Responses of Sap Flux Density to Changing Atmospheric Humidity in Three Common Street Tree Species in Bangkok, Thailand

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ABSTRACT

Efficient water management in urban landscape is imperative under the projected increases in drought stress under future climate. Because different tree species have different stomatal regulations to prevent water loss under water limitation, comparative study of species-specific responses of water use to changing weather conditions will benefit selective planting of urban trees for sustainable urban greening management. In this study, a simple and short-term investigation of water use characteristics of three common street tree species in Bangkok, a major city in Southeast Asia was performed. Species included *Pterocarpus indicus (Pi), Swietenia macrophylla (Sm)* and *Lagerstroemia speciosa (Ls).* Self-constructed heat dissipation probes were used to track water uptake rates, expressed as sap flux density (J_S), in stems of potted trees and to examine their diurnal variations with changing atmospheric humidity, represented by vapor pressure deficit (D). The results implied that two of the three species: *Pi* and *Sm*, may be selected for planting because their *Js* was less sensitive to changing D, compared to *Ls*. The sap flux density of *Ls* increased more rapidly with rising D, implying higher sensitivity to drought in *Ls*, compared to the other two species. Nevertheless, further study on large trees and under a longer period of investigation, covering both dry and wet seasons, is required to confirm this finding.

Keywords: Water use characteristics/ Sap flux density/ Vapor pressure deficit/ Urban trees
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1. INTRODUCTION

Urban trees mitigate negative environmental effects from urbanization, such as pollution, increased greenhouse gas emission, and urban heat island (Deloya, 1993). Trees of various species in urban areas provide ecosystem services including clean air, shade and cooling effects, and recreational and educational values (Akbari, 2002; Pataki et al., 2006). Different tree species, under the same environmental conditions, may require different amounts of water for growth (Dierick and Hölscher, 2009). Within the same area, trees that use less irrigated water for growth, compared to others, may be considered as ecosystem 'disservice' (Lyytimaki et al., 2008), leaving greater amount of unabsorbed water percolating into the soils. From the perspective of water conservation, urban trees with low water use may be preferred. However, the magnitude of water use rate alone may not indicate how trees perform under changing environmental conditions, especially the predicted increased drought stress.

In fact, how urban trees respond to changing climate is important in lieu of the projected climate change impacts including intensified storms and drought and changing precipitation pattern (Aitken et al., 2008). Trees that can withstand prolonged drought period should be selected for planting since they require less maintenance. Moreover, trees that use water conservatively throughout fluctuating weather conditions should be favored. Species with different wood structures, e.g., ring-, or diffuse-porous, possess different stomatal sensitivity to changing vapor pressure deficit and vulnerability to cavitation in xylem (Litvak et al., 2012). Disparities in hydraulic architectures and vulnerabilities to cavitation present different safety limit on transpiration among species (Tyree and Zimmermann, 2002), thus implying different strategies for coping with drought stress. Thus, investigation on water use characteristics of various urban tree species to select species with greater potential for sustainable urban greening management is needed.

With these regards, we investigated the water use characteristics of three common street tree species in Bangkok, Thailand which is a major city in Southeast Asia. The city experiences sunny and hot conditions during the dry period from December to April which may be exacerbated by the heat

