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RESEARCH ARTICLE

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Evaluation of the sap flow using heat pulse method to determine transpiration of the *Populus euphratica* canopy

Abstract The sap flow of the sampled *Populus euphratica* stems at different radial depths and directions had been studied in Ejina Oasis, in the lower reaches of the Heihe River. Based on sap flow measurements, the transpiration of the entire canopy was calculated. Results showed a linear correlation between the sap flow and the sapwood area of the *P. euphratica*. Through the analysis of the diameter at breast height in the sample plot, it was found that the distribution of the diameters and the corresponding sapwood area was exponentially correlated, with the coefficient of correlation being 0.976,7. The calculated transpiration of the *Populus euphratica* canopy was 214.9 mm based on the specific conductivity method.

Keywords *Populus euphratica*, sap flow, transpiration of the canopy

1 Introduction

In nature, sap flow controls the transpiration of the crown canopy in the soil-plant-atmosphere continuum. Because plant water consumption is a critical process in the water cycle of the soil-plant system, it is essential to have scientific understanding of the transpiration of the canopy for planning water resources and evaluating water demand. Two types of approaches have been developed to evaluate the quantity of water transpired by a plant canopy. The first type is based on direct canopy transpiration measurement such as the micrometeorological method. The disadvantage of this method is that it is hard to estimate the actual canopy transpiration for the forest evapotranspiration consists of the transpiration of herbs and shrubs and soil surface evaporation. The second type of approach is sap flow measurements, which extrapolate measurements of water use by individual stems to determine the transpiration of a canopy.

How is the flow from a stem sample extrapolated to the transpiration of the entire canopy? It is difficult. Several methods have been developed by previous research. Ladefoged (1963) evaluated the transpiration of the canopy by defining a relationship between sap flow and crown diameter but he found insignificant correlation between them. Cermark and Kucera (1987) estimated the transpiration of the canopy by establishing a relationship between sap flow and surface area. However, no obvious correlation was found (Denmead, 1984). Werk et al. (1988) also failed to find a significant correlation between sap flow and leaf area. Hatton and Vetessy (1990) calculated the transpiration of the canopy from the relationship between sap flow and surface area of the sampled individual stems, and the results were concordant with those measured by micrometeorological method. A reliable result was obtained by Grier and Running (1997) by defining a relationship between sap flow and sapwood area. Hatton and Wu (1995) suggested that the xylem transfusion cross-sectional area, leaf area, diameter at the breast height (DBH) and the surface area occupied by individual stems are all ideological spatial derived scalars. Of these, the leaf area is the most reliable variable for the extrapolation of the flow from the individual stems to the entire canopy. Furthermore, they put forward a non-linear theoretical model to express the relationship between the sap flow and the leaf area. They further derived a scalar, the DBH that can be precisely determined compared with the leaf area and the sapwood area. Moreover, better correlation between the DBH and transpiration was found. Therefore, according to Hatton, there are linear correlation between sapwood area and transpiration as well as between the DBH and transpiration. Little relevant research has been done in China. Ma et al. (2001) studied the sap flow measurement method and calculated the transpirations of the *Pinus tabulaeformis* canopy and *Robinia pseudoacacia* canopy. Zhai et al. (2004) estimated the transpiration of the mixed *Pinus tabulaeformis* and *Quercus varlablils* canopy using standard specific conductivity.

Based on the above discussion, this paper studies the relationship between *Populus euphratica* sap flow and sapwood

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area (the sapwood cross-sectional area at breast diameter position) in Ejina Oasis, which lies in the western Inner Mongolia of China. The objective is to identify the patterns of the correlation between the sap flow and sapwood area at various depths and directions. In the end, the transpiration of the *Populus euphratica* canopy is calculated using the specific conductivity of the sap flow.

