รายงานวิจัยฉบับสมบูรณ์

โครงการค่าประสิทธิภาพการใช้น้ำของพันธุ์ไม้ริมถนนเพื่อการจัดการพื้นที่สีเขียวในเขตเมือง

โดย ดร.พันธนา ตอเงิน

2 เมษายน 2562

สัญญาเลขที่ MRG6080211

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ดร.พันธนา ตอเงิน
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย
(ความเห็นในรายงานนี้เป็นของผู้วิจัย
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Investigator : 1. ผู้ช่วยศาสตราจารย์ ดร.พันธนา ตอเงิน (ผู้วิจัยหลัก)
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
2. รองศาสตราจารย์ ดร.ลดาวัลย์ พวงจิตร (นักวิจัยที่ปรึกษาอาวุโส)
คณะวนศาสตร์ มหาวิทยาลัยเกษตรศาสตร์

E-mail Address : Pantana.t@chula.ac.th

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บทคัดย่อ

ต้นไม้ในเมืองให้บริการเชิงนิเวศหลายประการ แต่ยังขาดการศึกษาวิจัยมากเมื่อเทียบกับต้นไม้ในระบบนิเวศธรรมชาติ การศึกษาวิจัยเกี่ยวกับการตอบสนองเชิงสรีรวิทยานิเวศของต้นไม้หลากชนิดพันธุ์ต่อการเปลี่ยนแปลงของสภาพอากาศตามฤดูกาล รวมถึงสภาวะแล้งจะช่วยให้การจัดการป่าไม้ในเมืองมีประสิทธิภาพมากขึ้น โครงการนี้จึงมุ่งเน้นศึกษาลักษณะการใช้น้ำของพันธุ์ไม้ในเมืองที่นิยมปลูกริมถนนในกรุงเทพมหานคร และมีลักษณะการผลัดใบที่แตกต่างกัน ได้แก่ ประดู่บ้าน (*Pterocarpus indicus; Pi*) มะฮอกกานีใบใหญ่ (*Swietenia macrophylla; Sm*) และอินทนิลน้ำ (*Lagerstroemia speciosa; Ls*) โดยทำการศึกษาในไม้กระถางจำนวน 30 ต้น (ชนิดพันธุ์ละ 10 ต้น) ที่ได้รับการรดน้ำทุกวันเพื่อให้ความชื้นในดินในกระถางมีค่ามากกว่าหรือเท่ากับ 80% ของความจุความชื้นสนาม (field capacity; θ_{FC}) ทำการวัดอัตราการไหลของน้ำด้วยหัววัดแบบ Granier ที่ประดิษฐ์ขึ้นเอง ตั้งแต่วันที่ 23 สิงหาคม 2561 ถึงวันที่ 18 ธันวาคม 2561 ซึ่งครอบคลุมช่วงของฤดูฝนและฤดูแล้ง ในแต่ละฤดูมีการทดสอบสภาวะแล้ง โดยงดให้น้ำแก่ไม้กระถางชนิดละ 5 ต้น เพื่อให้ระดับความชื้นในดินลดลงถึงประมาณ 50% θ_{FC} จากนั้นจึงรดน้ำอีกครั้ง ผลการทดลองบ่งชี้ว่าลักษณะการใช้น้ำของพันธุ์ไม้กึ่งไม่ผลัดใบและไม่ผลัดใบ (*Pi* และ *Sm* ตามลำดับ) ไม่เปลี่ยนแปลงไปตามสภาพอากาศและความชื้นในดินที่เปลี่ยนไปตามฤดูกาลรวมถึงการทดสอบสภาวะแล้ง แต่พันธุ์ไม้ผลัดใบ (*Ls*) กลับเปลี่ยนแปลงไปตามการเปลี่ยนแปลงของสภาพอากาศและความชื้นในดิน โดยแสดงการปิดปากใบเร็วขึ้นเมื่อดินแห้งในฤดูแล้ง ผลที่ได้นี้แสดงว่าพันธุ์ไม้ไม่ผลัดใบมีการใช้น้ำอย่างประหยัด ไม่ว่าสภาพแวดล้อมในการเจริญเติบโตจะเปลี่ยนแปลง ในขณะที่การรดน้ำให้แก่พันธุ์ไม้ผลัดใบอาจทำให้สิ้นเปลืองน้ำ ในฤดูฝน เนื่องจากมีอัตราการใช้น้ำสูง อย่างไรก็ตาม อาจเลือกพันธุ์ไม้ต่างๆ ไม่ว่าจะผลัดใบหรือไม่ผลัดใบมาปลูกในเขตเมืองเพื่อเพิ่มพื้นที่สีเขียวได้ตลอดทั้งปี ทั้งนี้ ความรู้เกี่ยวกับลักษณะการใช้น้ำที่แตกต่างกันของพันธุ์ไม้ต่างชนิดจะช่วยให้สามารถบริหารจัดการน้ำเพื่อการบำรุงรักษาพื้นที่สีเขียวในเมืองได้อย่างมีประสิทธิภาพ

Abstract

Urban trees provide several ecosystem services, yet they are less studied compared to trees in natural ecosystems. Investigating ecophysiological responses of different tree species to seasonal conditions and drought will help determine which would succeed in urban conditions. Here, we examined water use characteristics of common species in Bangkok, Thailand: *Pterocarpus indicus* (*Pi*), *Swietenia macrophylla* (*Sm*) and *Lagerstroemia speciosa* (*Ls*), with different phenology, under seasonal variations and soil drying. Thirty small trees were potted and irrigated to ≥80% of the field capacity (θ_{FC}) of the soil. Granier-type sensors were used to measure sap flux density from 23 August to 18 December 2017. Drought treatments were imposed on five trees of each species by withholding irrigation until θ reached ~50% θ_{FC}. Results suggested that water use patterns of semi-evergreen and evergreen species (*Pi* and *Sm*) were not sensitive to either seasonal or soil moisture variations while deciduous species (*Ls*) exhibited decreased water use and earlier stomatal closure upon soil drying in the dry season. These findings suggested that water use characteristics of the evergreen species may conserve water use regardless of atmospheric and soil moisture conditions while those of the deciduous species may result in high cost for irrigation in the wet season. Nevertheless, we believe that both evergreen and deciduous species may be selected for planting to maximize greening areas in cities throughout the year. However, knowledge of different water use characteristics of street tree species should be applied to devise strategic planning for optimized irrigation in urban greening.

Keywords : Sap flux density; Urban trees; *Pterocarpus indicus*; *Swietenia macrophylla*; *Lagerstroemia speciosa*

เนื้อหางานวิจัย

Introduction

Urban trees provide several ecosystem services, such as mitigating rising atmospheric carbon dioxide concentration (CO_2), shading and cooling effects, reducing pollution, and other recreational and psychological benefits (Akbari 2002; Pataki et al. 2006; Bowler et al. 2010). Yet, the understanding and management of urban trees in cities are still less investigated compared to those of trees in natural ecosystems. Provided that urban areas usually involve adverse environmental conditions, such as high temperature, greater CO_2 and air pollution, and poor soil, future climate change may exert greater impacts on urban environments than rural ones. Therefore, selecting species that can withstand such negative impacts will retain the intended ecosystem services by urban trees and fully benefit city dwellers.

Logically, species selection for urban planting should consider matching between urban climate and native habitat of the species from an appropriate forest type. For example, cities in equatorial wet climates, such as Singapore, use tree species from equatorial wet evergreen forests, albeit, it is possible that a monsoonal dry forest species is often used in cities in wet tropical climates (Kjelgren et al. 2011). However, cities in monsoonal climates with pronounced dry seasons, such as Bangkok, Thailand, may benefit from planting tree species from tropical monsoonal dry forests which are adapted to prolonged low rainfall condition (Miles et al. 2006). Such species either avoid drought with deciduous leaf habit or tolerate drought with evergreen foliage (Santiago et al. 2004). Nevertheless, species selection in some cities, such as Bangkok, is dominated by their floral displays which mostly include deciduous species while evergreen species are commonly old and large trees in protected areas (Thaiutsa et al. 2008). Such unequal distribution of deciduous and evergreen species may not optimize the ecosystem services that were originally intended for planting these trees in the city.

Trees of various species may have different water-use characteristics which affect transpiration and cooling of temperatures in cities. Urban trees are frequently maintained by irrigation which may not be cost effective if the species do not require much water for growth. Furthermore, with intensified climate change impacts in cities, such as drought which may impact water supply, urban trees that are sensitive to dry air and soil may become stressed, perform poorly, or die. Because of such variable responses, understanding differences in ecophysiological responses among tropical trees to season and dry soil can aid in identifying and selecting which are best suited to urban conditions.

In this study, we conducted drought experiments across dry and wet seasons on potted common street tree species in Bangkok, Thailand, a major and highly polluted city in Southeast Asia. Three species: *Pterocarpus indicus*, *Swietenia macrophylla* and *Lagerstroemia speciosa*; hereafter, *Pi*, *Sm* and *Ls*, respectively, were selected based on their different leaf phenology, and their frequency in the city (Kjelgren et al. 2008; Thaiutsa et al. 2008). Phenological characteristics of *Pi*, *Sm* and *Ls* species are semi-evergreen, evergreen and deciduous, respectively (Kjelgren et al. 2008). 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. We investigated water use characteristics of the species by comparing diurnal variations of sap flux density and daily water use with vapor pressure deficit under different soil water regimes and seasons. Our objectives were (1) to compare water-use characteristics of common street tree species in Bangkok, with different leaf habits that may affect water consumption rates, under artificial soil drying across wet and dry seasons and (2) to analyze daily water use by these species under well-watered conditions, whose conditions are assumed to be common for maintenance of street trees. The findings will provide better understanding of how different tropical species in a monsoonal climate city react to environmental changes and help selecting species that can withstand adverse impacts from climate and environmental changes when expanding green areas in the city.

