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RESEARCH ARTICLE

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Change of trunk sap flow of *Ginkgo biloba* L. and its response to inhibiting transpiration treatment

Abstract For this paper, GREENSPAN sap flow system was used to monitor the dynamics of trunk sap flow of *Gingkgo biloba*. Results indicate that sap flow velocity is significantly different among different heights, depths, and directions of the trunk. Sap flow velocity at the upper position of the trunk is higher than that of the middle and lower position, but cumulative flux is not significantly different among the upper, middle and lower sections. Sap flow velocity at 10 mm reached the most and that at 20 mm the least. However, sap flow velocity at 5 mm and 15 mm was similar and was second among the four depths. Results also showed that sap flow velocity of the south was the highest, and that of the west was next. An Automatic Weather Station of HOBO was synchronously applied to measure these meteorological parameters, and the relationship between these parameters and the changes of trunk sap flow velocity were analyzed. We found that the change of sap flow velocity was a single-crest curve on clear days and multi-crest curve on cloudy and rainy days. In addition, it is also revealed that by stepwise regression analyses photosynthetical active radiation (PAR), temperature and wind speed are the main environmental factors affecting sap flow velocity. The efficient methods of reducing water transpiration of trees, including leaf pruning, overshadowing and antitranspirant spraying, were found by investigating the effects on inhibiting transpiration, which indicated that spraying of antitranspirants, leaf pruning and overshadowing could significantly reduce transpiration but the effects of leaf pruning and overshadowing were far better than that of antitranspirant spraying.

Keywords *Gingkgo biloba*, trunk sap flow, heat-pulse technique, transpiration

1 Introduction

In order to satisfy the urgent demand on afforestation for city development, shadow and ornamental trees were planted at any time instead of the traditional planting periods in spring and autumn. Because the transplanted trees have to endure a transplanting process, water balances have become a key factor in limiting their survival. Therefore, the study on the water transportation feature and water regulating techniques are of great importance. By measuring the sap flow velocity, the special feature of water transportation of trees can be understood clearly. This is very important to test the efficiency of techniques of inhibiting transpiration. In previous studies, sap flow rules have been investigated by heat pulse method in different tree species, including *Betula dahurica*, *Acer mono* (Li et al., 1998), *Populus popular* (Gao et al., 2001), *Populus euphratica* and *Tamarix* spp. (Zhang et al., 2003) and *Populus euphratica* (Si et al., 2004). However, the rule about trunk sap flow of *Gingkgo biloba* has not been reported.

The common ornamental tree species, *G. biloba*, was chosen as the material; its special features of water transporting were investigated by monitoring the dynamics of trunk sap flow both in time and space. The effects on water transporting were also studied by using inhibiting transpiration treatments such as leaf pruning, overshadowing and spraying of antitranspirants. For this paper, we want to provide a theoretical basis to study water control techniques in the process of large-scale tree transplanting.

2 Materials and methods

2.1 Study area

Our experiments were carried out at the Beijing Institute of Landscape and Garden, Beijing (39°92′N, 116°52′E). Its

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climate belongs to the semi-arid monsoon weather in a temperate zone, with a mean annual temperature between 11 and 12°C, the maximum temperature is between 38 and 40°C, the lowest temperature is about −14 to −20°C, mean annual rainfall ranges from 500 to 600 mm, most of the rainfall occurs in June and September, mean annual wind speed is 2.7 ms/s, mean annual evaporation quantity is 1,956.8 mm, mean annual total sunlight time is 2,554.8 h and mean annual frost-free day is from 190 to 195 days.

2.2 Plant materials

Four *G. biloba* trees for transplanting were used as samples. The 15-year-old samples with straight form, good canopy and no obvious scar were selected as materials. A thick layer of pine tree bark was placed around the trunk bases. Outside the base, *Poa pratensis* was planted and was sprayed twice a week. Therefore, the transplanted trees were able to grow under good conditions (Table 1). Three experiment sites were selected. The top site was at the base of the canopy (2.2 m above the ground). The middle site was at DBH (1.3 m above the ground) and the low site was at the trunk base (0.2 m above the level). The measuring depth of xylems was 10 mm below the cambium. The sap flow velocity of different depths was measured at 5, 10, 15 and 20 mm below the cambium at the southern trunk of the middle site. The sap flow velocities at different directions were measured from southern, northern, eastern and western directions at the 10 mm depth below the cambium of the middle site.

