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Species-specific Responses of Water Use by Urban Trees to Artificial Soil Drought: Results from a Small-scale Study

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Abstract

Studying tree water relations in response to soil drought improves our understanding of hydrological processes that are central to most ecosystem modelling. Urban greening is an approach to ameliorate rising carbon dioxide emissions whose effects are intensified in cities. Thus, an investigation of water relations with respect to drought of urban trees is of interest for effective water management in urban greening. This study examined responses of sap flux density, water use and stomatal conductance of potted saplings of three common street trees in Bangkok: *Pterocarpus indicus* (*Pi*), *Swietenia macrophylla* (*Sm*) and *Lagerstroemia speciosa* (*Ls*); under one-week non-irrigated treatment. Results showed that *Pi* and *Sm* maintained their water use rate while *Ls* experienced reduction in water use under soil drying condition. Further analyses on stomatal conductance and leaf area suggested that leaf drop, which may be induced by soil drought, resulted in increases of stomatal conductance. The counteracting effect of increased stomatal conductance and decreased leaf area seems to explain the unaffected water use in *Pi* and *Sm* under drought conditions. However, a smaller compensatory effect was observed in *Ls*, resulting in significant reduction of water use in the non-irrigated saplings. Thus, these results indicate that *Pi* and *Sm* may be preferred for street tree planting since they would be less affected by drought stress than *Ls*. Nevertheless, further investigations, including detailed measurements of tree hydraulic variables and longer experimental duration, are advised to confirm these findings for extrapolation to a larger scale.

Keywords: *Pterocarpus indicus*; *Swietenia macrophylla*; *Lagerstroemia speciosa*; Sap flux density; Stomatal conductance; Drought

Introduction

Urban greening is increasingly used as a strategy for coping with climate change impacts in cities. Trees use carbon dioxide from the atmosphere for their growth, thus mitigating carbon emissions. Urban trees, whether in parks or along the streets, provide various ecosystem services, such as clean air, shade and cooling effects, recreational and educational values [1-2]. However, trees of various species have different water requirements and growth characteristics. Some tree species use more water than others, thus increasing the need for irrigation. Furthermore, under changing weather conditions such as drought, different tree species adopt different strategies to cope with stress conditions, even if they grow in the same area. Certain trees maintain their low transpiration rate throughout fluctuating weather conditions, while others may not survive a single drought. This latter case is of particular concern because drought impacts are exacerbated in urban areas due to the heat island effect [3]. Therefore, in lieu of the projected intensified drought [4], selective tree planting by choosing species that use water conservatively should be considered to achieve sustainable urban greening management.

Species-specific patterns of water use and responses to soil drying are areas of uncertainty in estimating transpiration, the major component of evapotranspiration in diverse ecosystems [5]. The uncertainty becomes aggravated with forests since it is difficult to directly measure entire canopy transpiration and stomatal conductance, the main variables for determining water and carbon fluxes in terrestrial ecosystem modelling. This issue has been addressed by using thermal methods for measuring sap flux density in stems of large trees. Such information is then used to estimate water use and canopy stomatal conductance. This technique allows researchers to examine tree water relations across multiple time and space scales. Quantifying water use and stomatal conductance and studying their responses to soil drought will thus offer better understanding of plant water relations, potentially leading to improved ecosystem modelling.