Materials and Methods

Settings

This study was conducted on the balcony of the 4th floor of the Department of Environmental Science building in Chulalongkorn University in Bangkok, Thailand (13°44'02.9" N 100°31'54.1" E). According to the 30-year record (1981-2010) of climatic data from a nearby Bangkok metropolis station (Thai Meteorological Department), mean annual air temperature was 28.6 °C and mean annual precipitation was 1648 mm. The weather in Bangkok is influenced by tropical monsoon climate with the wet season lasting from mid-May to October. The study period lasted from 23 August to 18 December 2017, covering parts of a wet and a dry season. Figure 1a shows the settings of this experiment. We purchased 10 small trees (stem diameter ranging approximately 2-3 cm, height ranging 2.5 – 3.2 m) per species from a local nursery and transported them to the site. The trees were potted in 20 L containers using soil substrate materials consisting of garden soil mixed with dried monkeypod leaves, husk, coconut husks and some manure with the proportion of 2:0.5:0.5:1. The growing medium was analyzed and identified as clay loam with bulk density of 0.74 g cm^{-3}. An automatic drip irrigation system was applied to supply 10 L water per tree at 16:00 (solar time) every 24 hours such that volumetric soil moisture (θ) was maintained at ≥80% of the field capacity (θ_{FC}).

Figure 1: Site establishments (a) settings of the studied potted trees and sap flux measurements (b) measurement setup of meteorological variables

Environmental measurements

Environmental variables were monitored continuously once the study site was established. An air temperature (T, °C) and relative humidity (RH, %) probe (HC2S3-L, Campbell Scientific, Logan UT, USA) and a quantum sensor (LI190R-L, LI-COR Biosciences, Lincoln NE, USA) measuring photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) were installed at ~2 m above the canopy. Figure 1b illustrates the setup of these measurements. Volumetric soil moisture (θ, m^3 m^{-3}) was continuously monitored with Time-Domain Reflectometry (TDR) probes (CS 616, Campbell Scientific, Logan UT, USA), with the factory calibration, in two pots per species (total is 6 probes) to track soil moisture in the irrigated trees and those under the drought experiment. All environmental sensors were connected to a data logger (CR1000, Campbell Scientific, Logan UT, USA) which logged data every 60 seconds and stored 30-minute averaged values. Evaporative demand was expressed as vapor pressure deficit (*D,* kPa), calculated as the difference between saturated and actual vapor pressure. The saturated vapor pressure (SVP, kPa) is expressed as (Monteith and Unsworth 1990)

$$\mathrm{SVP} = 0.611\times10^{7.5T/(237.3+T)} \tag{1}$$

$$D = \left(1 - \frac{RH}{100}\right) \times SVP \tag{2}$$

Field capacity (θ_{FC}) of the soil was determined by collecting three soil samples from three pots using a 25 cm^3 crucible. The samples were soaked with water in a beaker for 24 hours. Then, they were drained out for 2 hours before being weighed for wet mass. Next, the soil samples were dried in an oven at 110 °C until the mass was stable and obtained dry mass. The θ_{FC} was calculated as

$$\theta_{FC} = \frac{V_w}{V_c} \tag{3}$$

$$V_w = \frac{m_{wet} - m_{dry}}{\rho_w} \tag{4}$$

where V_w is the volume of water in the soil sample after drainage, V_c is the volume of the crucible which equals 25 cm^3, m_{wet} and m_{dry} are mass of wet and dry soil, respectively and ρ_w is specific gravity of water which is 1 g cm^{-3}. We used the average θ_{FC} of the three samples (0.54 ± 0.02 SD) to represent θ_{FC} of the soil in all pots and as a reference for the drought experiments.

Sap flux density measurement and calculation of daily tree water use

We used self-constructed, Granier-type thermal dissipation probes (TDPs, Granier 1985) for measuring sap flux density (J_S, g m^{-2} s^{-1}) of the trees. Each TDP pair consists of two probes made of steel needles cut into 10 mm length 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 many tree species (Clearwater et al. 1999; Catovsky et al. 2002; James et al. 2002). Each needle contained a T-type thermocouple (copper-constantan) whose tip has been in the middle of the steel needle. The constantan ends of the two thermocouples were connected to one another and each of the copper ends was connected to the data logger to measure temperature difference between the two probes. The downstream (upper) probe was continuously heated at constant power (~0.1 W) 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 heat dissipation effect of water flow in the vicinity of the heated probe. Data of the temperature difference were collected in millivolts every 60 seconds and stored as 30-minute averages by the same data logger as that connected to the environmental sensors. Water mass per unit sapwood area per time, or J_S, was then determined from the detected temperature difference as (Granier 1985)

$$J_s = 118.99 \times 10^{-6} \left(\frac{\Delta T_m - \Delta T}{\Delta T} \right)^{1.231} \quad (5)$$

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. We utilized the Baseliner program version 4.0 (Oishi et al. 2016) to convert the temperature difference data to J_S. The program considers potential nocturnal fluxes resulting from nighttime transpiration 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-hour vapor pressure deficit is <0.05 kPa, therefore ensuring transpiration is negligible, and (2) the standard deviation of the four highest ΔT 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 reflective cover to prevent the natural thermal gradient which may influence the measurements. Because the stem sizes were small (2.84 $\pm$ 0.33 cm), we assumed negligible spatial variation of J_S (Ford et al. 2004; Tateishi et al. 2008) and installed TDP at one depth into sapwood. As equation (5) was empirically obtained from the 20-mm length sensor design (Granier 1985), we note that the J_S values were estimated from uncalibrated sensors. However, the differences between sensor lengths are likely to be small and the comparisons are relative among treatments which would exert minimal effects on the analyses.

To explore daily water use, we scaled up the point measurement of J_S to tree-level transpiration. We assumed that the non-water 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 transpiration (E_{tree}; mm day^{-1}) was estimated by integrating J_S across the entire sapwood area (A_S, m^2) of the tree and summing over a day as follows.

$$E_{tree} = 1.8 \times A_S \times \sum_{t=1}^{48} J_S \tag{6}$$

where t is half-hourly point in time for one day. For inter-comparison of daily water use among the species, we applied a boundary line analysis (Schäfer et al. 2000; Ewers et al. 2001) to analyze variations of E_{tree} of irrigated trees to D, excluding potential confounding factors such as sunlight. Various studies showed that such response patterns followed a saturating exponential curve of the form (Ewers et al. 2001; Tor-ngern et al. 2017)

$$y = a(1 - e^{-bx}) \tag{7}$$

where y is E_{tree} under non-limiting soil water and sunlight conditions; $E_{tree,max}$ in mm day^{-1}, x is D in kPa. The a and b parameters represent saturating values of $E_{tree,max}$ and sensitivity of $E_{tree,max}$ to D, respectively.

Drought experiment

A drought experiment was performed during each season. The first drought experiment was during 23-30 October 2017, which was in the late wet season, and the second experiment in the dry season was during 27 November to 6 December 2017. We tested the effect of moderate water deficit rather than extreme drought, letting the soil dry to approximately 50% of θ_{FC}. For each species, trees were equally divided into two groups: (1) irrigated group in which the trees received continuous irrigation throughout the study period (hereafter, control) and (2) drought treated group in which the trees were not irrigated until soil moisture reached about 50% of θ_{FC} (hereafter, treated). In addition to withholding irrigation, we covered soil surface of the pots of the treated group with black plastic to prevent possible confounding water input from rainfall. Between each drought experiment, irrigation was resumed in the treated group once the defined drought condition was reached. For the analyses of responses to soil drying, we compared J_S values of the last day of each drought experiment (i.e. days when soil moisture reached 50% of θ_{FC}) to the average of 3 days with similar atmospheric conditions (PAR and *D*) prior to the experimental period.

Data analyses

We performed statistical tests including t-test for comparisons between control and treated groups, F-test for comparison between response patterns of the two groups, and regression analyses for the responses of daily water use to vapor pressure deficit. Calculations, 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).

Results and Discussion

Environmental conditions during the study period

During the study period, variations of light (expressed as PAR) and evaporative demand (*D*) were similar with slightly lower average in the wet (August – October) than in the dry (November - December) season (Figure 2a), due to greater cloud cover and rain in the wet season. Unfortunately, the quantum sensor that was used to measure PAR failed, causing a 2-month gap in data (Figure 2a, dashed line). Nevertheless, PAR and *D* were highly correlated (R = 0.75, $p < 0.001$) and therefore we used *D* to represent variation in atmospheric condition for further analyses. Volumetric soil moisture (θ) was monitored in six trees, two trees per species and one tree per treatment group. Figure 2b shows averages of θ for control and treated groups (n = 3). Field capacity (θ_{FC}) was 0.54 $\pm$ 0.02 and θ of both groups was maintained at ≥80% of θ_{FC} during irrigation periods (non-shaded regions in Figure 2). There were two drought experimental periods, one in each season (shaded regions in Figure 2). During both periods, irrigation of treated trees was withheld until θ dropped by 30% (Figure 2, gray shaded regions), then watering was resumed. During the drought experimental periods, *D* was slightly lower in the wet season (1.15 ± 0.3 kPa) than in the dry season (1.7 ± 0.32 kPa).

