7.7±0.7 cm h^{-1}). The daily water consumption was 104.5±7.1 L $tree^{-1}$ d^{-1}. The refilled water amount during the night was 15.3 L $tree^{-1}$ d^{-1}, and it accounted for 14.6% of diel consumed water.

SFV of *M. alba* started rising at 9:30 a.m. (3.4±0.6 cm h^{-1}), which was later than both *F. sogdiana* and *P. acerifolia* (*Fig. 2c*). It reached a maximum value of 5.5±0.9 cm h^{-1} at 2:00 p.m., and from 5:0 p.m. on it declined gradually until reaching its lower value of 4.0±0.4 cm h^{-1} at 8:30 a.m. During the measurement day, the total daily consumed water amount was 16.1±2.5 L $tree^{-1}$ d^{-1}. At night 5.0±0.5 L $tree^{-1}$ d^{-1} of water was refilled, which accounted for the 30.9% of diel consumed water.

3.2 Correlation between sap flow velocity and environmental variables

SFV is not only affected by the eco-physiological characteristics of the plant itself, but also by environmental variables (*Xu* et al. 2011; *Guo* et al. 2015; *Wang* et al. 2016). *Figures 2a, b* and *c* showed that *Ta*, *Rs* and VPD have significant circadian rhythm, and they have similar daily variation features with SFV. However, as *RH* was higher during the night, then decreased slowly after sunrise, it had the opposite daily variation feature to SFV. A Pearson correlation was calculated between the SFVs of three different tree species and the meteorological varibles *Ta*, *Rs*, *RH*, *Ws* and VPD (*Table 2*). The results showed that SFV was positively correlated with *Rs*, *Ta*, *Ws* and VPD, while it was negatively correlated with *RH*.

Table 2 Correlation coefficients between the SFV and meteorological variables. Source: Own elaboration

Tree species	Rs	RH	Ta	VPD	Ws
M. alba	0.602**	-0.802**	0.867**	0.887**	0.362**
F. sogdiana	0.889**	-0.969**	0.986**	0.994**	0.692**
P. acerifolia	0.868**	-0.970**	0.964**	0.957**	0.711**

** indicates correlation statistically significant at $p < 0.05$;
Rs: solar radiation, RH: relative humidity, Ta: air temperature, VPD: vapor pressure deficit, Ws: wind speed

Based on the above analysis, a multiple linear regression method was applied to establish a stepwise regression model between meteorological variables and SFV (*Table 3*). It can be seen from the regression models that the main influencing factors on SFV of the three tree species were different. VPD had the highest impact on SFV of *M. alba* and *F. sogdiana*, while the impact of *RH* was highest on *P. acerifolia.*

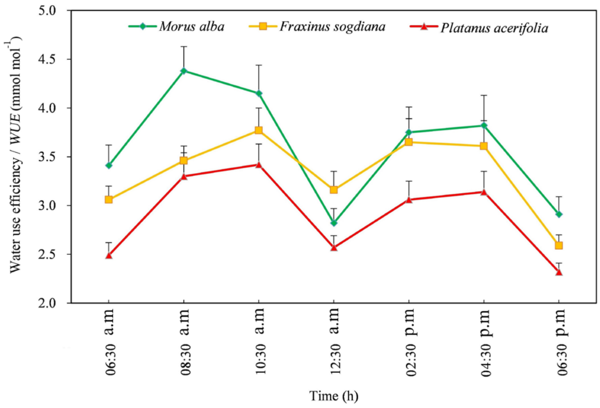

Fig. 3 *Diel variations of WUE (Water Use Efficiency) of three tree species. Source: Own elaboration*

Table 3 *Multiple regression models between meteorological variables and sap flow velocity. Source: Own elaboration*

Tree species	Stepwise regression equation	AIC	R^2	P
M. alba	Y=3.08±0.15+(0.56±0.05)VPD	-42.51	0.887	<0.001
F. sogdiana	Y=4.37±0.25+(3.46±0.12)VPD	-28.20	0.994	<0.001
P. acerifolia	Y=46.17±3.45-(0.61±0.08)RH	63.72	0.970	<0.001

AIC: Akaike Information Criteria

3.3 Water use efficiency of three tree species

Water use efficiency (WUE) is an objective reflection of a plant's water use status. It is the ratio between the amount of fixed carbon and the transpired water during plant photosynthetic process (*Jin* et al. 2015). *Cao* et al. (2009) showed that the ratio between the plant carbon assimilation and water consumption can indicate the plant adaptability to drought conditions. High water use efficiency is the determining factor of a plant to resist water stress. Under the same environmental conditions, the plant with higher water use efficiency has an extended drought resistance capacity (*Sobrado* 2000).