This study served as a pilot study to investigate the water relations of urban trees in Bangkok, Thailand. Two earlier studies had examined water relations in some street trees; one addressed different water use strategies among three species differing in leaf phenology based on leaf measurements [6] while the other measured the daily tree water use of four species of seedlings using direct measurement through the gravimetric method [7]. Nevertheless, a study of water relations involving sap flux density at finer timescale (*i.e.*, less than daily) and tree-level stomatal conductance is still lacking. In this study, three common street tree species [8]: *Pterocarpus indicus*, *Swietenia macrophylla* and *Lagerstroemia speciosa* (hereafter, *Pi*, *Sm* and *Ls*, respectively), were selected to investigate their responses to artificial soil drought during a one-week treatment. In particular, sap flux density was measured using the thermal dissipation technique [9] and scaled to whole-tree water use and stomatal conductance. Changes of these variables with soil drought were compared among the three species. The main research questions were (1) How would whole-tree water use and stomatal conductance of the non-irrigated trees differ from those under frequent irrigation? and (2) How does the difference in these variables between non-irrigated and irrigated trees vary with species? Based on previous findings relevant to water use [7], we hypothesized that *Pi* and *Sm* would maintain their water use patterns with minimal difference between the non-irrigated and irrigated trees after 7 days of treatment. Meanwhile, the non-irrigated *Ls* trees were hypothesized to experience reduction in water use compared to the irrigated trees. However, the responses of stomatal conductance were more difficult to discern.

Materials and Methods

This study was conducted on the balcony of the 4th floor in the Department of Environmental Science building located in Chulalongkorn University in Bangkok, Thailand (13 °N 100 °E). We purchased 30 saplings of the three species, each including 10 saplings with characteristics as summarized in Table 1. The saplings were originally grown in the same local field, harvested and potted into 20 L containers with mixed soil and bark growing medium. The potted saplings were transported to the study site and treated with frequent irrigation for five weeks to allow establishment of the trees prior to data collection. One *Pi* and one *Ls* sapling died before the experiment started. On December 19, 2015, each species was divided into two groups. One group of saplings continued to receive ~3 liters of water twice a day through pot watering (*i.e.,* irrigated group) while the other group received none (*i.e.,* non-irrigated group). Soil moisture level was checked by a soil tester (Takemura Japan test instruments) before each irrigation to ensure that the treated saplings were under well-watered condition (soil moisture level above 5 based on the scale from 1 to 8, indicating dry to wet conditions).

Thirty thermal dissipation sensors (TDPs) were constructed. Each pair comprised two probes made of steel needles which were the sensing part (*i.e.*, 10 mm long metallic parts of hypodermic needle). 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 measure the temperature difference between the two probes. The downstream (upper) probe was continuously heated at constant power while the downstream (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 (J_S), was then calculated from the detected changes in temperature difference as [9]

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

where J_S is sap flux density in $g_{H2O}\ m^{-2}{}_{sapwood}\ s^{-1}$, ΔT_m represents maximum temperature difference established between the heated and non-heated probes at zero flux (*i.e.*, $J_S = 0$) in °C and ΔT is temperature difference between the two probes at a given J_S.

Each TDP was installed at 10 mm depth from the inner bark of each tree sapling and covered by a plastic sheet coated with reflective paint to prevent the natural thermal gradient. Because the stem sizes were small, spatial variation of J_S 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 all stem cross-sectional area was equal to sapwood area. The whole-tree water use was estimated by integrating J_S across the entire sapwood area (A_S) of the tree. In other words,

$$E_t = J_S \times A_S \qquad (2)$$

where E_t represents whole-tree water use in $g_{H2O}\ s^{-1}$. The daily E_t was computed as the average of half-hourly E_t during the daytime, assuming from 0600 to 1800 hours.

Vapor pressure deficit (D) represents atmospheric demand and largely contributes to changes of stomatal conductance in plants. 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 [10]

$$SVP = 610.7\times10^{7.5T/(237.3+T)} \quad (3)$$

$$D = \left(1-\frac{RH}{100}\right)\times SVP \quad (4)$$

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

At the end of the experiment, total leaves from all saplings were harvested for leaf area (L) measurement. For each sapling, ten leaves were sampled for various sizes, scanned using a printer (LaserJet Pro MFP M125a) and analyzed with the ImageJ program [11]. Total number of leaves was counted and used to scale the scanned leaf area to total leaf area of each sapling.