2.3 Methods

Sap flow changes are measured with GREENSPAN sap flow system made by CSIRO in Australia. One data-logger connects with four SF-300 separate probe sets, each with a heater probe and two sensor probes. The heater and sensor probe length is 90 and 80 mm respectively, and the diameter for both is 2 mm. We attached to the trunk with a template and drilling horizontally with a 2 mm drilling bit, then inserted probe sets wrapped with aluminum foil to avoid solar radiation and sealed it airtight with adhesive tape to prevent rain from entering. At a certain position of the sapwood, we connected a data-logger with probe sets and joined the 12 V electrical source, then connected the data-logger with a computer, and set the working parameters. The reading frequency was set at an interval of 20 min with pulse time of 1.6 s, and then other parameters including xylem radius, heartwood radius, wood volume factor and water volume factor were set. Finally, we used SAPPRO and SPACAL software to process the data and calculate the sap flow velocity, sap flow flux and cumulative sap flow flux.

Weather factors are measured with the HOBO weather station from American Onset Computer Corporation Company. The data are collected once every two minutes, and the average values were recorded every ten records. Many parameters, including air temperature at central position of the tree canopy (4 m from the ground level), air relative humidity, photosynthetic active radiation (PAR), wind direction, wind velocity and soil temperature and humidity located 20 cm below the soil surface, are synchronously measured. Data were analyzed by the BOXCAR Pro4 software.

Overshadowing treatment is carried out with monolayer black overshadowing net. Only 46.2% light can penetrate the net through the measuring done with an ST-85 automatic luminometer. We diluted the antitranspirants made by Beijing Institute of Landscape and Garden 20 times and sprayed the leaves of the whole tree. About 2/3 leaves of the canopy were pruned in the leaf pruning treatment.

All measurements were carried out from August to September in 2004. The data were analyzed with MICROSOFT EXCEL and SAS 8.0 software.

3 Results and analysis

3.1 Changes of sap flow at different positions of *G. biloba* trunk

3.1.1 Axial changes of sap flow in the trunk

There are different sap flow velocities in the xylem at different height positions (Fig. 1). Sap flow velocity at the upper position is higher than that at the lower position, and the difference between them is more significant in the daytime than that at night. This is probably due to the diameter and sapwood area at upper position is smaller than those at lower position in the trunk. Sap flow velocity at the upper position is higher than that at the lower position if the same quantity of water is transported through the cross-section. It can be found that the diameter of the xylem conduit was gradually narrowed from the lower position to upper position in the trunk by tree trunk anatomy. The higher the position, the smaller the diameter of the xylem conduit. The sap flow velocity at the upper position is therefore higher than that at lower position

Table 1 General information of the four sampled *G. biloba* trees

Tree ID	Diameter /cm	Height /m	Cambium radius /cm	Heartwood radius /cm	Sapwood area /cm^2	Wood volume factor	Water volume factor	Pulse length /s
1	15.5	8.9	7.5	5.1	94.95	0.27	0.5	1.6
2	14.7	8.4	7.0	4.8	81.51	0.27	0.5	1.6
3	16.1	9.6	7.7	5.3	97.97	0.27	0.5	1.6
4	15.9	8.7	7.6	5.4	89.80	0.27	0.5	1.6

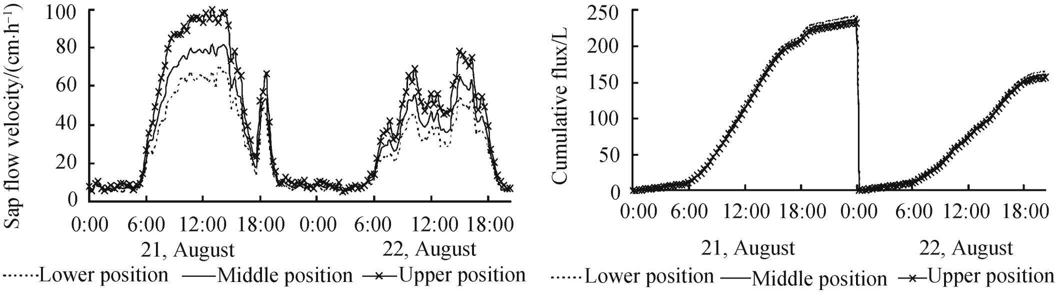

Fig. 1 Changes of sap flow velocity and cumulative flux at different positions of *G. biloba* trunk

if the same quantity of water is transported through the conduit at the same time. The differences of the cumulative sap flux among the upper, middle and lower positions are not significant (Fig. 1). The results show that the trunk is not the main part of evaporating water. The difference is probably relevant to hydraulic structure and water-holding feature of the tree (Goldstein et al., 1998).