The WUE of *M. alba*, *F. sogdiana* and *P. acerifolia* was calculated using a gas exchange method. The results showed that there were certain differences in the WUE of these urban greening tree species (*Fig. 3*). The daily average WUE were: 3.61 mmol mol^{-1} (*M. alba*) > 3.33 mmol mol^{-1} (*F. sogdiana*) > 2.90 mmol mol^{-1} (*P. acerifolia*). *Figure 3* shows that the diel WUE of these tree species had peak variation features. The whole variation process of WUE can be divided into morning and afternoon sections. In both sections, the WUE rose initially, and then decreased. WUE of three tree species was not only determined by tree physiological characteristics, but also influenced by environmental conditions.

4. Discussion

Under heterogeneous environmental conditions, not only the different tree species, but also the individual trees (within different vitality and age status) of the same species consume different amounts of water (*Bai* et al. 2008). Environmental factors influence the sap flow process of plants. Therefore, SFV of different plants varies through time and region (*Zwieniecki* and *Holbrook* 1998). Thus, carrying out a comparative analysis of SFV and water consumption strategies of different tree species requires simultaneous observations over a common period within the geographical domain of interest (*Ma* et al. 2003), and the results could explain the differences of sap flow characteristics of different tree species and their reaction to environmental factors (*Steinberg* et al. 1990).

The diel sap flow variation feature of three tree species in the present study were similar, they all showed obvious circadian rhythms. However, there were differences in the sap flow starting time points, average, maximum, and minimum sap flow. This was probably due to the larger average leaf area of *P. acerifolia* than *F. sogdiana* (*Baidourela* 2015). Larger leaf size helps to absorb more light energy, thus photosynthetic activity starts earlier (*Bolhar-Nordenkampf* 2014), and water is consumed at a higher transpiration rate. Furthermore, the biological and physiological differences among these tree species could be the reason for the different behavior of the diel sap flow variations.

The average SFV during the day was higher than at night. Although the sap flow process was weaker at night, it remained active. This was probably to refill the water loss during the day to keep its water balance (*Sun* 2006), and corresponds to the research results of *Zhang* et al. (2004, 2005), *Si* et al. (2007) and *Yu* et al. (2014). *Wang* et al.'s study suggested that a strong refilling ability represents a drought-resistance mechanism of tree species on some level (*Wang* et al., 2014). In the present study, the refilled water amount of *M. alba*, *F. sogdiana* and *P. acerifolia* during the night accounted for 30.9%, 24.2% and 14.6% of the total daily water consumed respectively. Based on this, the drought resistance of three tree species can be ranked as: *M. alba* > *F. sogdiana* > *P. acerifolia.*

The drought resistance is the ability of a plant to maintain favorable water balance and turgidity even when exposed to drought conditions, thereby avoiding stress and its consequences. This can be seen in water consumption, which is negatively correlated with turgidity (*Sun* 1996). Research results of *He* et al. (2014) indicated that drought resistance of *M. alba* is stronger than *F. sogidiana. Zhao* et al.'s (2012) study showed that drought resistance of *P. acerifolia* is smaller than *F. sogdiana*. Therefore, the drought resistance of these trees is *M. alba* > *F. sogdiana* > *P. acerifolia*. Based on this, the theoretical order of their water consumption is: *P. acerifolia* > *F. sogdiana* > *M. alba*. This corresponds with the field measurements of water consumption and average WUE in the present study.

Relevant studies reported that *Rs*, *RH*, *Ta* and *Ws* are the most influencing environmental factors on the sap flow velocity. Pearson correlation analysis between the meteorological variables and sap flow velocity of three different tree species showed that sap flow velocity positive correlates with *Ta*, *Rs*, VPD, and *Ws*, while it negatively correlates with *RH*. *Zhang* et al.'s (2006) study demonstrated that solar radiation is the main external factor which influences the photosynthetic and transpiration activities of plants; it increases the stomata activity, and also changes the air temperature and relative humidity both in direct and indirect ways. The relative humidity inside the stomatal cavity is higher than of outside *RH*, this creates vapor pressure potential and increases the transpiration, while higher outside *RH* decreases transpiration, and thus sap flow velocity. The regression model between sap flow velocity and meteorological variables showed that VPD is the most influential variable on the sap flow velocity of *M. alba* and *F. sogdiana*, while *RH* is the most influential variable on *P. acerifolia*. This is probably due to the difference in morphological structure and physiological characteristics of these three tree species.