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island effect from urban construction (Weng and Yang, 2004). Additionally, a recent study analyzing land use change in a sectional area in Bangkok showed that agricultural and green areas have decreased since 1984 and were predicted to decline in 2024 (Thanvisitthpon, 2016). A previous study was dedicated to inventory assessments of tree species in Bangkok (Thaiutsa et al., 2008). In addition, two studies examined water relations in some street trees. One addressed different water use strategies of three species differing in leaf phenology based on leaf measurements (Puangchit et al., 2014) while the other measured daily tree water use of four species of seedlings using direct measurement through gravimetric method (Kjelgren et al., 2008). Here, we applied a widely used technique of sap flow measurement based on heat dissipation between two points along the stem (Granier, 1985). This technique allows a continuous investigation of whole-tree water use at finer temporal resolution, such as diurnal timescale, where gravimetric or leaf-level measurements may not be practical. The instantaneous measurement of water uptake is useful because most ecosystem models incorporate stomatal dynamics which operate at fine timescale to determine plant responses to changing weather conditions (Bonan et al., 2014). Because vapor pressure decifit (D) has been shown as one of the main drivers for stomatal response in a wide range of tree species (Granier et al., 2000), we assessed changes of water use rate with variation of D. The main objective of this study was to compare water use responses to D at diurnal timescale among three common street tree species: *Pterocarpus indicus*, *Swietenia macrophylla*, and *Lagerstroemia speciosa*; hereafter, *Pi*, *Sm*, and *Ls*, respectively. According to Thaiutsa et al. (2008), the proportions of *Pi*, *Sm*, and *Ls* to the total number of street trees inventoried in Bangkok in 2001 were 41.9, 4.8 and 4.4 percent, respectively. The large difference between the proportions of *Pi* and the other two species was due to the much higher percentage of *Pi* street trees in Bangkok (see Table 3 in Thaiutsa et al., 2008). Another reason for choosing these species is because they have different leaf phenology and wood structure. The seasonality of leaf is facultative deciduous, evergreen and deciduous for *Pi*, *Sm* and *Ls*, respectively. The xylem arrangements of *Pi*, *Sm* and *Ls* are semi-ring-, diffuse- and ring-porous, respectively. Therefore, evaluating water use characteristics of the three species will provide insights into species-specific strategies to overcome drought stress, and hence the information for selective planting to achieve sustainable urban greening in the future.

2. METHODOLOGY

This study was conducted on the balcony of the 4th floor at the Department of Environmental Science building located in Chulalongkorn University in Bangkok, Thailand (13ºN 100ºE). The study period lasted one week, from December 13 to 19, 2015. We purchased 30 tree saplings of the three species and measured them to determine initial size (Table 1). Trees were originally grown in the same local field, harvested and potted into 20 L containers with mixed soil and bark growing medium. Potted trees were transported to the research site and irrigated with ~3 L water twice a day for four weeks to allow establishment of the trees prior to data collection. The same irrigation treatment was continued throughout the study period. Prior to each irrigation, soil moisture level was checked using a soil tester (Takemura Japan test instruments) to ensure that the trees were not under water limitation.

Thirty thermal dissipation probes (TDPs) were constructed. Each pair comprised two probes made of steel needles which were cut to 10 mm long for temperature sensing. Although this length of sensing part differs from the original design (20 mm; Granier, 1985), it was validated and used for sap flux measurements in some species (Clearwater et al., 1999; Catovsky et al., 2002; James et al., 2002). Each needle contained a T-type thermocouple (copper-constantan) whose tip was in the middle of the sensing part. The constantan ends of the two thermocouples were connected to each other and each of the copper ends was connected to data logger to measure the temperature difference between the two probes. Each pair of sensors was inserted into stem with ~10 cm vertical spacing to each other. The downstream (upper) probe was continuously heated at constant power while the upstream (lower) probe was unheated and thus tracking ambient temperature of sapwood as reference. The temperature difference between both probes was affected by the heat dissipation effect of water flow in the vicinity of the heated probe. The temperature difference data were collected in millivolts every 30 minutes by a data logger (CR1000, Campbell Scientific, Logan, UT, USA). Water mass per unit sapwood area per time, or sap flux density (*Js*), was then calculated from the detected changes in temperature difference as (Granier, 1985).

$$Js = 118.99 \times 10^{-6} \left(\frac{\Delta T_m - \Delta T}{\Delta T} \right)^{1.231} \quad (1)$$