3.1.2 Radial changes of sap flow in the trunk

The sap flow velocity changes of four measure positions were similar, but at the different depths were significantly different (Fig. 2). Among the four positions, sap flow of 10 mm position under the cambium was the fastest, and between 5 and 15 mm position under the cambium was similar, but sap flow of 20 mm position under the cambium was the least. The main reason may be that the structure heterogeneity of sapwood led to the difference of the hydraulic ability in different depth positions (Zimmermann, 1983).

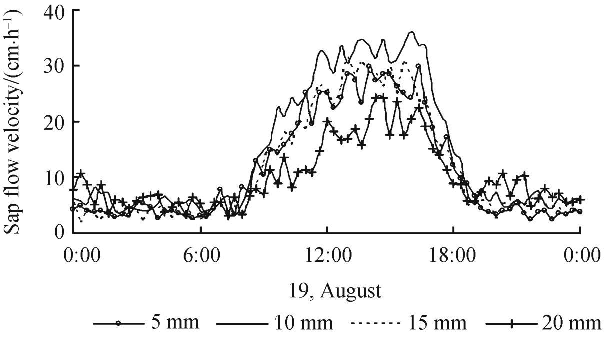

Fig. 2 Changes of sap flow velocity at different depths of *G. biloba* trunk

3.1.3 Changes of sap flow at different directions of *G. biloba* trunk

There was a similar trend of sap flow change among east, south, west and north directions. But change ranges of sap flow velocity at different directions had significant differences (Fig. 3). Among them, sap flow velocity at the south direction is the highest, and the differences, especially on a clear day, was more significant compared to other directions. The differences of sap flow velocity between the east and the west were not significant. Sap flow velocity at the north direction is the least.

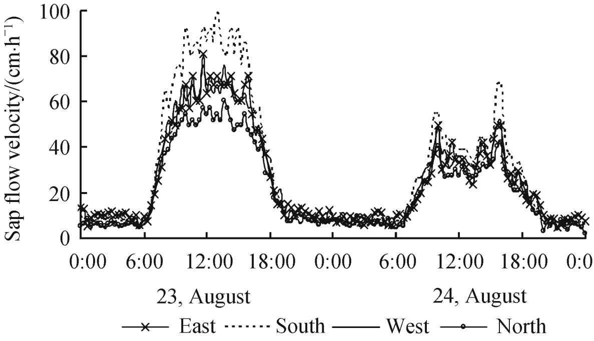

Fig. 3 Changes of sap flow velocity at different directions of *G. biloba* trunk

3.2 Changes of sap flow of *G. biloba* trunk under different weather conditions

3.2.1 Daily changes of sap flow velocity of *G. biloba* trunk

Change of sap flow velocity on a clear day (August, 1) was a quasi-single-crest curve (Fig. 4). There was less and steady sap flow velocity at night. Sap flow velocity began to increase sharply at 6:00, and increase in range became slow and gradually remained steady after 10:00, then decreased sharply at 15:30 and gradually became steady at a lower level after 19:30. Thus, the curve of sap flow velocity on a clear day had a trend of sharp increase and decrease. Change of sap flow velocity on a cloudy day (August, 10) was a multi-crest curve because the weather parameters including PAR and air temperature were unstable. Moreover, sap flow velocity on a cloudy day is lower than that on a clear day. Sap flow velocity on a rainy day (August, 12) was not significantly different between day and night because rain occurred in the daytime. From the above results, we concluded that there was a significant difference of sap flow velocity in *G. biloba* trunk under the different weather conditions.