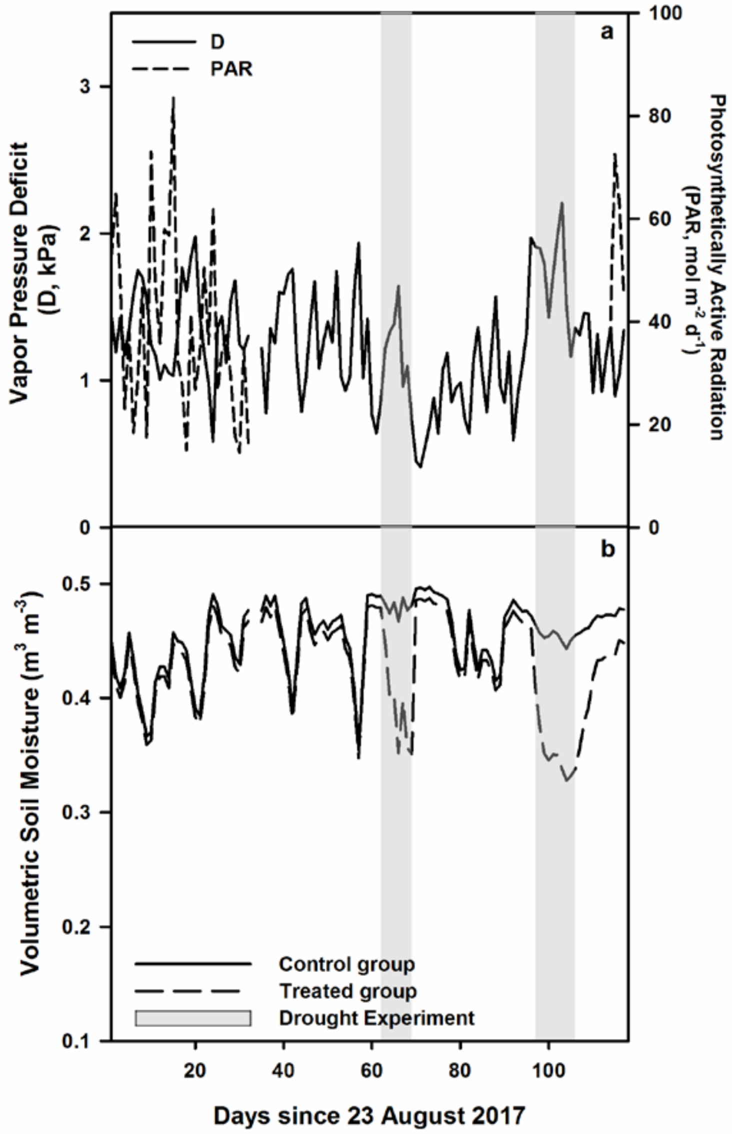

Figure 2: Environmental conditions during the study period. (a) daily variations of atmospheric conditions including vapor pressure deficit (solid line, *D*, kPa) and photosynthetically active radiation (dashed line, PAR, mol m^{-2} d^{-1}). Note the gap of PAR data due to instrumental failure and sensor was sent for a repair.

Seasonal variations of water use characteristics of the species

To investigate seasonal difference in water use patterns of the three species under well irrigation, we examined diurnal variations of J_S and their responses to D (Figure 3 and 4). Daily averaged D was slightly lower in the wet season (1.22 ± 0.17 kPa) than in the dry season (1.41 ± 0.19 kPa). In *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*), J_S was similar between both seasons ($p \geq 0.21$; compare panel a and c in Figure 3 and 4). However, *Lagerstroemia speciosa* (*Ls*) had significantly lower J_S in the dry season. This may be associated with some defoliation observed in December, leading to decline in J_S. Tree species with different leaf phenology exhibit differences in stem sapwood area, wood density, hydraulic conductance, water storage capacity, and characteristics of leaf gas exchange (Mienzer et al. 2003; Choat et al. 2004; Meinzer et al. 2008; Zhang et al. 2013). These factors affect the amount and patterns of tree water-use.

In the dry season, constrained water use behavior and later stomatal closure during periods of high atmospheric demand were observed in all species. These were demonstrated by relatively flat peaks of the diurnal patterns (Figure 4a, c, e) and the later decreases in J_S (after 14:00 solar time) compared to in the wet season (at or close to 14:00 solar time, Figure 3a, c, e). Considering diurnal variations of J_S with D of all species, results showed clockwise hysteresis (insets in Figure 3 and 4, arrows), implying that J_S increased with D in the morning at different rates than J_S decreasing with D in the afternoon. This pattern may result from high water supply capacity of the plants and even in the soil in the morning and that plants may be partially dehydrated in the afternoon (O'Grady et al. 1999, 2008; Gwenzi et al. 2012). The stomatal behavior might also contribute to the observed hysteresis. Previous studies reported different stomatal responses to diurnal changes in environmental factors (e.g. D), with larger stomatal conductance in the morning (Yu et al. 1996; Eamus and Cole 1997), indicating higher canopy conductance (Wilson and Baldocchi 2000) and therefore higher J_S in the morning compared with the afternoon. In this study, we found that hysteresis loops of all species were larger in the dry season than in the wet season (compare insets in Figure 4a, c and e with those in Figure 3a, c and e, respectively). The larger hysteresis loops in the dry season may be attributed to faster stomatal closing in the afternoon compared to the slower response in the wet season when the air is moist.

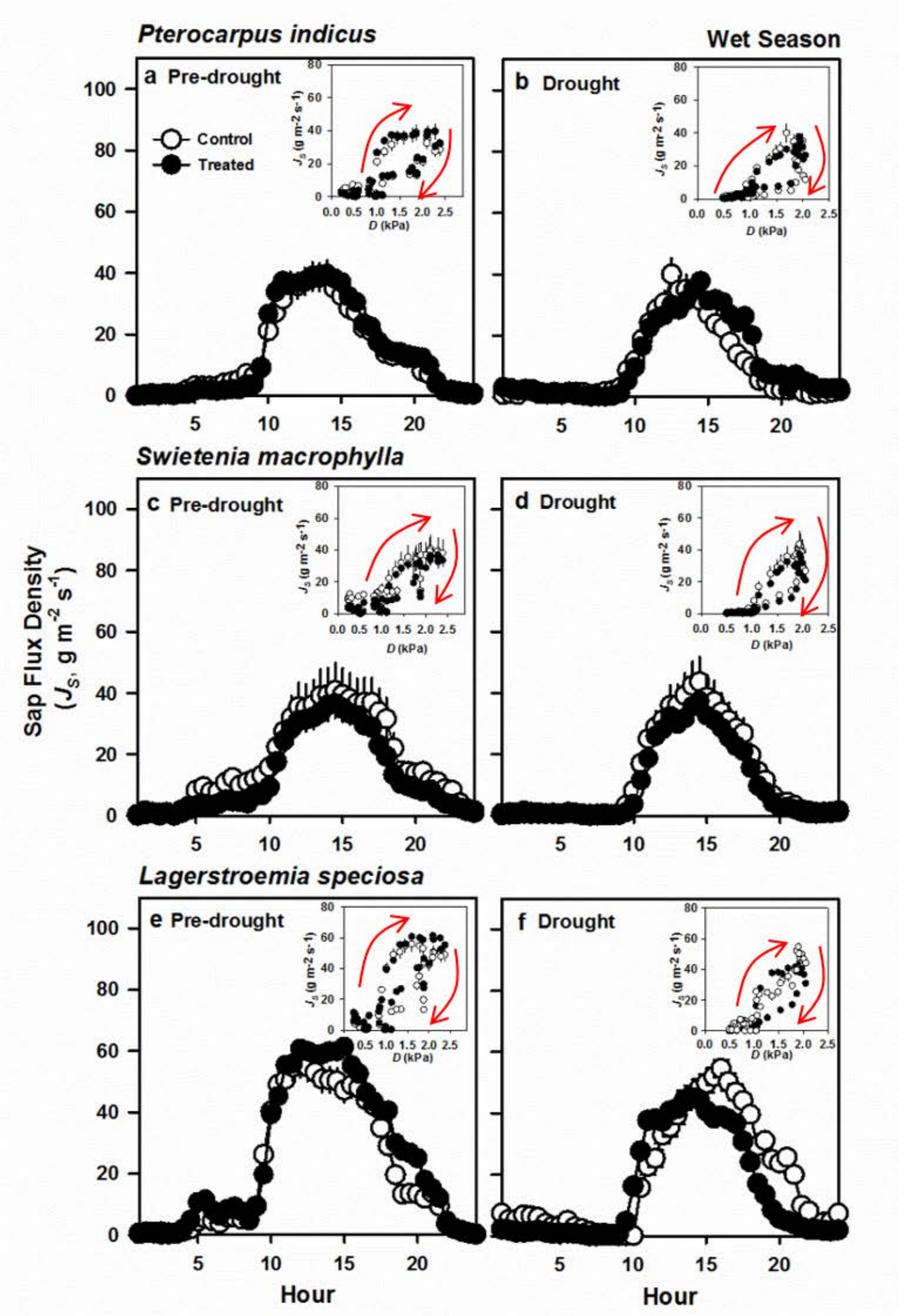

Figure 3: Diurnal variations of sap flux density (J_S) during pre-drought and drought experiments in the wet season. Open symbols represent values of trees in irrigated group (control) and closed symbols represent those of trees in drought treated group (treated). Error bars indicate one standard deviation of the mean of three-day data for the control group. Insets show J_S variation with vapor pressure deficit (D), corresponding to soil water regime with arrows indicating directions of hysteresis.