M. alba is a native tree species in southern Xinjiang with a very long history of cultivation. Locals use it as greening trees at their homes and along streets; besides, it is inseparable from the local Uighur ethnic courtyard culture (*Halik* 2003). However, in the recent urban modernization process, a large number of exotic tree species (e.g., *F. sogdiana*, *P. acerifolia*) were introduced in the urban greening practices. Although these exotic tree species enhance the aesthetic effect of the urban landscape, they significantly increase the water consumption of urban greening.

In all oasis cities of southern Xinjiang, water shortage is the bottleneck for sustainable urban development. In relevant studies (*Halik* 2003; *Zerbe* et al. 2005; *Halik* et al. 2008), it was pointed out that many urban greening patterns and modes in southern Xinjiang were borrowed from inner Chinese cities which can be characterized by warm and humid climate conditions. However, this increases the water demand of urban ecosystems and requires the rational allocation of limited water resources in arid regions. Therefore, urban greening should be adopted to the local environmental conditions and economic strength of the region to become sustainable.

5. Conclusion

The results of this study displayed that there were certain similarities and differences of sap flow process of *M. alba*, *F. sogdiana*, and *P. acerifolia*. Sap flow velocity (SFV) of all three tree species had an obvious circadian rhythm, which was positively correlated with *Rs*, *Ta*, VPD and *Ws.* However, it was negatively related to *RH*. The average daily SFV decreased in the order *P. acerifolia* > *F. sogdiana* > *M. alba*. The daily water consumption of *M. alba*, *F. sogdiana* and *P. acerifolia* was 104.45±7.1 L tree^{-1} d^{-1}, 51.6±4.4 L tree^{-1} d^{-1}, 16.11±1.8 L tree^{-1} d^{-1} respectively. WUE of these tree species was ranked as: *M. alba* (3.61 mmol/mol) > *F. sogdiana* (3.33 mmol/mol) > *P. acerifolia* (2.90 mmol/mol). Our results showed that *M. alba* (native tree species) has a relatively high drought resistance capacity and consumes less water than the other two species investigated in this study. Therefore, it is suggested to give *M. alba* priority in the selection of urban greening tree species.

Acknowledgments

This research work was supported by the National Natural Science Foundation of China (Grant No.: 31770750, 31270742), German Volkswagen Foundation within the framework of EcoCAR project (Az.: 88497), and WP 4.3: “EES & EEF of urban and peri-urban oasis vegetation” of SuMaRiO project (Grant No.: 01LL0918C), which was funded by the German Federal Ministry of Education and Research (BMBF). We express our gratitude toward Ms. Gulibiya Wumaier and Ms. Gulikamaer Dilimulati from Xinjiang University for their dedication during the fieldwork. In addition, we thank Aksu Vocational and Technical College and Kökyar Forestry Management Station for their support during our field work and laboratory experiment. We also thank Prof. Johannes Küchler (TU Berlin) and Mr. Keyum Rozi (first author’s father, Turpan/China) for providing us with some important knowledge and innovative idea about the selection of tree species for our study. Thanks also to the editors and anonymous reviewers for their constructive comments on the manuscript.

References

Bai, Y.G., J.H. Zhang, X.Y. Wang, B. Li and *H.B. Fan* 2008: Studies on scale convention of individual *Populus euphratica* and forest water consumption in Tarim Basin. – China Water Resources **5**: 24-25 (in Chinese with English abstract)

Baidourela, A. 2015: Dust retention capacity of common tree species for urban greening in Aksu City, Northwest China. – Dissertation, Xinjiang University, Urumqi, China (in Chinese with English abstract)

Barrett, J., T.J. Hatton, J.E. Ash, M.C., Ball and *G.E. Ash* 1996: Transpiration by trees from contrasting forest types. – Australian Journal of Botany **4**: 249-263, doi:10.1071/BT9960249