3.2.2 Change of sap flow velocity in several consecutive days

Figure 5 shows the change characteristic of sap flow velocity between day and night at three different weather conditions

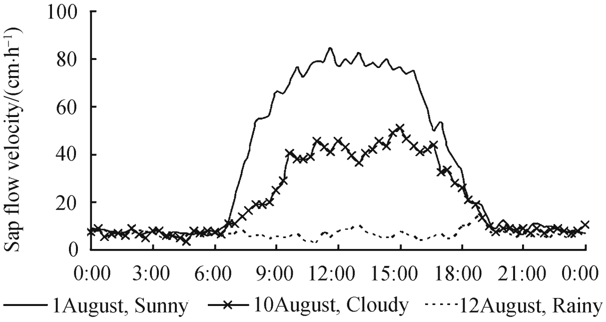

Fig. 4 Daily changes of sap flow velocity of *G. biloba* trunk under different weather conditions

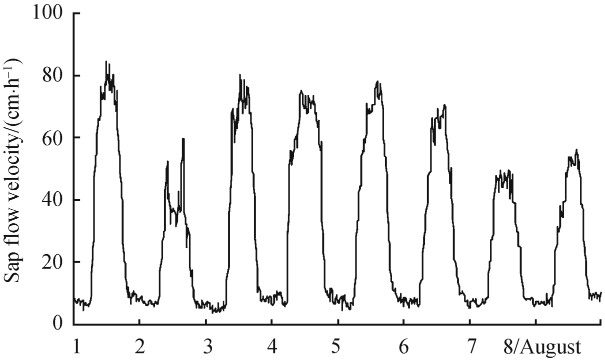

Fig. 5 Changes of sap flow velocity of *G. biloba* trunk from 1st to 8th August, 2004

(clear day, August 1, and August 3 to 6; rainy day, August 2; cloudy day, August 7 to 8). The results indicate that sap flow velocity in the daytime was higher than that at night among those days, and on a clear day was higher than the other days. In the daytime, sap flow velocity started to increase at about 6:00 and stopped decreasing at about 19:30 on clear days, but the velocity on cloudy and rainy days started to increase at about 6:30 and stopped decreasing at about 16:00. The results obviously show sap flow velocity on clear day starts to increase earlier and stops decreasing later than the other days. Sap flow velocity after the midday (August 2) was lower than that in other days because there was rain in the midday, which increased air relative humidity. It was also found that the sap flow velocity in the trunk at night was lower. The flow was not water transpiration by plant at night but because root pressure can drive the sap flow to move and supply the water evaporating in the daytime.

Figure 6 shows that there was a similar change trend between sap flow velocity and PAR on clear days, and the time of sap flow velocity starting to increase was almost as simultaneous as PAR. The reason was that PAR can control the stoma activity. The lower the PAR in the cloudy and rainy days was, the lower the sap flow velocity in the trunk is. Air temperature at 5:00 in the morning is the lowest and then starts increasing. The time the air temperature starts to increase was half an hour later than that of sap flow velocity increase, and the trunk sap flow reached the peak value at 15:00. Change trend between relative humidity and trunk sap flow is just contrary to that between air temperature and sap flow. The time, when trunk sap flow velocity reached the peak value, coincided with the time air temperature ascended the peak value and relative air humidity declining wave trough. The reason may be that PAR declined and the stoma opened again at this time, and the collective action resulted in the difference of vapor pressure between the inside and outside of the leaf, which is beneficial to water evaporation from leaves. All of those changes made the sap flow velocity higher. The result also showed that sap flow velocity did not decline when PAR started to decrease. Their differences resulted from non-synchronization between PAR and other parameters such as air temperature and air relative humidity.

From Fig. 6, we also found that wind speed was higher in the daytime and lower at night, which showed that it had some relationship with sap flow velocity, but the relationship between wind direction and sap flow needs further study.

Sap flow velocity had a lower value on rainy days. Sap flow declined sharply at the beginning of the rain and ascended sharply after the rain ended, and the curve had a larger wave trough during the rainy days (9 and 10, August). The main reason was that the gradient of vapor pressure between the inside and outside of the leaves reduced when the rain made air relative humidity increase.

3.2.3 Formulating estimate model of sap flow velocity of *G. biloba* trunk by stepwise regression analysis

Stepwise regression analysis is processed on sap flow velocities in three different weathers and environmental parameters including soil temperature (x_1), rainfall (x_2), wind speed (x_3), wind direction (x_4), soil water content (x_5), atmospheric pressure (x_6), air temperature (x_7), air relative humidity (x_8) and PAR (x_9). The results are shown in Table 2.

From Table 2, we can see that all correlation coefficients R of three equations were over 0.9 and coefficient of determinations R^2 over 0.8. Moreover, three equations could reach 0.01 significant levels. Therefore, we can conclude that PAR and air temperature can significantly affect the change of sap flow under the three weather conditions. On a cloudy day and rainy day, wind speed was also one of the main factors influencing sap flow, because wind can influence sap flow by blowing away water vapor outside the stoma and reducing boundary layer resistance. In addition, air relative humidity increased due to the rains, thus air relative humidity was another key factor affecting sap flow.