Where Js is sap flux density in $g_{H2O}/m^2_{sapwood}$ S, ΔT_m represents maximum temperature difference established between the heated and non-heated probes at zero flux (i.e., Js=0) in °C and ΔT is temperature difference between the two probes at a given time. We used the Baseliner program version 3.0.7 (C-H_2O Ecology Group, Duke University, Durham, North Carolina, USA) to convert the voltage difference data to *Js* The program takes into account potential nocturnal fluxes resulting from nighttime transpiretion and water recharge in the stem by selecting the highest daily ΔT to represent ΔT_m The criteria for selection were conditions when (1) the average, minimum 2 h vapor pressure deficit is < 0.05 kPa, therefore ensuring transpiration is negligible, and (2) the standard deviation of the four highest values is < 0.5% of the mean of these values, thus assuring water recharge above the sensor height is negligible (Oishi et al., 2008). Each TDP was installed at 10 mm depth from the inner bark of each tree and covered by a plastic sheet coated with reflective paint to prevent the natural thermal gradient. Because the stem sizes were small, radial variation of *Js* should be minimal and only one depth of sensor was sufficient. Furthermore, we assumed that the non-conductive part of the stem was negligible due to small tree size and that stem cross-sectional area was equal to sapwood area.

Vapor pressure deficit (D) was used to represent atmospheric demand and was the main focus of environmental response of *Js* in this study. We installed two portable temperature and humidity data loggers (OM-92, Omega Engineering, Stamford, CT, USA) to measure air temperature and relative humidity at the site. The data were averaged to 30-minute values. Then, D was calculated as the difference between saturated and actual vapor pressure. The saturated vapor pressure (SVP in Pa) is expressed as (Monteith and Unsworth, 1990).

$$SVP = 610.7\times10^{7.5T/(237.3+T)} \qquad (2)$$

$$D = \left(1-\frac{RH}{100}\right)\times SVP \qquad (3)$$

Where T and RH are air temperature (°C) and relative humidity (%), respectively.

We applied a t-test for comparison between *Js* of each species on low and high *D* days. We utilized regression analyses for the *Js* responses to D and an F-test for comparison of the response among species. Data analyses and visualization were conducted using MATLAB 7.12.0 R2011a (The MathWorks, Inc., Natick, Massachusetts, USA) and SigmaPlot 12.0 (Systat Software, Inc., San Jose, California, USA).

3. RESULTS AND DISCUSSION

Table 1 summarizes characteristics of the trees used in this study. Mean stem diameters at ~1 m above ground, i.e., approximately at sensor location, ranged from 2.72 to 3.34 cm among the three species with the coefficient of variation (CV) ranging from 9 to 22%. The relatively large range of CV values of tree size should not confound the comparison of *Js* because it measures the value of water mass per unit area of sapwood covered by the sensing part of the probe.

During the one-week period, half-hourly vapor pressure deficit (D) ranged from 0.24 to 3.24 kPa. Trees experienced sunny condition during daytime with no cloudy or rain events observed. First, we evaluated *Js* of all trees during two 24 h periods for high and low D days (Figure 1). Overall, the average half-hourly *Js* of all species followed the pattern of D on both days (compare Figure 1(a) and 1(c) for high D day, and Figure 1(b) and 1(d) for low D day). While average *Js* of *Ls* was significantly lower on the low D day ($p < 0.0001$), *Js* of *Pi* and *Sm* remained similarly low compared to that on the high D day (compare Figure 1(a) and 1(b); $p \geq 0.18$).

Table 1. Characteristics of the trees

Species	H (m)	d (cm)	A_S (cm^2)	n
Pterocarpus indicus (*Pi*)	2.86 ± 0.18	2.72 ± 0.59	6.04 ± 2.93	9
Swietenia macrophylla (*Sm*)	2.86 ± 0.22	3.34 ± 0.32	8.83 ± 1.67	10
Lagerstroemia speciosa (*Ls*)	2.77 ± 0.17	3.13 ± 0.39	7.80 ± 1.91	10

*H = tree height measured from the bottom of the pot to the tree top; d = stem diameter at 1 m from the pot base; A_S = sapwood area at 1 m from the bottom of the pot i.e. sensor location; n = number of plants used in the study. All values are expressed as mean ± one standard deviation (SD).