2 Materials and methods

2.1 Site description

The experiments were carried out in a *Populus euphratica* Reserve in the Ejina Oasis, in the lower reaches of the Heihe River Basin from May to October, 2003. The geographical location is eastern longitude 101°14′ and northern latitude 42°01′. This area is 920.5 m above sea level. The climate belongs to the extremely arid regions with an annual average temperature of 8.2°C. Wind velocity is 4.7 m/s. The annual mean precipitation is 37.9 mm and the annual mean evaporation is 3,700 mm, which is approximately 100 times as much as the precipitation. With an aridity of 13.7, this area is one of the driest regions in China. It also is a typical desert area in western Inner Mongolia.

An experiment plot with an area of 30 m × 20 m was selected in the center of the *P. euphratica* forest reserve with a plant density of 1,500 plants per hm^2 and a plant age of 25-years old. The average diameter at breast height (DBH) was 20 cm, the mean height was 6 m and the average crown canopy was 2 m × 2 m in the experiment plot. Based on the principle of no-shading on the crown canopy, two typical trees were chosen as the reference plants and were termed as Reference A plant and Reference B plant, respectively. The Reference A plant had DBH of 21 cm, height of 5.2 m and crown canopy of 2.3 m × 2.3 m while the Reference B plant had DBH of 15 cm, height of 4.8 m and crown canopy of 2 m × 2 m. The criteria for selecting the reference plants were well-growing, erect trunk, appropriate crown diameter, slick bark and no insect infection.

The *P. euphratica* canopy in the nature reserve had an average height of 10 m, mean breast DBH of 12 cm, plant density of 1,500 plants per hm^2, 25-years old and canopy coverage of 0.8. It is classified as young aged trees. There were few *Tamarix* spp. and *Sophana alopecuroides* shrubs under the *P. euphratica* trees. In this area, the soil is called *P. euphratica* soil with an organic matter content of 0.724% in the depths of 0–30 cm, and 0.127% in the depths of 30–200 cm. Groundwater table was generally shallow with the depths fluctuating between 1.5–3.5 m during the observation period. There was no river flooding during the experimental period.

2.2 Methods

The water consumption of the individual stems was estimated using the sap flow measurement based on the heat pulse described in the literature (Walker et al., 1989). The sap flows of four *P. euphratica* trees with different DBHs (12.7, 12.4, 15.9 and 20.9 cm, respectively) had been monitored from June 13 to 19, 2003. From July 11 to 23, 2003, the sap flows in four directions (east, north, west and south) had been measured for the selected Reference B plant. From August 11 to 25, 2003, the sap flows of the Reference B plant in different radial depths had been recorded. For long-term information, a tree was selected to monitor its sap flow for ten days each month from May to October.

A reconnaissance of the forest in the experiment site was carried out. The height, DBH, age and the surrounding conditions of every tree were measured and recorded. Sapwood area was measured at the height of 1.3 m using vegetative cones. The *P. euphratica* has a distinguished white sapwood and brown heartwood so it was easy to measure the sapwood area.

Climate parameters of the microenvironment had been monitored simultaneously using the field automatic facilities made by the Australian ICT Company.

3 Results and discussion

3.1 Sap flow measurements of the sampled individual stems

3.1.1 Variations of the sap flow at different radial depths

The transfusion of sap flow mainly takes place in the xylem, of which 98% occur in the sapwood area, which is 40–60 mm below the cambium (Liu et al., 1993). The radial distribution of the sap flow is one of the important subjects in the study of plant physiology. According to the research of Philips et al. (1996), the sap flow in conifers such as *Pinus telda* L. mainly occurs in the layer extending from cambium to about 40 mm below the cambium; the width of the heartwood consists of 7–10 years growth rings which started from the pith. The reconnaissance found that the age of the *P. euphratica* was around 25 years and the width of the sapwood was 30–50 mm in the experiment site. In order to measure the sap flow at different radial depths of a stem, the Reference A plant with sapwood width of 22 mm had been monitored for 12 days from August 12 to 23. The observation depths were 5, 10, 15 and 20 mm.