Stomatal conductance (G_S) of the saplings was calculated from J_S using a simplified version of the Penman-Monteith equation [12]:

$$G_S = \frac{\gamma\lambda E_t}{\rho c_p DL} \quad (5)$$

where γ is the psychrometric constant (kPa K^{-1}), λ is the latent heat of vaporization (J kg^{-1}), ρ is the density of moist air (kg m^{-3}) and c_p is the heat capacity of moist air (J kg^{-1} K^{-1}).

This equation assumes that (1) J_S is uniform throughout the cross-sectional sapwood area, (2) stem capacitance may be neglected, and (3) canopy aerodynamic conductance is much larger than G_S. These conditions were held in this study because of small tree size with minimal variation in J_S across the sapwood area and stem capacitance which is usually evident in large trees. Moreover, because the saplings were potted and arranged in similar distance apart from one another, they should experience strong aerodynamic coupling.

Analyses of variables on the final treatment day were based on their ratios. The ratios were computed as daily mean values of E_t, G_S and L of the non-irrigated saplings to those of the irrigated ones. Statistical tests included t-test for comparisons between the two treatment groups. Data analyses and visualization were conducted using MATLAB 7.12.0 R2011a (The MathWorks, Inc., Natick, Massachusetts, USA) and Sigma Plot 12.0 (Systat Software, Inc., San Jose, California, USA).

Results and Discussion

Table 1 summarizes characteristics of the saplings used in this study. Mean stem diameters at ~1 m above ground, *i.e.,* approximately at TDP 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 mean sapwood area also varied with CV ranging from 19 to 49%. Such high CV values of tree size are not trivial and could indicate some variability of sap flow within species [13] which could confound the comparison of water use responses among these species. However, we confirmed that no intra-variability of sap flow existed within each of these species ($p \geq 0.23$) and thus tree-size effect should not impede further analyses. During the study period, vapor pressure deficit (D) at daily intervals ranged from 1.8 to 2.2 kPa, averaged 1.98 ± 0.18 kPa. The sunlight was mostly constant during daytime and no rain events were observed. Thus, the weather conditions were similar throughout the study period and should not confound the comparisons between the non-irrigated and irrigated groups of saplings.

Table 1 Characteristics of the tree saplings

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 speciose (*Ls*)	2.77 ± 0.17	3.13 ± 0.39	7.80 ± 1.91	9

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

We first evaluated the raw data without scaling, *i.e.,* sap flux density (J_S), of all trees during the first (Day 1) and the last (Day 7) day of the experimental period (Figure 1) which had similar D of 1.95 and 1.8 kPa, respectively. On Day 1, the diurnal J_S patterns were similar between the two groups in all species (p ranged 0.12 – 0.32; Fig. 1a, c, e) as this was the onset of the soil drought effect that would be imposed further. During Day 1, the effect from withholding water may not happen yet, especially in *Pi* (Fig. 1a), but there was some insignificant reduction in *Sm* and *Ls* during the afternoon periods in the non-irrigated groups (Fig. 1c, e). On Day 7, the J_S patterns were still similar between two groups in *Pi* and *Sm* (Fig. 1b, d; p = 0.17 and 0.26 for *Pi* and *Sm*, respectively) but significant reduction was seen in *Ls* (Fig. 1f; p = 0.02). Note that the high mean J_S of non-irrigated *Pi* group in the morning (Fig. 1b, open circles) was contributed by a few saplings that were located on the east side of the balcony and thus may be exposed to stronger sunlight than the other *Pi* saplings. Nevertheless, based on these observations, saplings with treated soil drought in the non-irrigated groups of *Pi* and *Sm* did not demonstrate J_S reduction and possibly maintained water use throughout the study period. In contrast, *Ls* saplings in the non-irrigated group experienced J_S reduction after 7 days of treatment. This result supported the hypothesis and agreed with the previous study [7] on similar species as mentioned in the Introduction.