Next, we examined variations of half-hourly *Js* relative to D of all species for the one-week period Figure 2. The response patterns corresponded well to diurnal *Js* under different D conditions (Figure 1) as previously described. Half-hourly *Js* of *Pi* and *Sm* (solid and dotted curves in Figure 2) were less sensitive to D, increasing at a slower rate at low D compared to the response of *Ls* (dashed curve in Figure 2; see Table 2 for regression statistics). Moreover, *Js* reached a saturation value which was higher in *Ls* compared to *Pi* and *Sm* (compare values at high D in Figure 2). The inset in Figure 2 shows the same fitting curves as in the main figure but with 95% confidence bounds. The inset indicates that water uptake rate of *Ls* was significantly greater than that of *Pi* and *Sm* across the wide range of D. Thus, when atmospheric demand increases, i.e., low humidity, high D, *Ls* uses a greater amount of water when compared to *Pi* and *Sm*. In other words, during a dry period, such as in the middle of the day, *Pi* and *Sm* use water more conservatively than *Ls*.

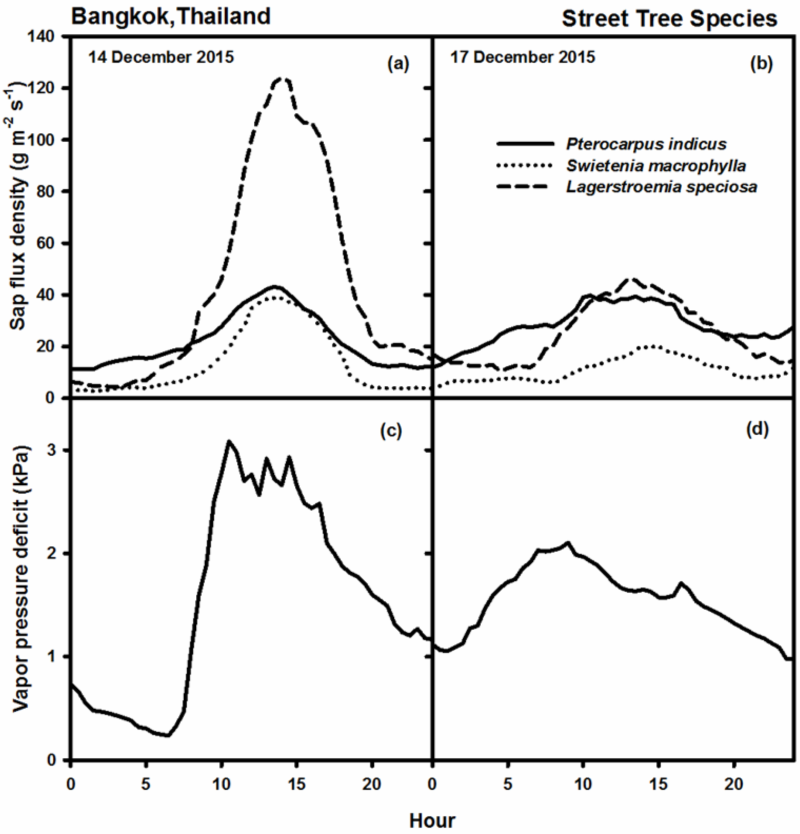

Figure 1. Diurnal patterns of sap flux density of all species during a high (a) and low (b) atmospheric demand days. Variation of vapor pressure deficit during a 24 h period ((c) and (d))

Table 2. Regression statistics of responses of sap flux density (*Js*) to vapor pressure deficit (D) in Figure 2

Species	*a*	*b*	r^2	*p*
Pterocarpus indicus (*Pi*)	35.84	0.55	0.22	<0.0001
Swietenia macrophylla (*Sm*)	23.06	0.66	0.25	<0.0001
Lagerstroemia speciosa (*Ls*)	49.96	1.12	0.18	0.0003

**a* and *b* are fitting parameters for the response of sap flux density (*Js*) to vapor pressure deficit (D). The function is $Js = a(1-e^{(-bD)})$, where a is the saturating *Js* at high D and b is the increasing rate of *Js* relative to increasing D.