Figure 1 showed the observed variations of the sap flow in the *P. euphratica* at different radial depths. It was found that the sap flow rates in the xylem at different radial depths demonstrated significant variations but the variation patterns were similar. Starting from the xylem the sap flow rates increased with increasing depth and reached the maximum value at 15 mm; then it started to decrease with increasing depth. The nearer to the cambium, the earlier the sap flow started and the decrease in sap flow showed a time lag at night. Therefore, the maximum sap flow rate of the *P. euphratica* occurred at 15 mm depth below the cambium.

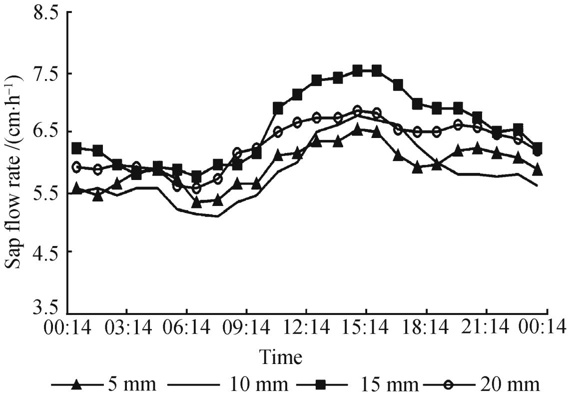

Fig. 1 The daily changes of mean sapflow of *P. euphratica* at different depths

3.1.2 Variations of the sap flow in different directions

The sap flows were measured in four directions (east, west, south and north) at the same radial depth of 15 mm. The results found that the sap flows at the same depths but different directions showed comparatively large variations. The vacations could be classified into two groups and there were significant differences between groups (Fig. 2). The sap flow rates in south and west directions were explicitly higher than that in north and east directions. However, the sap flow rates within the groups showed little differences. The sap flow in the south started in the early morning but it soon decreased in the early time of a day. There was a time lag of the sap flow decreasing point in the west compared with that in south. The daily variations of sap flow in the north and east almost followed the same pattern. The variations of the sap flow in the different directions could be caused by the sunshine because the direct point of the sunshine always lies in the south of a stem, and the uneven distribution of the crown canopy as the canopy of individual stems is usually larger in the south than that in the north. These results also proved that the movement of the sap flow in a stem is upward following a straight line. Therefore, to accurately estimate the sap flow of a stem, sap flow measurements should be conducted in two directions, which are north-east and south-west.

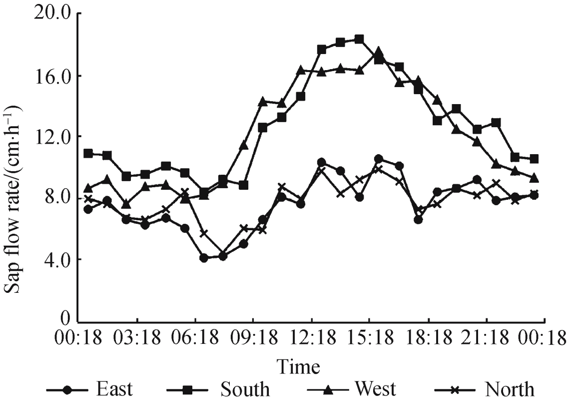

Fig. 2 The daily changes of stem sap flow of *P. euphratica* in different directions

3.1.3 Daily sap flow of individual stems with different DBHs

Table 1 showed the sap flow rates of the trees with different DBHs (June 10 to 15). Four *P. euphratica* trees were chosen for measurements. Their DBHs were 12.7, 14.3, 15.9 and 23.9 cm with the sapwood areas of 61.39, 82.24, 89.68 and 232.39 cm^2, respectively. The corresponding measured daily accumulated quantity of the sap flow were 7.62, 11.95, 11.41 and 32.78 L, the sap flow rates were 5.21, 6.08, 5.26 and 6.21 cm/h, and the sap flow fluxes were 0.32, 0.50, 0.47 and 1.42 L/h, respectively. Standard specific conductivity was used as a scalar in order to compare the sap flow of the trees with different DBHs (Ma et al., 2001). The specific conductivity indicates the mean water consumption of the unit sapwood cross-sectional area of the sample tree per unit of time at the breast diameter height in given period. The water consumption of the specific conductivity can be expressed as volume (L) or water depth (mm); the latter could be obtained through the conversion of the nutrition area of a sampled stem. The measured daily specific conductivities of the four selected trees were 0.13, 0.15, 0.13 and 0.14 L/(d·cm^2), indicating no significant differences among them. This result revealed that the specific conductivity of a canopy represented the external impacts on the entire canopy and there were little differences in terms of the individual stems.