On the last day of the experiment, water use, stomatal conductance and leaf dry mass were compared as the ratio between those under non-irrigated and irrigated treatments (Figure 2). The result showed that, after one-week of treatment, *Pi* and *Sm* saplings maintained similar levels of water use compared to the beginning of the experiment (p = 0.12 and 0.25) but *Ls* saplings in the non-irrigated group used 30% less water than the irrigated one (Figure 2, compare black bars). Thus, a similar result to the J_S patterns in Figure 1 was confirmed with the result from this water use analysis.

Whole-tree stomatal conductance (G_S) of the non-irrigated saplings significantly increased in all species ($p \leq 0.03$). The percentage of increases was smallest in *Ls* (26%) compared to the other two species (Figure 2, compare light gray bars). Conversely, leaf drop was observed in all species, with 16 – 31% decreases in leaf area among the three species (Figure 2, compare dark gray bars). The enhanced G_S in these species may be associated with leaf loss due to water withdrawal. Increased gas exchange rates with respect to defoliation have been commonly observed in many species [14-16]. Furthermore, transpiration per unit leaf area and stomatal conductance were found to increase with decreasing leaf area [16-18]. Such effect was attributed to microclimatic changes of the remaining foliage and increases of leaf specific hydraulic conductance [19-20] as stomatal conductance has been shown to increase with hydraulic conductance [21-22]. Another study demonstrated enhanced water relations of the remaining foliage after defoliation in *Populus tremuloides* [23]. They observed increased stomatal conductance in trees with 50 and 98% defoliation but no change in leaf water potential. In addition, they also addressed the compensatory photosynthesis following defoliation with increased stomatal conductance which may attribute to the increases in leaf specific hydraulic conductance. Based on these previous studies, it may be implied that soil drought induced leaf loss which resulted in enhanced stomatal conductance. The increased stomatal conductance may compensate for the reduced leaf area, leading to unaffected water use. These implications were clearly demonstrated in *Pi* and *Sm* but to a lesser extent in *Ls*. The smaller increase in stomatal conductance of *Ls* following leaf loss may contribute to significant reduction in water use after the one-week treatment. Nevertheless, this finding requires further investigation over a longer non-irrigation period to explore whether such a compensatory effect is sustained. Additionally, detailed measurements of tree hydraulics should be performed to confirm if increases in leaf hydraulic conductance plays a role in the enhanced water relations.