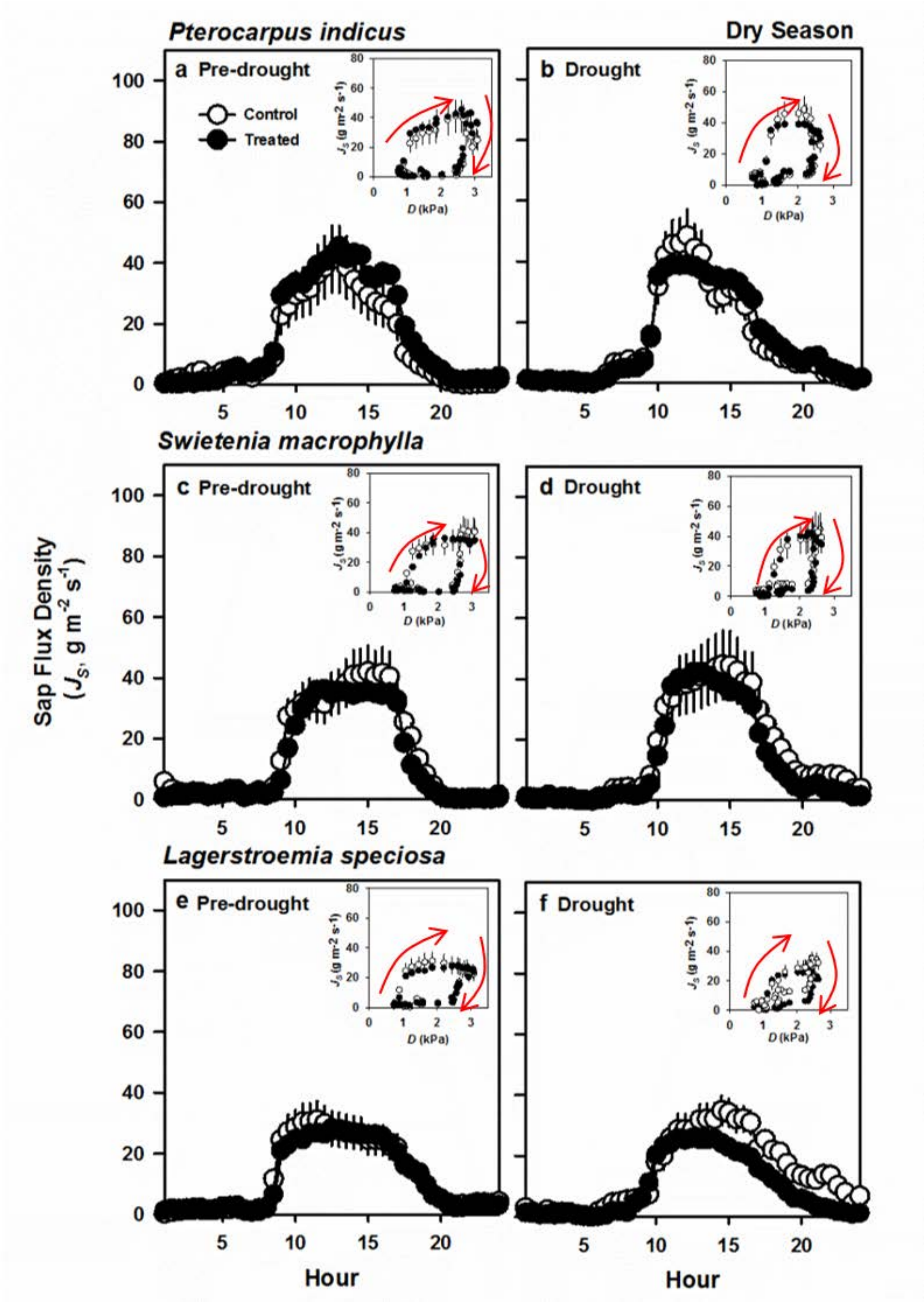

Figure 4: Diurnal variations of sap flux density (J_S) during pre-drought and drought experiments in the dry season. Open symbols represent values of trees in irrigated group (control) and closed symbols represent those of trees in drought treated group (treated). Error bars indicate one standard deviation of the mean of three-day data for the control group. Insets show J_S variation with vapor pressure deficit (D), corresponding to soil water regime with arrows indicating directions of hysteresis.

Species-specific responses to drought experiments

In the drought experiments of both seasons, diurnal J_S patterns of control and treated trees in *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*) were similar ($p \geq 0.32$; Figure 3b, d and 4b, d), indicating that soil water deficit did not affect water use patterns in these species. In contrast, diurnal J_S variations of *Lagerstroemia speciosa* (*Ls*) treated trees were different from those of control trees across seasons (Figure 3f and 4f). In the wet season, *Ls* treated trees showed earlier stomatal closure compared to the control ones (Figure 3f). The hysteresis loop of the control trees was narrow (inset in Figure 3f, open symbols), suggesting strong sensitivity to irrigation that allows the trees to keep up with increasing atmospheric demand in the afternoon. In the dry season, *Ls* treated trees closed their stomata earlier than the control trees, and the timing was earlier than in the wet season (Figure 4f, closed symbols). These results suggested that *Ls* was more sensitive to air and soil drying conditions than the other species. When water is well-supplied with irrigation, *Ls* used water as much as it could to meet the high transpirational demand in the afternoon. In the dry season, *Ls* adjusted to the drier atmospheric condition by closing their stomata earlier under increasing *D* in the afternoon and soil drought, resulting in larger hysteresis. These results agreed with previous studies, in which hysteresis loops were larger upon soil drying to avoid excessive water loss (O'Grady et al. 1999; Zhang et al. 2014; Brito et al. 2015). Additionally, J_S of the irrigated *Ls* trees in the wet season was approximately 30% higher than the other species, showing a physiological response that seems to appear in other deciduous species. The stomatal sensitivity to dry air and soil may be related to dormancy trigger, resulting in lower J_S in the dry season even under irrigation. Overall, during the drought experiments, water use characteristics of *Pi* and *Sm* were maintained across seasons while that of *Ls* was sensitive to the changing soil water conditions, closing their stomata earlier in response to drought in the dry season.

Daily tree water use of the species

To gain insights into practical applications, we compared daily water use by the species under well-irrigated conditions across seasons. Scaling up from the point measurement to tree level, we evaluated variations of daily tree water use (E_{tree}) of all species with vapor pressure deficit. In both seasons, average E_{tree} of *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*) was similar (*Pi*: 0.59 ± 0.06 (wet season) versus 0.50 ± 0.08 (dry season) mm day^{-1}, $p = 0.28$; *Sm*: 0.56 ± 0.10 (wet season) versus 0.51 ± 0.09 (dry season) mm day^{-1}, p = 0.12). However, average E_{tree} of *Lagerstroemia speciosa* (*Ls*) was significantly lower in the dry season (0.41 ± 0.10 mm day^{-1}) than in the wet season (0.69 ± 0.08 mm day^{-1}). To analyze the daily responses of E_{tree} to D, we applied a boundary line analysis (Schäfer et al. 2000; Ewers et al. 2001) which eliminates variations due to potential confounding factors (such as sunlight), allowing us to consider the responses of daily maximum E_{tree} ($E_{tree,max}$) to D as shown in Figure 5 (regression results are presented in Table 1). Results showed that $E_{tree,max}$ of *Pi* and *Sm* was similar across seasons throughout D ranges ($p \geq$ 0.21, open symbols in Figure 5a, b) while that of *Ls* was significantly greater in the wet season (p < 0.001, open symbols in Figure 5c). For *Pi* and *Sm*, $E_{tree,max}$ increased similarly at low D and saturated at ~0.6 kPa in both seasons, suggesting similar responses to atmospheric demand regardless of seasonal variations in these species. The saturation of $E_{tree,max}$ at low D indicated stomatal closure to prevent water loss as D increases, implying conservative water-use strategy which can prevent negative effects from droughts. In contrast, $E_{tree,max}$ of *Ls* displayed different $E_{tree,max}$ responses to D, saturating at much lower D (~0.5 kPa) in the dry season, compared to in the wet season (at D >1.5 kPa). Such behavior may be supported by the deciduousness of *Ls* as they shed leaves to prevent further water loss through transpiration as D is high in the dry season, resulting in low water use and abrupt stomatal closure. Thus, the different $E_{tree,max}$ response to D may result in different total water use by *Ls* trees, depending on irrigation rate and seasonal climates, while such factors exerted no impacts on how water is withdrawn from the soil by *Pi* and *Sm*.

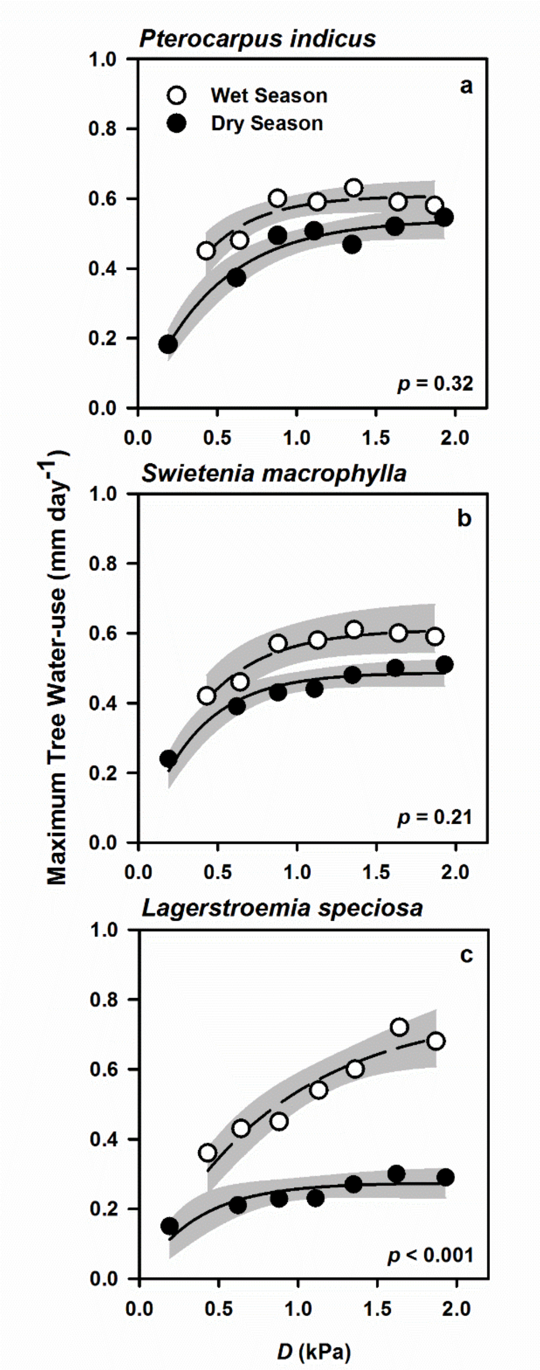

Figure 5: Maximum daily tree water use ($E_{tree,max}$) as a function of vapor pressure deficit (*D*) of the control trees in wet (open symbols) and dry (closed symbols) season. Regression statistics are shown in Table 1. Gray-shaded regions represent 95% confidence level of the regression lines. *P* values are results from F-test comparisons between patterns in wet and dry seasons (α=0.05).

Table 1: Regression statistics for the analysis of responses of maximum tree water-use ($E_{tree,max}$) to vapor pressure deficit (*D*) in each species. Open (closed) symbols show patterns in wet (dry) season. The fitting equation is of the form y = *a*×(1-exp(-*b*x)), where *a* and *b* are fitting parameters (see text for details) as shown in this table.