3.1.4 Monthly variations of the sap flow

Both the monthly average sap flow and the daily accumulated sap flow in different months were found (Figs. 3 and 4). From June to September, the daily variation of the sap flow showed

Table 1 The sap flow rates of the selected trees with different DBHs

DBH /cm	Tree height /m	Xylem diameter /cm	Heartwood diameter /cm	Sapwood area /cm^2	Sap flow rate /(cm·h^{-1})	Sap flow flux /(L·h^{-1})	Daily accumulated sap flow flux /(L·d^{-1})
12.7	9.0	10.7	6.2	61.39	5.21	0.32	7.62
14.3	9.8	12.4	7.1	82.24	6.08	0.50	11.95
15.9	10.5	12.9	7.4	89.68	5.26	0.47	11.41
23.9	13.0	20.3	10.8	231.39	6.21	1.42	32.78

a unimodal curve with the peak flow occurring around at 15:00 (local time); the sap flow started at 6:00 and stopped at 21:00. The daily change of the sap flow in April, May and October had small irregular fluctuation but the sap flow in daytime was generally higher than that in nighttime. It had been observed that a small amount of the sap flow happened during the night (from 21:00 to 6:00 of the next day). Active water moves in plant pressurized by the root in order to compensate for the water deficit caused by transpiration during the day and to recover the water balance in the plant. Therefore, if a plant suffered severe water stress, the sap flow of the plant during the night would move fast and last for a relatively long time. In terms of the sap flow variations in different months, July had the largest sap flow velocity and daily accumulated sap flow, followed by June, September and May. April and October had very small sap flow rate and the accumulated daily sap flow, was generally less than 9 L/d. In October, due to the decrease in air temperature, total solar radiation and sunshine hour, particularly the shortage of water, there was no significant peak flow. Moreover, the sap flow showed a discontinuous change. It was caused by the broken water pass and cavitation owing to severe water stress (Li et al., 2002).

