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Research Article

An Urban Tree (*Tabebuia argentea*) Exhibits Higher Sensitivity to Environmental Conditions than an Urban Palm (*Ptychosperma macarthurii*) Growing in the Same Roof Garden: An Implication for Sustainable Urban Water Use

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Abstract

Roof gardening is popular for increasing green space in cities due to the restricted urban areas. However, when watering plants on a roof garden, one should consider loading capacity of the roof, which may limit water supply to the plants therein. To improve the efficiency in irrigating trees in a roof garden, we evaluated plant water status, represented by midday leaf water potential (Ψ_L), and leaf gas exchange parameters including stomatal conductance (g_s) and net photosynthesis (A_n) of a tree (*Tabebuia argentea*, *Ta*) and a palm (*Ptychosperma macarthurii*, *Pm*) species, which dominate the garden. The Ψ_L mediated responses of g_s and A_n, regulating plant water use and growth, to soil moisture. Results showed that Ψ_L of *Ta* significantly varied with changes in soil moisture, being low at low and high soil moisture. Nevertheless, g_s of *Ta* linearly decreased when Ψ_L increased, suggesting a stronger response of g_s to atmospheric demand. In contrast, no significant responses among the study variables were observed in *Pm*. For both species, A_n initially increased with g_s and saturated after g_s reached 200 mmol m^{-2} s^{-1}, indicating similar stomatal regulation on atmospheric carbon dioxide absorption. The limited space for root growth and the location with surrounded building walls contributed to unconventional response patterns observed in *Ta*. Nonetheless, our results suggested that *Ta* was more sensitive to changing environments, especially the atmospheric demand, than *Pm*. Additionally, *Ta* should be irrigated during daytime and when atmospheric vapor pressure deficit is less than 2.6 kPa to allow high photosynthesis and evaporative cooling while *Pm* may be watered less frequently to reduce the roof's loading and save water. This initial investigation implied that maintaining urban trees using appropriate irrigation that is specific to tree species is the key to maximize benefits from urban trees and optimize urban water use.

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Introduction

Ongoing urbanization is increasing in several urban areas causing increased temperature of cities through the urban heat island effect [1–2]. The expansion of towns mostly involves concrete buildings, resulting in less green space. Such limited capacity for expanding urban green space brings about the establishments of green areas in buildings, such as on a balcony or a roof garden. Rooftop gardening is a sustainable approach for mitigating adverse environmental effects in urban areas [3] but it requires intensive management because the roofs involve specific load-bearing capacity. Roof gardens provide many environmental benefits including conserving energy through improved building energy efficiency [4], enhancing urban biodiversity through provision of habitats for wildlife [5] and mitigating the urban heat island effect [6]. However, the ecosystem services by various plant species in a roof garden can be impaired by limited water availability in soils [7], where root space and soil water holding capacity are restricted. Therefore, plant and tree species growing in a roof garden need careful management, particularly for irrigation. In fact, irrigation is often controlled to reduce the chance of overloading the roof's structure [8]. Because different tree species use different amount of water for growth [9–10], in the same roof garden, some tree species may be prone to frequent water deficit while others may receive too much water, leaving unused water infiltrating to the soils and resulting in ecosystem disservice [11]. Because various tree species respond differently to changing environments, information regarding ecophysiological responses of different tree species to environmental conditions is useful for managing irrigation schedule for efficient urban water use.

Landscape trees and palms are commonly planted in many cities for scenic views and are maintained with frequent irrigation. Palms can be found planted alongside trees in many cities, such as Los Angeles in USA, Olhro in Portugal and Bangalore in India [12–14]. To obtain the information for effective maintenance of urban tree and palm species, one can explore how their physiological parameters respond to various environmental conditions. A previous study showed that the hydraulic efficiency of palm species was higher than that of tree species in a tropical region [15] because palm species, which are monocots, have broader vessels than dicot tree species. [16]. However, the broader vessels in palm species could result in higher risk in embolism [17]. Differences in the hydraulic efficiency are linked to physiological processes, such as transpiration and photosynthesis, which are regulated by stomata in leaves. Stomatal regulation of certain tree species varies with their water status, which is represented by leaf water potential [18]. Some species reduce stomatal conductance rapidly as soil water dries, thereby restricting excessive water loss, while other species allow stomatal opening despite the drying soil, thereby maintaining the uptake of atmospheric carbon dioxide for photosynthesis [19]. However, the response of physiological parameters to various environmental conditions in tree and palm species are still lacking especially in urban areas. Investigating how responses of leaf water status and leaf gas exchange to various environmental conditions differ among species, such as in tree and palm species, will offer fundamental knowledge for managing irrigation schedule to optimize urban water use.