Species	Parameter	Wet Season	Dry Season
Pterocarpus indicus	*a*	0.608	0.541
	b	3.012	2.136
	r^2	0.79	0.95
	p	0.005	0.001
Swietenia macrophylla	*a*	0.612	0.488
	b	2.570	2.887
	r^2	0.92	0.92
	p	0.0004	0.0004
Lagerstroemia speciosa	*a*	0.772	0.275
	b	1.191	2.767
	r^2	0.87	0.69
	p	0.001	0.013

Conclusions

Based on these findings, the representative evergreen and deciduous species possess advantages and disadvantages for management of irrigation. *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*), representing evergreen species, conservatively used water across seasons, requiring relatively low amount of water despite increasing air dryness. This may save the amount of water needed for irrigation. *Lagerstroemia speciosa* (*Ls*), representing deciduous species, consumed more water in the wet season which may require much watering unless high rainfall is expected. However, *Ls* prevented much water loss during the dry season by rapidly closing their stomata (and shedding leaves) in response to drier air, thus saving costs for irrigation. Drought did not influence water use patterns of *Pi* and *Sm* but affected only *Ls* which may be associated with its deciduousness, inducing leaf loss when the soil becomes dry and decreasing water use. Based on this study, it may be implied that at least 50% of field capacity should be maintained to gain the conservative water use behavior in *Pi* and *Sm*. However, this level of soil moisture may not be suitable for species that are sensitive to environmental conditions, such as *Ls*. In our opinion, all of these species may be selected for planting in cities, depending on the desired functions, such as scenic view due to beautiful flowers and leaf arrangements and large crown providing shades. However, city planners should be aware that these species have disparate water use characteristics and may manage irrigation strategies accordingly to optimize water use in urban greening. Nevertheless, field experiments on street trees should be performed to confirm these findings and to gain useful insights for real applications.

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Output ที่ได้จากโครงการ

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Effects of varying soil and atmospheric water deficit on water use characteristics of tropical street tree species

Pantana Tor-ngern[a,*], Ladawan Puangchit[b]

[a] Department of Environmental Science, Faculty of Science, Chulalongkorn University, Bangkok, 10330, Thailand
[b] Department of Silviculture, Faculty of Forestry, Kasetsart University, Bangkok, 10900, Thailand

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ABSTRACT

Urban trees provide several ecosystem services, yet they are less studied compared to trees in natural ecosystems. Investigating ecophysiological responses of different tree species to seasonal conditions and drought will help determine which would succeed in urban conditions. Here, we examined water use characteristics of common species in Bangkok, Thailand: *Pterocarpus indicus* (*Pi*), *Swietenia macrophylla* (*Sm*) and *Lagerstroemia speciosa* (*Ls*), with different phenology, under seasonal variations and soil drying. Thirty small trees were potted and irrigated to ≥80% of the field capacity (θ_{FC}) of the soil. Granier-type sensors were used to measure sap flux density from 23 August to 18 December 2017. Drought treatments were imposed on five trees of each species by withholding irrigation until θ reached ~50% θ_{FC}. Results suggested that water use patterns of semi-evergreen and evergreen species (*Pi* and *Sm*) were not sensitive to either seasonal or soil moisture variations while deciduous species (*Ls*) exhibited decreased water use and earlier stomatal closure upon soil drying in the dry season. These findings suggested that water use characteristics of the evergreen species may conserve water use regardless of atmospheric and soil moisture conditions while those of the deciduous species may result in high cost for irrigation in the wet season. Nevertheless, we believe that both evergreen and deciduous species may be selected for planting to maximize greening areas in cities throughout the year. However, knowledge of different water use characteristics of street tree species should be applied to devise strategic planning for optimized irrigation in urban greening.

1. Introduction

Urban trees provide several ecosystem services, such as mitigating rising atmospheric carbon dioxide concentration (CO_2), shading and cooling effects, reducing pollution, and other recreational and psychological benefits (Akbari, 2002; Pataki et al., 2006; Bowler et al., 2010). Yet, the understanding and management of urban trees in cities are still less investigated compared to those of trees in natural ecosystems. Provided that urban areas usually involve adverse environmental conditions, such as high temperature, greater CO_2 and air pollution, and poor soil, future climate change may exert greater impacts on urban environments than rural ones. Therefore, selecting species that can withstand such negative impacts will retain the intended ecosystem services by urban trees and fully benefit city dwellers.

Logically, species selection for urban planting should consider matching between urban climate and native habitat of the species from an appropriate forest type. For example, cities in equatorial wet climates, such as Singapore, use tree species from equatorial wet evergreen forests, albeit, it is possible that a monsoonal dry forest species is often used in cities in wet tropical climates (Kjelgren et al., 2011). However, cities in monsoonal climates with pronounced dry seasons, such as Bangkok, Thailand, may benefit from planting tree species from tropical monsoonal dry forests which are adapted to prolonged low rainfall condition (Miles et al., 2006). Such species either avoid drought with deciduous leaf habit or tolerate drought with evergreen foliage (Santiago et al., 2004). Nevertheless, species selection in some cities, such as Bangkok, is dominated by their floral displays which mostly include deciduous species while evergreen species are commonly old and large trees in protected areas (Thaiutsa et al., 2008). Such unequal distribution of deciduous and evergreen species may not optimize the ecosystem services that were originally intended for planting these trees in the city.

Trees of various species may have different water-use characteristics which affect transpiration and cooling of temperatures in cities. Urban trees are frequently maintained by irrigation which may not be cost effective if the species do not require much water for growth.

* Correspondence author.
E-mail address: pantana.t@chula.ac.th (P. Tor-ngern).

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Furthermore, with intensified climate change impacts in cities, such as drought which may impact water supply, urban trees that are sensitive to dry air and soil may become stressed, perform poorly, or die. Because of such variable responses, understanding differences in ecophysiological responses among tropical trees to season and dry soil can aid in identifying and selecting which are best suited to urban conditions.

In this study, we conducted drought experiments across dry and wet seasons on potted common street tree species in Bangkok, Thailand, a major and highly polluted city in Southeast Asia. Three species: *Pterocarpus indicus*, *Swietenia macrophylla* and *Lagerstroemia speciosa*; hereafter, *Pi*, *Sm* and *Ls*, respectively, were selected based on their different leaf phenology, and their frequency in the city (Kjelgren et al., 2008; Thaiutsa et al., 2008). Phenological characteristics of *Pi*, *Sm* and *Ls* species are semi-evergreen, evergreen and deciduous, respectively (Kjelgren et al., 2008). 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. We investigated water use characteristics of the species by comparing diurnal variations of sap flux density and daily water use with vapor pressure deficit under different soil water regimes and seasons. Our objectives were (1) to compare water-use characteristics of common street tree species in Bangkok, with different leaf habits that may affect water consumption rates, under artificial soil drying across wet and dry seasons and (2) to analyze daily water use by these species under well-watered conditions, whose conditions are assumed to be common for maintenance of street trees. The findings will provide better understanding of how different tropical species in a monsoonal climate city react to environmental changes and help selecting species that can withstand adverse impacts from climate and environmental changes when expanding green areas in the city.

2. Materials and methods

2.1. Settings

This study was conducted on the balcony of the 4th floor of the Department of Environmental Science building in Chulalongkorn University in Bangkok, Thailand (13°44′02.9″ N 100°31′54.1″ E). According to the 30-year record (1981–2010) of climatic data from a nearby Bangkok metropolis station (Thai Meteorological Department), mean annual air temperature was 28.6 °C and mean annual precipitation was 1648 mm. The weather in Bangkok is influenced by tropical monsoon climate with the wet season lasting from mid-May to October. The study period lasted from 23 August to 18 December 2017, covering parts of a wet and a dry season. Fig. 1a shows the settings of this experiment. We purchased 10 small trees (stem diameter ranging approximately 2–3 cm, height ranging 2.5–3.2 m) per species from a local nursery and transported them to the site. The trees were potted in 20 L containers using soil substrate materials consisting of garden soil mixed with dried monkeypod leaves, husk, coconut husks and some manure with the proportion of 2:0.5:0.5:1. The growing medium was analyzed and identified as clay loam with bulk density of 0.74 g cm^{-3}. An automatic drip irrigation system was applied to supply 10 L water per tree at 16:00 (solar time) every 24 h such that volumetric soil moisture (θ) was maintained at ≥80% of the field capacity (θ_{FC}).

2.2. Environmental measurements

Environmental variables were monitored continuously once the study site was established. An air temperature (T, °C) and relative humidity (RH, %) probe (HC2S3-L, Campbell Scientific, Logan UT, USA) and a quantum sensor (LI190R-L, LI−COR Biosciences, Lincoln NE, USA) measuring photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) were installed at ~2 m above the canopy. Fig. 1b illustrates the setup of these measurements. Volumetric soil moisture (θ, m^3 m^{-3}) was continuously monitored with Time-Domain Reflectometry (TDR) probes (CS 616, Campbell Scientific, Logan UT, USA), with the factory calibration, in two pots per species (total is 6 probes) to track soil moisture in the irrigated trees and those under the drought experiment. All environmental sensors were connected to a data logger (CR1000, Campbell Scientific, Logan UT, USA) which logged data every 60 s and stored 30-minute averaged values. Evaporative demand was expressed as vapor pressure deficit (*D,* kPa), calculated as the difference between saturated and actual vapor pressure. The saturated vapor pressure (SVP, kPa) is expressed as (Monteith and Unsworth, 1990)

$$\mathrm{SVP} = 0.611 \times 10^{7.5\mathrm{T}/(237.3+\mathrm{T})} \quad (1)$$

$$D = \left(1 - \frac{RH}{100}\right) \times SVP \quad (2)$$

Field capacity (θ_{FC}) of the soil was determined by collecting three soil samples from three pots using a 25 cm^3 crucible. The samples were soaked with water in a beaker for 24 h. Then, they were drained out for 2 h before being weighed for wet mass. Next, the soil samples were dried in an oven at 110 °C until the mass was stable and obtained dry mass. The θ_{FC} was calculated as

$$\theta_{FC} = \frac{V_w}{V_c} \quad (3)$$

$$V_w = \frac{m_{wet} - m_{dry}}{\rho_w} \quad (4)$$

where V_w is the volume of water in the soil sample after drainage, V_c is the volume of the crucible which equals 25 cm^3, m_{wet} and m_{dry} are mass of wet and dry soil, respectively and ρ_w is specific gravity of water which is 1 g cm^{-3}. We used the average θ_{FC} of the three samples (0.54 ± 0.02 SD) to represent θ_{FC} of the soil in all pots and as a reference for the drought experiments.