Bleby, T.M., S.S.O. Burgess and *M.A. Adams* 2004: A validation, comparison and error analysis of two heat-pulse methods for measuring sap flow in *eucalyptus marginata* saplings. – Functional Plant Biology **31** (6): 645-658, doi:10.1071/FP04013

Bolhar-Nordenkampf, H.R. 2014: Shoot morphology and leaf anatomy in relation to photosynthesis. – Techniques in Bioproductivity and Photosynthesis: Pergamon International Library of Science, Technology, Engineering and Social Studies **107**. – Oxford

Buckley, T.N., T.L. Turnbull, S. Pfautsch and *M.A. Adams* 2011: Nocturnal water loss in mature subalpine *Eucalyptus delegatensis* tall open forests and adjacent *E. pauciflora* woodlands. – Ecology and Evolution **1** (3), 435-450, doi:10.1002/ece3.44

Campbell, G.S. and *J.M. Norman* 1998: An introduction to environmental biophysics. – New York et al.

Cao, S.K., Q. Feng, J.H. Si, Z.Q. Chang, M.C. Zhuo, H.Y. Xi and *Y.H. Su* 2009: Summary on the plant water use efficiency at leaf level. – Acta Ecologica Sinica **29** (7): 3882-3892 (in Chinese with English abstract)

González-Altozano, P., E.W. Pavel, J.A. Oncins, J. Doltra, M. Cohen, T. Paço and *J.R. Castel* 2008: Comparative assessment of five methods of determining sap flow in peach trees. – Agricultural water management **95** (5): 503-515, doi:10.1016/j.agwat.2007.11.008

Granier, A. 1987: Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. – Tree physiology **3** (4): 309-320, doi:10.1093/treephys/3.4.309

Halik, Ü. and *B. Hamann* 1999: Stadtbegrünung im ariden Milieu. – Stadt und Grün **48** (10): 680-685

Halik, Ü. 2003: Urban greening in arid regions, the example of the oasis cities in southern Xinjiang/China, with special consideration of ecological, socio-economic and cultural aspects. – Dissertation, Technical University of Berlin. Berliner Beiträge zu Umwelt und Entwicklung **20**. – Berlin

Halik, Ü., B. Eitel and *J. Küchler* 2008: Wasserverknappung und Wasserkonflikte in der zentralasiatischen Wüstenmetropole Urumqi. – TU International **61**: 12-14

Han, L.Y., Q. Zhang, N. Guo, P.L. Ma, T. Han and *X. Wan* 2012: Temporal and spatial characteristics of dust events in Northwest China. – Journal of Desert Research **32** (2): 454-457 (in Chinese with English abstract)

He, D.D., W.G. Zhang, T.J. Guo, L.J. Ma and *S.P. Chen* 2014: Studies on the water physiological characteristics and drought resistance of seventy-five species of landscape trees. – Hubei Agricultural Sciences **53** (1): 116-121 (in Chinese with English abstract)

Jansen, S., B. Schuldt and *B. Choat* 2015: Current controversies and challenges in applying plant hydraulic techniques. – New Phytologist **205** (3): 961-964, doi:10.1111/nph.13229

Jin, H., U. Halik, A. Baidourela, A. Ailiyasi and *A. Wubuli* 2015: Characteristics of leaf water use efficiency of eight common tree species in Aksu. – Journal of Northwest Forestry University **30** (2): 44-50 (in Chinese with English abstract)

Keyimu, M., U. Halik and *A. Kurban* 2017a: Estimation of water consumption of riparian forest in the lower reaches of Tarim River, northwest China. – Environmental Earth Sciences **76**: 547, doi:10.1007/s12665-017-6801-8

Keyimu, M., U. Halik and *A. Rouzi* 2017b: Relating water use to tree vitality of *Populus euphratica* Oliv. in the lower Tarim River, NW China. – Water **9** (8), 622, doi:10.3390/w9080622

Li, X.Y., N.N. Lai, Sun L, Y.B. Qie and *Y. Lin* 2008: Comparison of whole-tree transpiration of five greening tree species in Beijing. – Chinese Bulletin of Botany **25**: 315-321 (in Chinese with English abstract)

Lin, Z.M., W.B. Jiang, J.X. Wei, M.L. Weng and *J. Han* 2013: On the comprehensive value of mulberry and its application in landscaping. – Jiangsu Agricultural Science **41** (7): 179-182