We compare the differences between calculated values based on stepwise regression equation and measured values at 12:00, from 1 to 16 in August (Table 3). The results showed that calculated values were in agreement with the measured values. The maximal relative error was 14.04% and the minimal relative error was only 0.04%, which indicates that it is possible to forecast the sap flow velocity by using stepwise regression equation.

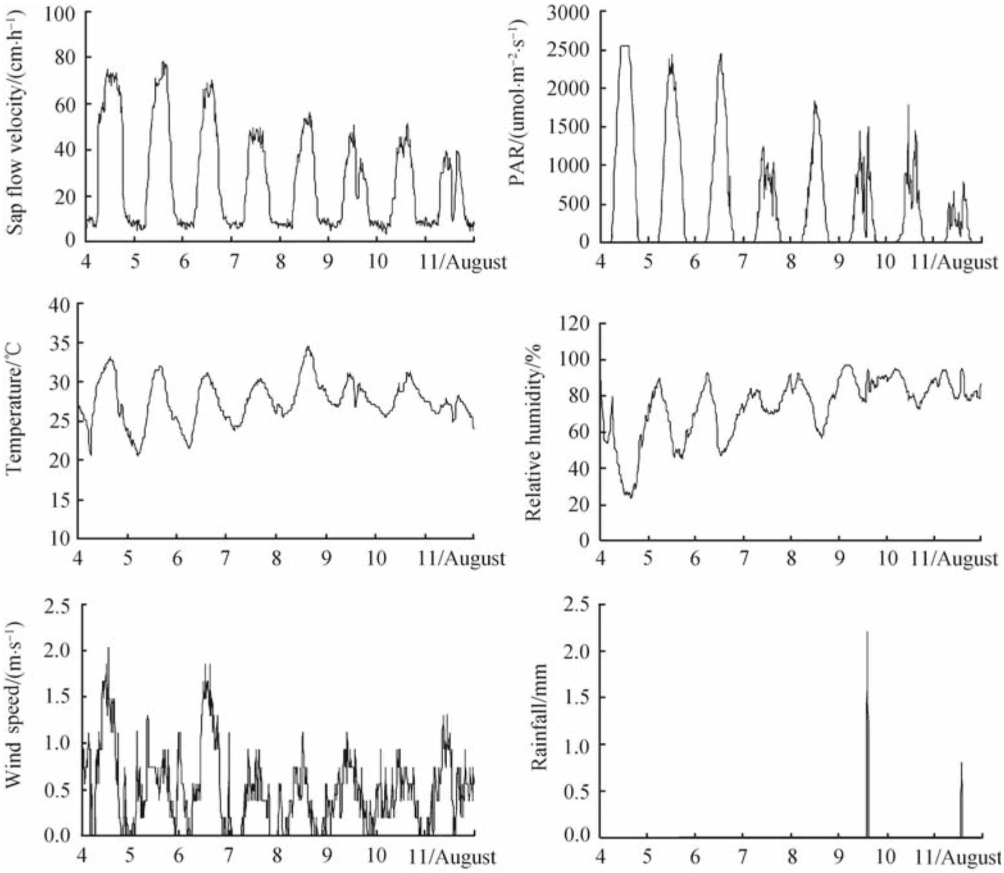

Fig. 6 Correlation between sap flow velocity and environmental factors including PAR, temperature, relative humidity, wind speed and rainfall during August 4 to11, 2004

Table 2 Stepwise regression analysis of sap flow velocity of *G. biloba* trunk and environmental factors

Weather	Sample	Stepwise regression equation	*R*	R^2	*F* value	Sig.
Clear	360	$y = -24.732 + 0.024{,}47x_9 + 1.469x_7$	0.964	0.930	2,365.561	0.000
Cloudy	288	$y = 47.835 + 0.013{,}7x_9 + 3.502x_7 - 4.812x_1 + 8.532x_3$	0.919	0.844	478.965	0.000
Rainy	360	$y = 30.089 + 0.025{,}31x_9 - 0.469x_8 + 0.833x_7 + 3.999x_3$	0.908	0.824	526.952	0.000