2.3. Sap flux density measurement and calculation of daily tree water use

We used self-constructed, Granier-type thermal dissipation probes (TDPs, Granier, 1985) for measuring sap flux density (J_S, g m^{-2} s^{-1}) of the trees. Each TDP pair consists of two probes made of steel needles cut into 10 mm length 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 many tree species (Clearwater et al., 1999; Catovsky et al., 2002; James et al., 2002). Each needle contained a T-type thermocouple (copper-constantan) whose tip has been in the middle of the steel needle. The constantan ends of the two thermocouples were connected to one another and each of the copper ends was connected to the data logger to measure temperature difference between the two probes. The downstream (upper) probe was continuously heated at constant power (~0.1 W) 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 heat dissipation effect of water flow in the vicinity of the heated probe. Data of the temperature difference were collected in millivolts every 60 s and stored as 30-minute averages by the same data logger as that connected to the environmental sensors. Water mass per unit sapwood area per time, or J_S, was then determined from the detected temperature difference as (Granier, 1985)

$$J_s = 118.99 \times 10^{-6}\left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231} \quad (5)$$

where J_S is sap flux density in $\mathrm{g_{H2O}\,m_{sapwood}^{-2}\,s^{-1}}$, 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. We utilized the Baseliner program version 4.0 (Oishi et al., 2016) to convert the temperature difference data to J_S. The program considers potential nocturnal fluxes resulting from nighttime transpiration and water recharge in the stem by selecting the highest daily ΔT to represent ΔT_m. The

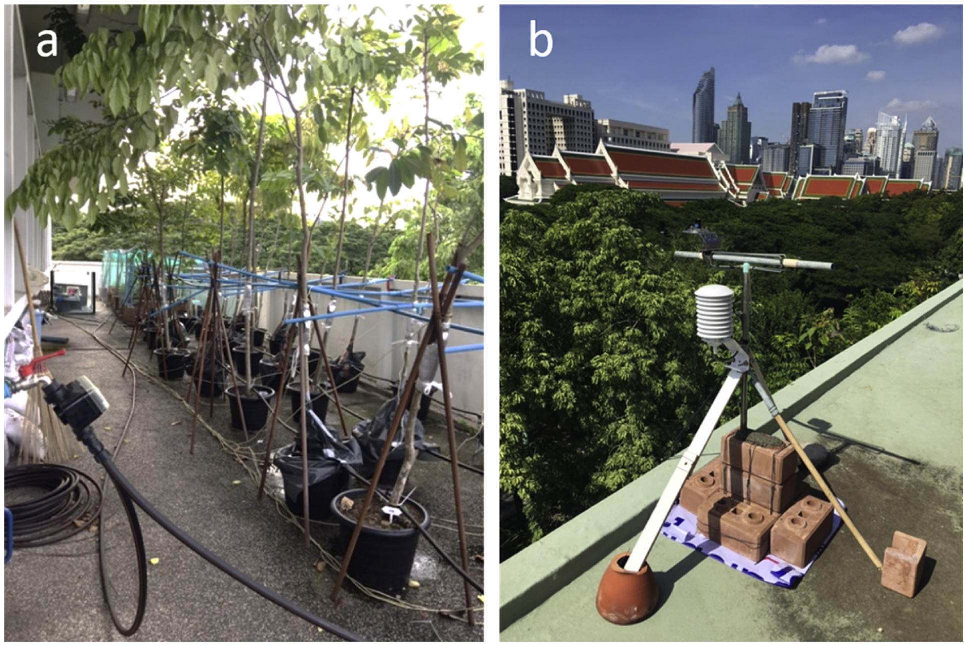

Fig. 1. Site establishments (a) settings of the studied potted trees and sap flux measurements (b) measurement setup of meteorological variables.

criteria for selection were conditions when (1) the average, minimum 2-hour vapor pressure deficit is < 0.05 kPa, therefore ensuring transpiration is negligible, and (2) the standard deviation of the four highest ΔT 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 reflective cover to prevent the natural thermal gradient which may influence the measurements. Because the stem sizes were small (2.84 ± 0.33 cm), we assumed negligible spatial variation of J_S (Ford et al., 2004; Tateishi et al., 2008) and installed TDP at one depth into sapwood. As equation (5) was empirically obtained from the 20-mm length sensor design (Granier, 1985), we note that the J_S values were estimated from uncalibrated sensors. However, the differences between sensor lengths are likely to be small and the comparisons are relative among treatments which would exert minimal effects on the analyses.

To explore daily water use, we scaled up the point measurement of J_S to tree-level transpiration. We assumed that the non-water 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 transpiration (E_{tree}; mm day^{-1}) was estimated by integrating J_S across the entire sapwood area (A_S, m^2) of the tree and summing over a day as follows.

$$E_{tree} = 1.8 \times A_S \times \sum_{t=1}^{48} J_S \tag{6}$$

where t is half-hourly point in time for one day. For inter-comparison of daily water use among the species, we applied a boundary line analysis (Schäfer et al., 2000; Ewers et al., 2001) to analyze variations of E_{tree} of irrigated trees to D, excluding potential confounding factors such as sunlight. Various studies showed that such response patterns followed a saturating exponential curve of the form (Ewers et al., 2001; Tor-ngern et al., 2017)

$$y = a(1 - e^{-bx}) \tag{7}$$

where y is E_{tree} under non-limiting soil water and sunlight conditions; $E_{tree,max}$ in mm day^{-1}, x is D in kPa. The a and b parameters represent saturating values of $E_{tree,max}$ and sensitivity of $E_{tree,max}$ to D, respectively.

2.4. Drought experiment

A drought experiment was performed during each season. The first drought experiment was during 23–30 October 2017, which was in the late wet season, and the second experiment in the dry season was during 27 November to 6 December 2017. We tested the effect of moderate water deficit rather than extreme drought, letting the soil dry to approximately 50% of θ_{FC}. For each species, trees were equally divided into two groups: (1) irrigated group in which the trees received continuous irrigation throughout the study period (hereafter, control) and (2) drought treated group in which the trees were not irrigated until soil moisture reached about 50% of θ_{FC} (hereafter, treated). In addition to withholding irrigation, we covered soil surface of the pots of the treated group with black plastic to prevent possible confounding water input from rainfall. Between each drought experiment, irrigation was resumed in the treated group once the defined drought condition was reached. For the analyses of responses to soil drying, we compared J_S values of the last day of each drought experiment (i.e. days when soil moisture reached 50% of θ_{FC}) to the average of 3 days with similar atmospheric conditions (PAR and D) prior to the experimental period.

2.5. Data analyses

We performed statistical tests including t-test for comparisons between control and treated groups, F-test for comparison between response patterns of the two groups, and regression analyses for the responses of daily water use to vapor pressure deficit. Calculations, 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

3.1. Environmental conditions during the study period

During the study period, variations of light (expressed as PAR) and evaporative demand (D) were similar with slightly lower average in the wet (August–October) than in the dry (November - December) season (Fig. 2a), due to greater cloud cover and rain in the wet season. Unfortunately, the quantum sensor that was used to measure PAR failed,

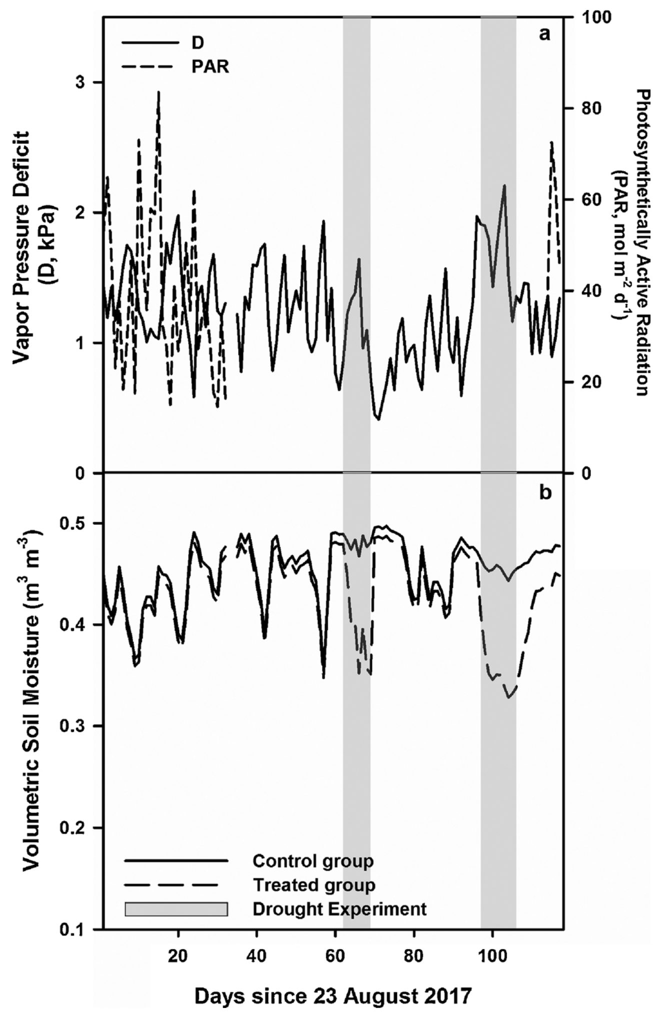

Fig. 2. Environmental conditions during the study period. (a) daily variations of atmospheric conditions including vapor pressure deficit (solid line, D, kPa) and photosynthetically active radiation (dashed line, PAR, mol m^{-2} d^{-1}). Note the gap of PAR data due to instrumental failure and sensor was sent for a repair.

causing a 2-month gap in data (Fig. 2a, dashed line). Nevertheless, PAR and D were highly correlated (R = 0.75, $p < 0.001$) and therefore we used D to represent variation in atmospheric condition for further analyses. Volumetric soil moisture (θ) was monitored in six trees, two trees per species and one tree per treatment group. Fig. 2b shows averages of θ for control and treated groups (n = 3). Field capacity (θ_{FC}) was 0.54 ± 0.02 and θ of both groups was maintained at ≥80% of θ_{FC} during irrigation periods (non-shaded regions in Fig. 2). There were two drought experimental periods, one in each season (shaded regions in Fig. 2). During both periods, irrigation of treated trees was withheld until θ dropped by 30% (Fig. 2, gray shaded regions), then watering was resumed. During the drought experimental periods, D was slightly lower in the wet season (1.15 ± 0.3 kPa) than in the dry season (1.7 ± 0.32 kPa).