Liu, B., W. Zhao and *B. Jin* 2011: The response of sap flow in desert shrubs to environmental variables in an arid region of China. – Ecohydrology **4** (3): 448-457, doi:10.1002/eco.151

Lu, P., L. Urban and *P. Zhao* 2004: Granier‘s thermal dissipation probe (TDP) method for measuring sap flow in trees: theory and practice. – Acta Botanica Sinica (English Edition) **46** (6): 631-646

Ma, J.X., Y.N. Chen, W.H. Li and *X. Huang* 2010: Characteristics of sap flow of 4 typical shelter-belt tree species and it‘s relationships with environmental factors in the desert region of Northwest China. – Acta Ecologica Sinica **30** (3): 579-586 (in Chinese with English abstract)

Ma, L.Y., H.T. Wang and *P. Lin* 2003: Comparison of water consumption of some afforestation species in Beijing area. – Journal of Beijing Forestry University **25** (2): 1-7 (in Chinese with English abstract)

Marshall, C. 1958: Measurement of sap flow in conifers by heat transport. – Plant Physiology **33** (6): 385-396

Pfautsch, S., T.M. Bleby, H. Rennenberg and *M.A. Adams* 2010: Sap flow measurements reveal influence of temperature and stand structure on water use of Eucalyptus regnans forests. – Forest Ecology and Management **259** (6): 1190-1199

Pfautsch, S., C. Keitel, T.L. Turnbull, M.J. Braimbridge, T.E. Wright, R.R. Simpson, J.A. O'Brien and *M.A. Adams* 2011: Diurnal patterns of water use in *Eucalyptus victrix* indicate pronounced desiccation–rehydration cycles despite unlimited water supply. – Tree physiology **31** (10): 1041-1051

Pfautsch, S., W. Dodson, S. Madden and *M.A. Adams* 2015. Assessing the impact of large-scale water table modifications on riparian trees: a case study from Australia. – Ecohydrology **8** (4): 642-651

Richards, A.E., A. Shapcott, J. Playford, B. Morrison, C. Critchley and *S. Schmidt* 2003: Physiological profiles of restricted endemic plants and their widespread congenors in the North Queensland wet tropics, Australia. – Biological Conservation **111** (1): 41-52, doi:10.1016/S0006-3207(02)00245-8

Si, J.H., Q. Feng and *X.Y. Zhang* 2004: Application of heat-pulse technique to determine the stem sap flow of *Populus euphratica*. – Journal of Glaciology and Geocryology **26** (4): 503-508 (in Chinese with English abstract)

Si, J.H., Q. Fen, X.Y. Zhang, Z.Q. Chang, H.Y. Xi and *K. Zhang* 2007: Sap flow of *Populus Euphratica* in desert riparian forest in extreme arid region during the growing season. – Journal of Desert Research **27** (3): 442-447 (in Chinese with English abstract)

Si, J.H., Q. Feng, X.Y. Zhang, Y.W. Zhang and *Y.H. Su* 2005: Research progress on surveying and calculation of evapotranspiration of plants and its prospects. – Advances in Water Sciences **16** (3): 450-459 (in Chinese with English abstract)

Sobrado, M.A. 2000: Relation of water transport to leaf gas exchange properties in three mangrove species. – Trees **14** (5): 258-262, doi:10.1007/s004680050011

Steinberg, S.L., M.J. McFarland and *J.W. Worthington* 1990: Comparison of trunk and branch sap flow with canopy transpiration in pecan. – Journal of Experimental Botany **41** (6): 653-659, doi:10.1093/jxb/41.6.653

Sun, L. 2006: Sap flow flux of main forest types in eastern region of northeast China. – Dissertation, Northeast Forestry University. – Haerbin, China (in Chinese with English abstract)

Sun, Z.X., D.X. Li, Y. Zhao, C.K. Zhu, Y.F. Wei and *X.C. Yu* 1996: Study on water consumption and drought resistance of Maize in different growth stages. – Liaoning Agricultural Sciences **2**: 11-14 (in Chinese)

Swanson, R.H. 1994: Significant historical developments in thermal methods for measuring sap flow in trees. – Agricultural and Forest Meteorology **72** (1): 113-132, doi:10.1016/0168-1923(94)90094-9

Van de Wal, B.A., A. Guyot, C.E. Lovelock, D.A. Lockington and *K. Steppe* 2015: Influence of temporospatial variation in sap flux density on estimates of whole-tree water use in *Avicennia marina*. – Trees **29** (1): 215-222, – doi:10.13140/2.1.1561.4244