Table 3 Comparison between calculated values based on stepwise regression equation and measured values at 12:00, during August 1–16, 2004

Weather	Date	Measured	Calculated	Error /%	Weather	Date	Measured	Calculated	Error /%
Clear	08-01	80.094	80.507	0.516	Rainy	08-09	42.091	47.780	13.515
Rainy	08-02	37.374	35.775	–4.280	Cloudy	08-10	41.782	35.957	–13.942
Clear	08-03	70.200	72.892	3.834	Rainy	08-11	31.995	28.305	–11.535
Clear	08-04	77.673	84.062	8.223	Rainy	08-12	7.688	8.658	12.616
Clear	08-05	69.302	73109	5.493	Clear	08-13	47.483	51.374	8.195
Clear	080 6	72.302	78.614	8.730	Cloudy	08-14	30.918	30.022	–2.897
Cloudy	08-07	44.881	38.581	–14.036	Rainy	08-15	33.010	32.996	–0.042
Cloudy	08-08	53.619	57.875	7.938	Cloudy	08-16	49.889	54.669	9.581

3.3 Sap flow of *G. biloba* trunk responds to inhibiting transpiration treatment

Figure 7 shows that the differences were not significant before treatment, but sap flow velocity in the daytime obviously declined after inhibiting transpiration treatments at 10:00. Sap flow velocity in the daytime with overshadowing treatment obviously decreased and the maximum was about 1/3 of that before treatment. The value with leaf pruning treatment declines greatly and the maximum was about 1/2 of that before treatment. The value with spraying of antitranspirant treatment declined more than the other treatments, and the

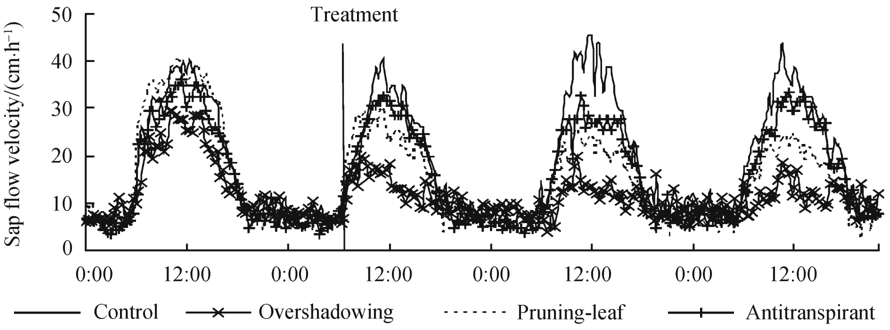

Fig. 7 Effect of different treatments of inhibiting transpiration on sap flow velocity of *G. biloba* trunk during 28th to 31st August 2004

maximum was about 10% of that before treatment. The results also showed that the differences of sap flow velocity changes were not significant at night. The main reason was that transpiration generally stopped and only the root pressure maintained water flow in the trunk at night.

The sap flow velocity was converted into cumulative flux and the results are shown in Table 4. The cumulative flux with different treatments including overshadowing, leaf pruning and antitranspirant spraying obviously declined. Compared with the control, the effects of the overshadowing and leaf pruning treatment were obvious, and the cumulative flux declined by 37.2% and 35.4% respectively. The cumulative flux with antitranspirant spraying treatment only reduced by 9.7%.

The differences of sap cumulative flux between treatments and control of the four sample trees were statistically analyzed by one-way analysis of variance (ANOVA) and LSD test (Table 4). The difference of sap cumulative flux between treatment and control was not significant at both 0.05 and 0.01 levels. Thus, it indicates that the experimental materials were very similar. After treatments, the difference of sap cumulative flux was significant at 0.05 level, and the difference of cumulative flux was significant at 0.01 level. However, the difference of sap cumulative flux between overshadowing and leaf pruning treatment was not significant. The results indicated that three inhibiting transpiration treatments can effectively decrease water transpiration, but the effect of overshadowing and leaf pruning treatment was more obviously significant than that of the spraying of antitranspirants.