3.2. Seasonal variations of water use characteristics of the species

To investigate seasonal difference in water use patterns of the three species under well irrigation, we examined diurnal variations of J_S and their responses to D (Fig. 3 and 4). Daily averaged D was slightly lower in the wet season (1.22 ± 0.17 kPa) than in the dry season (1.41 ± 0.19 kPa). In *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*), J_S was similar between both seasons ($p \geq 0.21$; compare panel a and c in Fig. 3 and 4). However, *Lagerstroemia speciosa* (*Ls*) had significantly lower J_S in the dry season. This may be associated with some defoliation observed in December, leading to decline in J_S. Tree species with different leaf phenology exhibit differences in stem sapwood area, wood density, hydraulic conductance, water storage capacity, and characteristics of leaf gas exchange Meinzer et al. (2003); Choat et al., 2004; Meinzer et al., 2008; Zhang et al., 2013). These factors affect the amount and patterns of tree water-use.

In the dry season, constrained water use behavior and later stomatal closure during periods of high atmospheric demand were observed in all species. These were demonstrated by relatively flat peaks of the diurnal patterns (Fig. 4a, c, e) and the later decreases in J_S (after 14:00 solar time) compared to in the wet season (at or close to 14:00 solar time, Fig. 3a, c, e). Considering diurnal variations of J_S with D of all species, results showed clockwise hysteresis (insets in Fig. 3 and 4, arrows), implying that J_S increased with D in the morning at different rates than J_S decreasing with D in the afternoon. This pattern may result from high water supply capacity of the plants and even in the soil in the morning and that plants may be partially dehydrated in the afternoon (O'Grady et al., 1999, 2008; Gwenzi et al., 2012). The stomatal behavior might also contribute to the observed hysteresis. Previous studies reported different stomatal responses to diurnal changes in environmental factors (e.g. D), with larger stomatal conductance in the morning (Yu et al., 1996; Eamus and Cole, 1997), indicating higher canopy conductance (Wilson and Baldocchi, 2000) and therefore higher J_S in the morning compared with the afternoon. In this study, we found that hysteresis loops of all species were larger in the dry season than in the wet season (compare insets in Fig. 4a, c and e with those in Fig. 3a, c and e, respectively). The larger hysteresis loops in the dry season may be attributed to faster stomatal closing in the afternoon compared to the slower response in the wet season when the air is moist.

3.3. Species-specific responses to drought experiments

In the drought experiments of both seasons, diurnal J_S patterns of control and treated trees in *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*) were similar ($p \geq 0.32$; Fig. 3b, d and 4b, d), indicating that soil water deficit did not affect water use patterns in these species. In contrast, diurnal J_S variations of *Lagerstroemia speciosa* (*Ls*) treated trees were different from those of control trees across seasons (Fig. 3f and 4f). In the wet season, *Ls* treated trees showed earlier stomatal closure compared to the control ones (Fig. 3f). The hysteresis loop of the control trees was narrow (inset in Fig. 3f, open symbols), suggesting strong sensitivity to irrigation that allows the trees to keep up with increasing atmospheric demand in the afternoon. In the dry season, *Ls* treated trees closed their stomata earlier than the control trees, and the timing was earlier than in the wet season (Fig. 4f, closed symbols). These results suggested that *Ls* was more sensitive to air and soil drying conditions than the other species. When water is well-supplied with irrigation, *Ls* used water as much as it could to meet the high transpirational demand in the afternoon. In the dry season, *Ls* adjusted to the drier atmospheric condition by closing their stomata earlier under increasing D in the afternoon and soil drought, resulting in larger hysteresis. These results agreed with previous studies, in which hysteresis loops were larger upon soil drying to avoid excessive water loss (O'Grady et al., 1999; Zhang et al., 2014; Brito et al., 2015). Additionally, J_S of the irrigated *Ls* trees in the wet season was approximately 30% higher than the other species, showing a physiological response that seems to appear in other deciduous species. The stomatal sensitivity to dry air and soil may be related to dormancy trigger, resulting in lower J_S in the dry season even under irrigation. Overall, during the drought experiments, water use characteristics of *Pi* and *Sm* were maintained across seasons while that of *Ls* was sensitive to the changing soil water conditions, closing their stomata earlier in response to drought in the dry season.

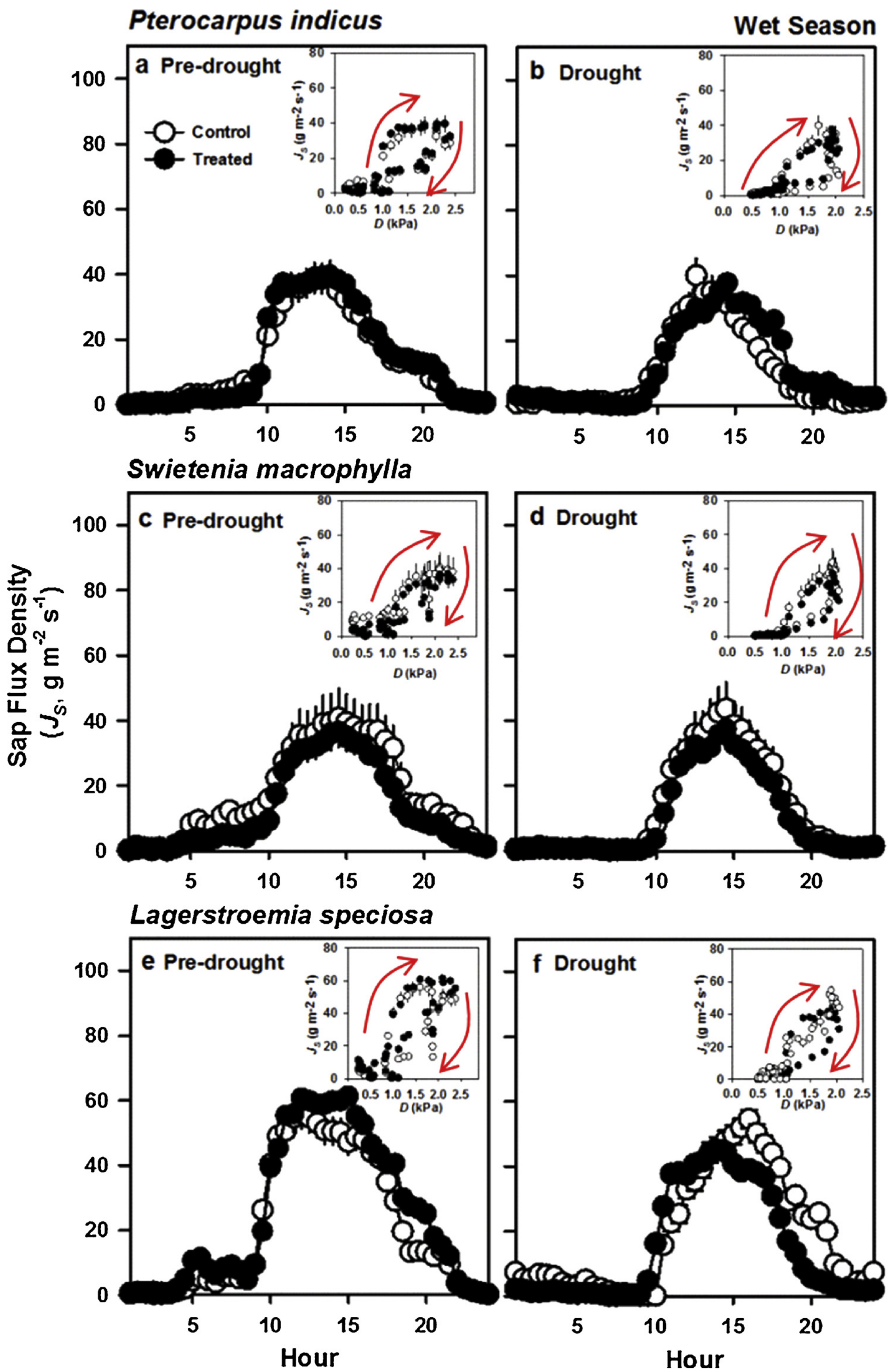

Fig. 3. Diurnal variations of sap flux density (J_S) during pre-drought and drought experiments in the wet season. Open symbols represent values of trees in irrigated group (control) and closed symbols represent those of trees in drought treated group (treated). Error bars indicate one standard deviation of the mean of three-day data for the control group. Insets show J_S variation with vapor pressure deficit (D), corresponding to soil water regime with arrows indicating directions of hysteresis.

3.4. Daily tree water use of the species

To gain insights into practical applications, we compared daily water use by the species under well-irrigated conditions across seasons. Scaling up from the point measurement to tree level, we evaluated variations of daily tree water use (E_{tree}) of all species with vapor pressure deficit. In both seasons, average E_{tree} of *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*) was similar (*Pi*: 0.59 ± 0.06 (wet season) versus 0.50 ± 0.08 (dry season) mm day^{-1}, $p = 0.28$; *Sm*: 0.56 ± 0.10 (wet season) versus 0.51 ± 0.09 (dry season) mm day^{-1}, $p = 0.12$). However, average E_{tree} of *Lagerstroemia speciosa* (*Ls*) was significantly lower in the dry season (0.41 ± 0.10 mm day^{-1}) than in the wet season (0.69 ± 0.08 mm day^{-1}). To analyze the daily responses of E_{tree} to D, we applied a boundary line analysis (Schäfer et al., 2000; Ewers et al., 2001) which eliminates variations due to potential confounding factors (such as sunlight), allowing us to consider the