Vertessy, R.A., T.J. Hatton, P. Reece, S.K. O'sullivan and *R.G. Benyon* 1997: Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. – Tree Physiology **17** (12): 747-756, doi:10.1093/treephys/17.12.747

Wang, H., P. Zhao, Q. Wang, X. Cai, L. Ma and *X.Q. Rao* 2007: Characteristics of nighttime sap flow and water recharge in *Acacia mangium* trunk. – Chinese Journal of Ecology **26** (4): 476-482 (in Chinese with English abstract)

Wang, X.F., J.F. Liu, Y.Y. Sun, K. Li and *C.H. Zhang* 2016: Sap flow characteristics of three afforestation species during the wet and dry seasons in a dry-hot valley in Southwest China. – Journal of Forestry Research **28** (1): 1-12, doi:10.1007/s11676-016-0273-7

Wu, Z.Y., D.J. Yu and *R. Lin* 2004: Flora Reipublicae Popularis Sinicae. – Beijing

Wullschleger, S.D., F.C. Meinzer and *R.A. Vertessy* 1998: A review of whole-plant water use studies in tree. – Tree physiology **18** (8-9): 499-512, doi:10.1093/treephys/18.8-9.499

Wumaier, G., Ü. Halik, M. Keyimu, G. Dilimulati and *W. Han* 2016: Study on gas exchange characteristics of six urban tree species in Aksu city. – Journal of Xinjiang University (Natural Science Edition) **33** (3): 343-349 (in Chinese with English abstract)

Xu, X., L. Tong, F. Li, S. Kang and *Y. Qu* 2011: Sap flow of irrigated *Populus alba* var. *pyramidalis* and its relationship with environmental factors and leaf area index in an arid region of Northwest China. – Journal of Forest Research **16** (2): 144-152, doi:10.1007/s10310-010-0220-y

Yu, J., S. Yu, N. Xu and *Y.P. Xiao* 2015: Ecological application of mulberry. – Newsletter of Sericulture and Tea **6**: 12-14 (in Chinese with English abstract)

Yu, M.M., X.J. Zhang, F.H. Yuan, H.E. Xiu, D.X. Guan, A.Z. Wang, J.B. Wu and *C.J. Jin* 2014: Characteristics of sap flow velocities for three tree species in a broad-leaved Korean pine forest of Changbai mountain, in relation to environmental factors. – Chinese Journal of Ecology **33** (7): 1707-1714 (in Chinese with English abstract)

Zerbe, S., Ü. Halik and *J. Küchler* 2005: Urban greening in the oases of continental arid Southern Xinjiang (NW China) - an interdisciplinary approach. – Die Erde **136** (3): 245-266

Zhang, W. and *X.B. Ning* 2014: Application of *Platanus* in highway greening. – China Venture Capital **A16**: 347-347

Zhang, X.Y., J.D. Gong, M.X. Zhou and *J.H. Si* 2004: Spatial and temporal characteristics of stem sap flow of *Populus euphratica*. – Journal of Desert Research **24** (4): 489-492 (in Chinese with English abstract)

Zhang, X.Y., E.S. Kang and *Z.H. Zhang* 2005: A study of the stem sap flux of *Populus euphratica* in the lower reaches of Heihe River. – Journal of Glaciololgy and Geocryology **27**: 742-746 (in Chinese with English abstract)

Zhang, X.Y., E.S. Kang, Z.H. Zhang, M.X. Zhou and *S.I. Jian-Hua* 2006: Research on dynamics of stem sap flow of *Elaeagnus angustifolia*. – Journal of Desert Research **26** (1): 146-151 (in Chinese with English abstract)

Zhao, J.Y. 2012: Studies on several physiological indexes of the drought resistance of nine species of Gardening trees and comprehensive evaluation. – Dissertation, Linfen, Shanxi Normal University, Xi'an, China (in Chinese with English abstract)

Zwieniecki, M.A. and *N.M. Holbrook* 1998: Diurnal variation in xylem hydraulic conductivity in white ash (*Fraxinus americana* L.), red maple (*Acer rubrum* L.) and red spruce (*Picea rubens* Sarg.). – Plant, Cell & Environment **21** (11): 1173-1180, doi:10.1046/j.1365-3040.1998.00342.x