4 Discussion

The position of water transportation mainly occurred in the xylem of the sapwood. Edwards and Booker (1984) studied the radial changes of hydraulic conductance using Toluidine blue dyeing method, and they concluded that there were significant differences of hydraulic conductance at different depth positions in the sapwood. Edwards (1996) put forward the conics theory between sap flow change and xylem depth. In our study, sap flow velocity in the xylem of *G. biloba* trunk could not gradually decrease at an increasing depth. The velocity at 10 mm depth position in the xylem was the greatest, and the difference between 5 mm depth position and 10 mm depth position was not obvious, and the result agreed with the study of *Pinus sylvestris* var. *mongolica* (Wu et al., 2003), but disagreed with the study of *Pinus tabulaeformis* (Sun et al., 2000), which was possibly due to the differences of sapwood structure among different tree species resulting in the differences of hydraulic ability in the xylem (Zimmermann, 1983).

There were significant differences of the sap flow velocity of the xylem at different directions. Sap flow velocity at the south was the most, and the least at the north. There are two reasons for this phenomenon. One is that xylem growth rate and conduit system development is higher at the south direction; the second is that the time of the sun's rays irradiating the south direction of the trunk is longer than that of the other directions.

Sap flow rise was not helical along the conduit (Gong et al., 2001). In our study, the difference of sap flow volume

Table 4 Effect of different means of inhibiting transpiration on cumulative flux and LSD test of average cumulative flux before and after treatment (treating at 10:00, on August 29, 2004)

Treatment	Cumulative flux /L							Decrease /%	ACFBT	ACFAT
	08-25	08-26	08-27	08-28	08-29	08-30	08-31			
Control	37.50	55.50	47.80	69.60	62.80	70.50	69.20		52.60 aA	67.50 aA
Overshadowing	30.30	40.40	35.70	50.90	36.90	33.40	32.70	37.20	39.33 aA	34.33 dC
Pruning-leaf	29.70	48.30	41.50	62.80	45.40	39.40	38.00	35.40	45.58 aA	40.93 cC
Antitranspirant	32.60	49.40	42.20	62.10	50.70	54.80	56.60	9.70	46.58 aA	54.03 bB

Reduced percentage = [1 − (Σbefore treatment/control)/(Σafter treatment/control)] × 100; ACFBT: average cumulative flux before treatment; ACFAT: average cumulative flux after treatment; small letters: differences significant at $\alpha = 0.05$ level; capital letters: differences significant at $\alpha = 0.01$ level.

and cumulative flux was not significant among upper, middle and lower positions. But the result was not similar with the data measured at *Pinus tabulaeformis* (Wang et al., 2003). The reason is may be that the upper position measured was at the base of the canopy, where the trunk was bare without branch and leaf. Thus, the tree trunk was not the main part of water transpiration.

Water transportation in plant is a complicated process, which is not only decided by the physiological characteristic (Gullo et al., 1992), but also related closely with environmental factors such as PAR, air temperature, air relative humidity, wind speed, soil water content, soil temperature and atmospheric pressure (Ding et al., 2004). The difference of daily change of sap low velocity in *G. biloba* trunk under clear, cloudy and rainy day was significant. The sap flow movement was earlier and the peak value reached the maximum on a clear day, and the change of daytime sap flow was a multi-peak curve on a cloudy day and had no clear rule. The velocity on a rainy day was lower and began later, then gradually descended after the peak value. The sap flow velocity change between day and night was also significant. The velocity in the daytime was more than that at night because leaf transpiration volume was larger and the transpiration tension was the main factor driving water to flow. The velocity at night was small but still existed because the root pressure can drive water to flow, which can supply water for plant transpiration in the daytime and maintained the water balance in plant body (Clark et al., 1957). By stepwise regression analysis, we found that PAR and air temperature were the key factors affecting the changes of sap flow velocity in the trunk under three weather conditions (clear, cloudy and rainy day). Wind speed was a main factor under cloudy and rainy days. Air relative humidity was also an important factor affecting flow velocity on a rainy day.

The imbalance of water can result in water stress in the course of tree transplant, which is an important factor limiting tree survival. The ability of water absorption of transplanted trees would be greatly reduced because of the heavy damage of the root system. It is pivotal to ensure tree survival by reducing water evaporation as much as possible. All treatments including leaf pruning, overshadowing and spraying of antitranspirants can effectively reduce water transpiration through the leaves. The effect of leaf pruning and overshadowing treatments was very obvious, reducing water transpiration by 1/3, but with higher cost and time consumption. Antitranspirant spraying can reduce water transpiration by only 10% but it can be easily applied. Therefore, to reduce water stress degree and improve the survival rate of transplanted tree, three inhabiting transpiration treatments should be synthetically used when tree is transplanted in the growing season.

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