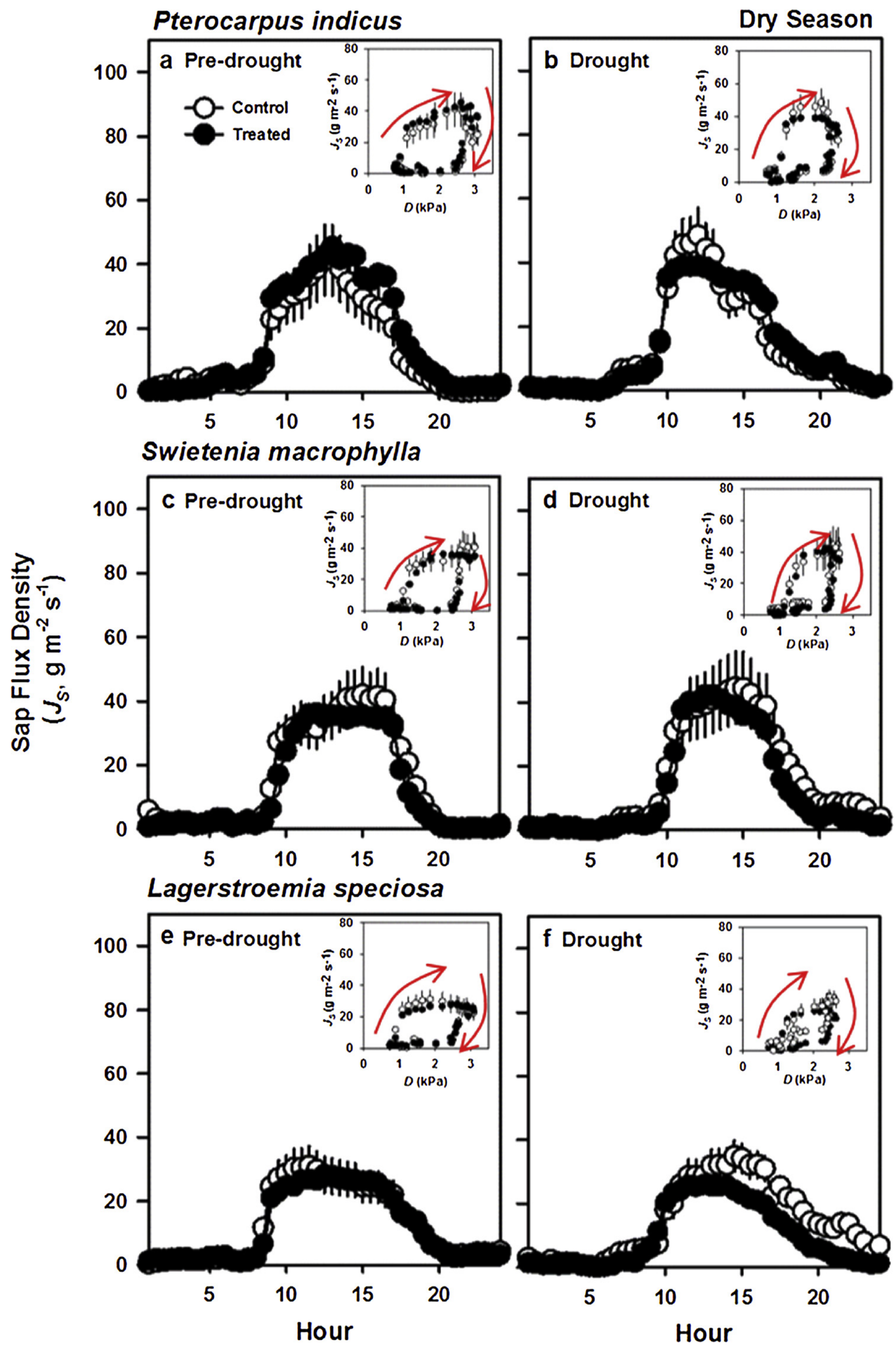

Fig. 4. Diurnal variations of sap flux density (J_S) during pre-drought and drought experiments in the dry season. Open symbols represent values of trees in irrigated group (control) and closed symbols represent those of trees in drought treated group (treated). Error bars indicate one standard deviation of the mean of three-day data for the control group. Insets show J_S variation with vapor pressure deficit (D), corresponding to soil water regime with arrows indicating directions of hysteresis.

responses of daily maximum E_{tree} ($E_{tree,max}$) to D as shown in Fig. 5 (regression results are presented in Table 1). Results showed that $E_{tree,max}$ of *Pi* and *Sm* was similar across seasons throughout D ranges ($p \geq 0.21$, open symbols in Fig. 5a, b) while that of *Ls* was significantly greater in the wet season ($p < 0.001$, open symbols in Fig. 5c). For *Pi* and *Sm*, $E_{tree,max}$ increased similarly at low D and saturated at ~0.6 kPa in both seasons, suggesting similar responses to atmospheric demand regardless of seasonal variations in these species. The saturation of $E_{tree,max}$ at low D indicated stomatal closure to prevent water loss as D increases, implying conservative water-use strategy which can prevent negative effects from droughts. In contrast, $E_{tree,max}$ of *Ls* displayed different $E_{tree,max}$ responses to D, saturating at much lower D (~0.5 kPa) in the dry season, compared to in the wet season (at $D > 1.5$ kPa). Such behavior may be supported by the deciduousness of *Ls* as they shed leaves to prevent further water loss through transpiration as D is high in the dry season, resulting in low water use and abrupt stomatal closure. Thus, the different $E_{tree,max}$ response to D may result in different total water use by *Ls* trees, depending on irrigation rate and seasonal

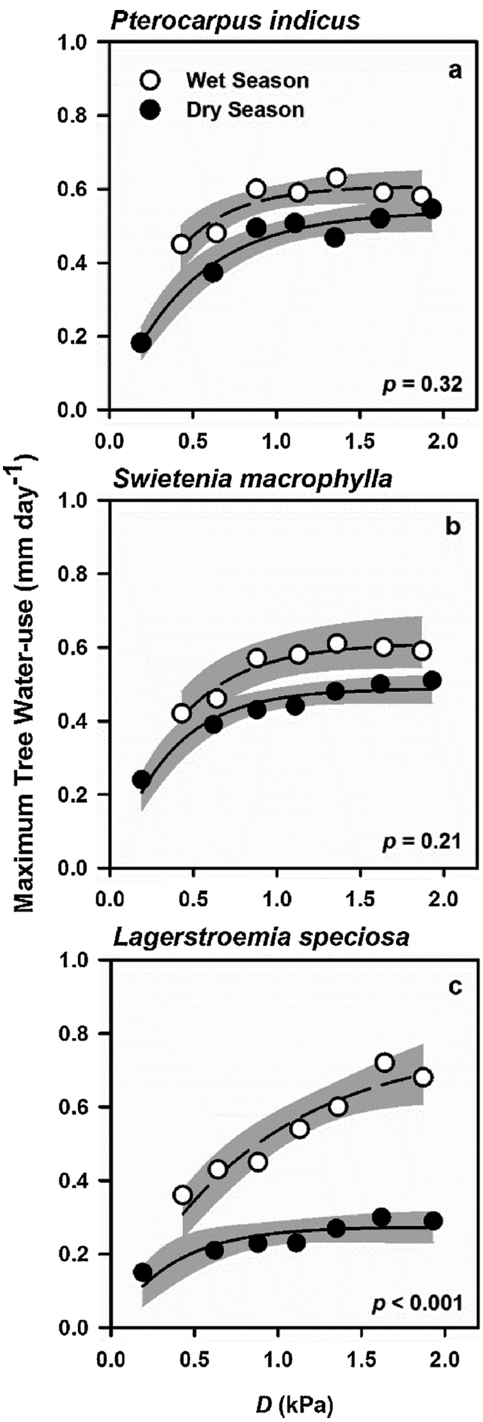

Fig. 5. Maximum daily tree water use ($E_{tree,max}$) as a function of vapor pressure deficit (D) of the control trees in wet (open symbols) and dry (closed symbols) season. Regression statistics are shown in Table 1. Gray-shaded regions represent 95% confidence level of the regression lines. P values are results from F-test comparisons between patterns in wet and dry seasons (α = 0.05).

climates, while such factors exerted no impacts on how water is withdrawn from the soil by *Pi* and *Sm*.

4. Conclusions

Based on these findings, the representative evergreen and deciduous species possess advantages and disadvantages for management of irrigation. *Pterocarpus indicus* (*Pi*) and *Swietenia macrophylla* (*Sm*), representing evergreen species, conservatively used water across seasons,

Table 1
Regression statistics for the analysis of responses of maximum tree water-use ($E_{tree,max}$) to vapor pressure deficit (D) in each species. Open (closed) symbols show patterns in wet (dry) season. The fitting equation is of the form $y = a \times (1 - \exp(-bx))$, where a and b are fitting parameters (see text for details) as shown in this table.

Species	Parameter	Wet Season	Dry Season
Pterocarpus indicus	a	0.608	0.541
	b	3.012	2.136
	r^2	0.79	0.95
	p	0.005	0.001
Swietenia macrophylla	a	0.612	0.488
	b	2.570	2.887
	r^2	0.92	0.92
	p	0.0004	0.0004
Lagerstroemia speciosa	a	0.772	0.275
	b	1.191	2.767
	r^2	0.87	0.69
	p	0.001	0.013

requiring relatively low amount of water despite increasing air dryness. This may save the amount of water needed for irrigation. *Lagerstroemia speciosa* (*Ls*), representing deciduous species, consumed more water in the wet season which may require much watering unless high rainfall is expected. However, *Ls* prevented much water loss during the dry season by rapidly closing their stomata (and shedding leaves) in response to drier air, thus saving costs for irrigation. Drought did not influence water use patterns of *Pi* and *Sm* but affected only *Ls* which may be associated with its deciduousness, inducing leaf loss when the soil becomes dry and decreasing water use. Based on this study, it may be implied that at least 50% of field capacity should be maintained to gain the conservative water use behavior in *Pi* and *Sm*. However, this level of soil moisture may not be suitable for species that are sensitive to environmental conditions, such as *Ls*. In our opinion, all of these species may be selected for planting in cities, depending on the desired functions, such as scenic view due to beautiful flowers and leaf arrangements and large crown providing shades. However, city planners should be aware that these species have disparate water use characteristics and may manage irrigation strategies accordingly to optimize water use in urban greening. Nevertheless, field experiments on street trees should be performed to confirm these findings and to gain useful insights for real applications.

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Friday, June 8, 2018

Dr. Pantana Tor-ngern
Chulalongkorn University
254 Payathai Rd, Wang Mai, Pathumwan

Bangkok, 10330
Thailand
Email: pantana.t@chula.ac.th
Registration ID: 15444
Nationality: Thai
Passport Number: AA2848736
Passport Expiry Date: 19 April 2020
Date of Birth: 3 September 1985

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