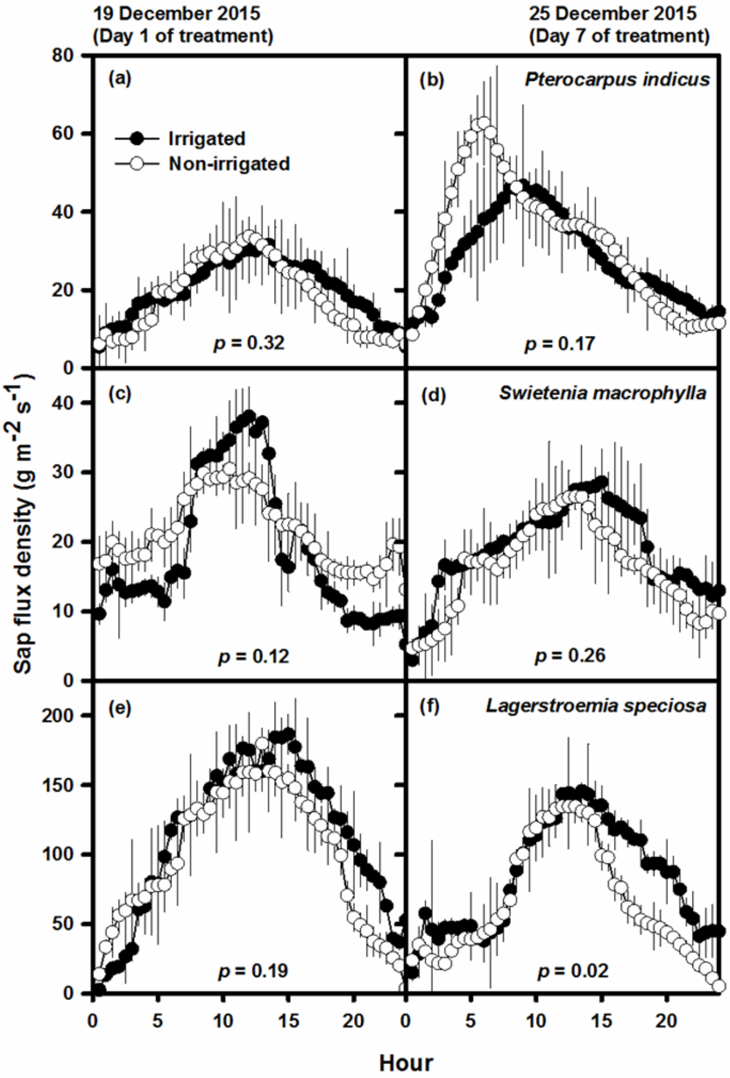

Figure 1 Comparisons of diurnal patterns of sap flux density between the non-irrigated and irrigated saplings in all species during the first and last day of the experiment.
P values indicate the t-test comparison between diurnal sap flux density of the two groups

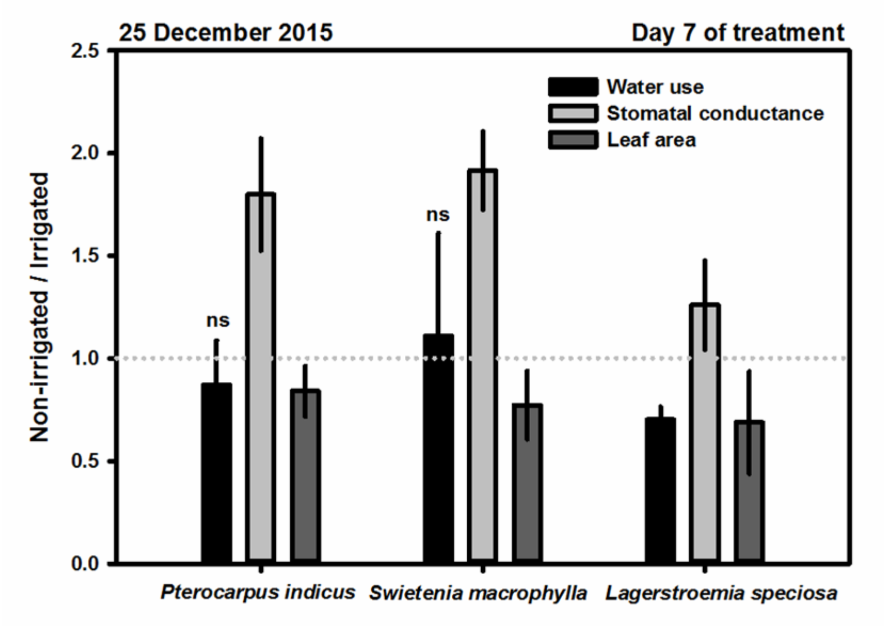

Figure 2 Ratios of daily water use, stomatal conductance and total leaf area between non-irrigated and irrigated saplings on the last day of the experiment. Error bars indicate one standard error of the ratios. "ns" refers to ratios that were not significantly different from one.

Conclusions

Species differences in water use and responses to soil drought are important for selective planting for sustainable urban greening. This small-scale study carries implications for water management in street tree planting in Bangkok. Specifically, based on the observations in this study, *Pterocarpus indicus* and *Swietenia macrophylla* may be favored because they maintain water use pattern even when receiving no water for one week. This may be due to compensation of increases in stomatal conductance for the drought-induced leaf loss. However, such compensatory effect was not evident in *Lagerstroemia speciosa*, leading to reduction in water use under drought stress.

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