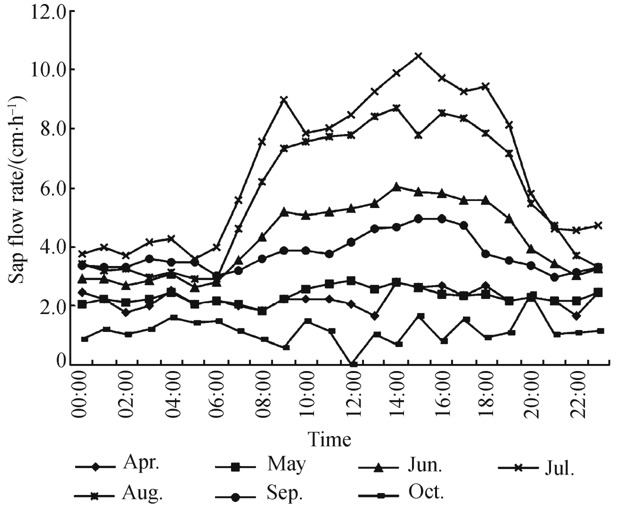

Fig. 3 Monthly variations of the sap flow rate

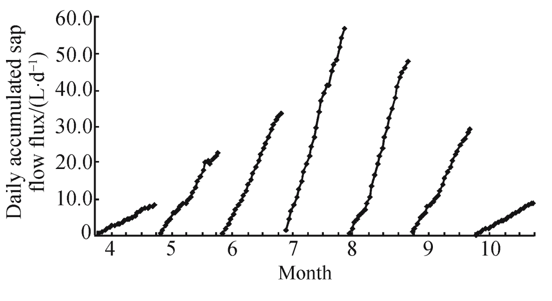

Fig. 4 Variations of daily average accumulated sap flow in different months

3.2 Calculation of the transpiration of the *P. euphratica* canopy

3.2.1 The relationship between the DBH and the sapwood area

According to the sap flow determination principle of the heat pulse method, the sapwood area of individual stems plays a role water transfusion tissue so the size of the sapwood area directly influences the magnitude of the plant hydraulic conductivity. The relationship between the sapwood area and water consumption is positive. Based on the mass balance theory, the same quantity of water should be transported by all the processes in a plant if the plant, from its roots to branches, was considered as a unified equilibrium system. Therefore, the transpiration of the entire canopy could be calculated through defining a relationship between the measured sap flow and the sapwood area. Because of the heterogeneity of plant development, there are great variations in the sapwood areas of individual stems. It is necessary to estimate the distribution of the sapwood areas in the canopy and to define a relationship between a common indicator such as DBH and the sapwood area before the transpiration of the canopy is calculated. The reconnaissance collected data of the sapwood areas, heartwood areas, DBH and the ages of the every tree in the experiment site. Statistic analysis had been conducted using Excel spreadsheet and the best fit models including the linear model, the exponential model, power model and multinomial model had been tested. It was found that there was a relatively high correlation between the sapwood area and the DBH ($R^2 = 0.904$, $n = 18$). This result was in good agreement with the model given by Hatton (Hatton and Wu, 1995). Figure 5 and Table 2 showed the relationship between these two morphological indicators.

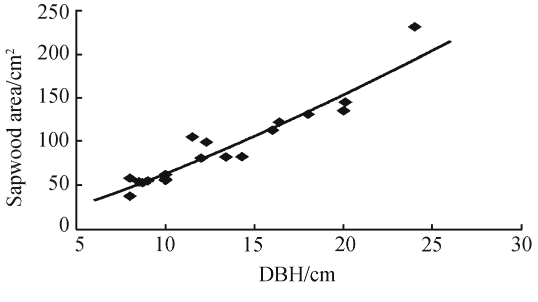

Fig. 5 Relationship between DBH and sapflow area of *P. euphratica*

Before understanding the distribution pattern of the sapwood area in the canopy, it is necessary to find the distribution pattern of the DBHs. Based on the reconnaissance (Table 2), the DBHs in the canopy were mostly distributed in the range of 12–16 cm. The average value was 14.6 cm. A curve of the plants numbers against the DBHs, which are integralized by 2 cm, showed a normal distribution, in which the plants with 14 cm DBH were the most in number. The total sapwood area of the plants with 14 cm DBH was higher

Table 2 Sapwood area distribution in different classes of *P. euphratica* sampling stand

Diameter	Tree number class /cm	Sapwood area of standard trees /cm^2	Total sapwood area /cm^2
8	1	37.68	37.68
10	3	55.61	166.83
12	8	80.87	647.09
14	14	103.60	1450.68
16	6	112.76	676.54
18	4	165.04	660.15
20	2	160.14	320.28
22	1	130.97	130.97
24	1	235.3	235.3

than those in other diameters but the sapwood area of individual stems in this diameter was not the highest. Figure 6 showed the relationship between the DBH and the sapwood area in the corresponding diameters. They were exponential in function and the coefficient of the correlation is 0.976,7. The sapwood areas of individual stems did not always increase with the increase in DBH. The sapwood area would reach a maximum value at a certain age. Therefore, the trend of the sapwood area against the diameter should show an "S"-shaped curve in the whole life of a plant. The *P. euphratica* in the experiment site was comparatively young and it had not reached the highest growth stage yet.