Our findings, based on simple measurement and analyses of *Js*, agreed with results from the study using gravimetric method (Kjelgren et al., 2008) that observed high daily water use, i.e., the product of *Js* and sapwood area in Lagerstroemia loudonii, a similar species to *Ls*, and low and constant daily water use in *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*). They showed that these response patterns were consistent over cool and hot periods of mid and late dry season. Furthermore, ring-porous species, which is *Ls* in this study, exhibit greater sensitivity of transpiration to D compared to diffuse-porous species (Litvak et al., 2012), supporting our observed highest sensitivity of *Js* to D in *Ls*. Thus, our results implied that, at the same level of atmospheric humidity, *Ls* uses more water per unit sapwood area than *Pi* and *Sm*. With increasing transpirational demand and drought stress, water uptake rate of *Ls* increases faster than *Pi* and *Sm* and may risk hydraulic failure by exceeding the safety limit on transpiration.

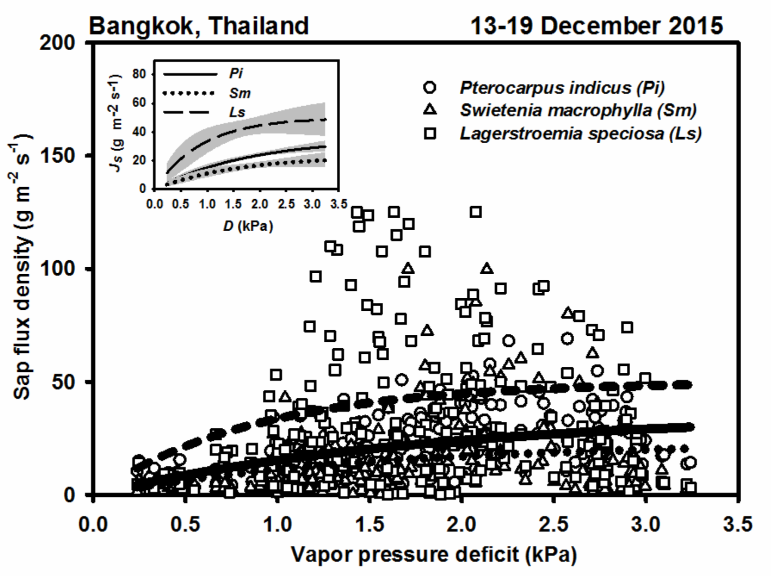

Figure 2. Responses of half-hourly sap flux density to changing transpirational demand, expressed as vapor pressure deficit, during the one-week period. Inset shows the same fitting functions as in the large figure with 95% confidence bounds. Regression statistics are presented in Table 2.

We note that our *Js* values were obtained from uncalibrated sensors. Equation (1), proposed by Granier (1985), has been widely used to compute *Js* across a wide range of species but shown to underestimate the water use rate directly measured from gravimetric method in some species (Bush et al., 2010; Sun et al., 2012). Therefore, sensor calibration is recommended to obtain a new equation when studying new species (Sun et al., 2012). However, our comparative study focused on the response patterns rather than the absolute values of water uptake rate. Thus, the lack of sensor calibration should not be greatly affected.

4. CONCLUSIONS

Our study revealed that *Pterocarpus indicus* and *Swietenia macrophylla* may be preferred under conditions of high transpirational demand, or during the dry period, which is usually experienced in urban areas with the heat island effect. This is because of their conservative water use characteristics relative to that of *Lagerstroemia speciosa* which is highly sensitive to changing atmospheric humidity. However, further study conducted on large, intact trees and under seasonal variations of atmospheric conditions is needed to confirm this finding. Additionally, other aspects may need to be concurrently considered since water use is also associated with other ecosystem services, such as, carbon sequestration and canopy size (for shades). Such ecosystem services are also of consideration when making decisions about tree planting in cities.

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