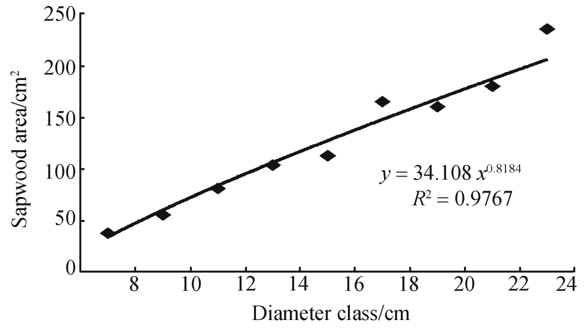

Fig. 6 Relation between diameter class and sapwood area distribution in *P. euphratica* sampling stands

3.2.2 Calculation of the transpiration of the canopy

According to the results of the reconnaissance, the sapwood area in the canopy could be calculated using following formula

$$y = 3.292,2x^{1.281,9}$$

The calculated result was 4,090.22 cm^2. This number multiplied by the monthly standard specific conductivity of *P. euphratica* (Table 3) equaled the transpiration of the *P. euphratica* canopy in the experiment site.

For convenient comparison, the volumetric transpiration of the canopy was calculated using the monthly standard specific conductivity, which needed to be changed into water depth, and was based on the conversion between the nutrition area and the water depth. The monthly standard specific conductivity is an indicator representing the circumstance of the entire canopy so it would be influenced neither by environmental factors such as solar radiation, temperature, humidity and soil moisture content nor by the growth stage of individual stems. It was found from Table 3 that the transpiration of the *P. euphratica* canopy during the growing season was 190.32 m^3, which was 214.9 mm through the conversion of the nutrition area into water depth. This result was smaller than the 310.7 mm measured by Zhai et al. (2004), from the mixed *P. tabulaeformis* and *Q. variabilis* canopy in Beijing. This may be attributable to environmental differences (The precipitation in Beijing was 373.4 mm while in Ejina it was 16 mm during the studied period).

4 Conclusions

1) The sap flow of the *P. euphratica* mainly occurred in the xylem. The radial distribution of the sap flow in a stem was varied. Starting from the xylem, the sap flow rate increased with the increase in depth. It reached the maximum value at the 15 mm depth. Then it decreased with the increased depth. The nearer to the cambium, the earlier the sap flow started. The sap flow rate at night was small and there was a time lag. In general, the daily variations of the sap flow at different radial depths were similar.

2) The sap flow rates at different depths in the same direction varied significantly. Meanwhile, the sap flow rates at the same depth but in the different directions showed great heterogeneity. The sap flow rates in the south and west side of a stem were significant higher than those in the north and west. Their daily patterns were also different. In the south, the sap flow started in early morning and then reduced. The reduction point of the sap flow in the west was later than that in south. The daily patterns of the sap flow in the north and east were similar. The daily change of the sap flow of a *P. euphratica* stem was a linear upward movement.

3) The daily and monthly variations of the sap flow in a *P. euphratica* stem showed that the sap flow at daytime was a unimodal curve. The sap flow started explicitly at 6:00–7:00. It reached the peak at about 15:00. Then it started to decline and reached a comparative low level at 22:00. There small amount of the sap flow at nighttime is probably

Table 3 Monthly standard specific conductivity and transpiration of *P. euphratica* canopy during growing period

	April	May	June	July	August	September	October	April to October
Specific conductivity /(L·d^{-1}·cm^{-2})	0.039	0.095	0.176	0.258	0.387	0.260	0.110	0.210
Transpiration of the canopy /L	4,785.6	12,045.7	31,658.3	49,328.1	49,070.4	32,967.2	13,497.7	190,317.9

caused by the active compensation of the plant to the water deficit. In terms of the monthly sap flow variations, the sap flow in July was the highest. The substantial daily accumulated sap flow in July was also the highest. The sap flows in August, June, September and May were medium. Both the sap flow rate and the daily accumulated sap flow in April and October were the smallest, generally less than 9 L/d.

4) An exponential model was found to be the best fit to the curve of the DBH against the sapwood area in the *P. euphratica* canopy and the coefficient of correlation was 0.976,7.

5) The transpiration of the *P. euphratica* canopy was calculated based on the standard specific conductivity of the sample individual stems and the relationship between the DBH and the sapwood area. The calculated transpiration of the *P. euphratica* canopy during growing season was 214.9 mm.

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