With these regards, we analyzed leaf water status (i.e., leaf water potential at midday; Ψ_L) and leaf gas exchange parameters (i.e., stomatal conductance; g_s and net photosynthesis; A_n) of a tree species, *Tabebuia argentea*, and a palm species, *Ptychosperma macarthurii*, which dominated the same tropical roof garden in Bangkok, Thailand. This roof garden had been established and maintained with frequent irrigation for more than 5 years. We performed measurement and analysis only in the dry season, from January to February in 2021, to fully explore the responses under rain-free conditions, provided the trees received regular irrigation. Results from this study offer insights for achieving sustainable urban forest management through better irrigation regimes that are specific to tree species.

Methods

1) Site description

The study site was in a roof garden of Mahitaladhibesra building at Chulalongkorn University, Bangkok Thailand (13°44′02.9″N 100°31′54.1″E). The garden had been established and maintained with frequent irrigation for more than 5 years. The total area was 355 m^2 and was at 15 m from the ground of the building. The garden was in the west side of the building with ~10 m tall stories of the same building in the east, partially shading the site in the morning. Vegetation in this garden consisted of two tree species (*Tabebuia argentea and Plumeria spp.*), one palm species (*Ptychosperma macarthurii*) and a few herbaceous species (e.g., *Ixora coccine* and *Crinum asiaticum*) whose statures were less than 50 cm above the ground. We selected *Tabebuia argentea* and *Ptychosperma macarthurii*, hereafter *Ta* and *Pm* respectively, the dominant tree and palm species in this garden for our study. Eight *Ta* and *Pm* individuals were planted on the south and the west side of the garden, respectively. However, we selected three individuals from each species group for leaf measurement after surveying for individuals with leaves that were fully expanded and exposed to sunlight throughout the day. According to a 30-year record of climatic data (1990–2020) obtained from a Bangkok metropolis station nearby (Thai Meteorological Department), mean annual air temperature was 28.9 °C and mean annual rainfall was 1689 mm. The weather in Bangkok is influenced by tropical monsoon climate with wet season lasting from mid-May to October. The soil was identified as clay loam and highly compacted with bulk density of 1.49 g cm^{-3}. The study period was in the dry season, starting from January 12 to February 6, 2021.

2) Environmental measurements

We monitored environmental variables that may affect plant water relation and gas exchange, including air temperature (T, °C), relative humidity (RH, %), solar radiation (represented by photosynthetically active radiation or PAR in μmol m^{-2} s^{-1}), and volumetric soil moisture in the root zone [20–21]. We collected PAR data using a quantum sensor (LI190R-L, LI-COR Biosciences, Lincoln NE, USA) and measured T and RH using a probe (HC2S3-L, Campbell Scientific, Logan UT, USA). These sensors were installed approximately 2 m above the canopy. A soil moisture probe (CS616; Campbell Scientific, Logan, UT) was installed at 5 cm depth in each plot, measuring volumetric soil moisture (θ) for the tree and the palm species. All sensors were connected to a datalogger (CR1000; Campbell Scientific, Logan, UT) which recorded data every 30 minutes.

3) Plant materials and measurements

For our analyses, we measured leaf water potential (Ψ_L; MPa) and leaf gas exchange parameters including stomatal conductance (g_s, mmol m^{-2} s^{-1}) and net photosynthesis (A_n, μmol m^{-2} s^{-1}) during midday (1,000–1,400 h) to obtain values under non-limiting light conditions [22–23]. Stomatal conductance is the measure of the rate of passage of carbon dioxide (CO_2) entering and water vapor exiting through the stomata of a leaf. Midday Ψ_L represents the minimum leaf water potential which show plant water status during which high gas exchange rates occur [24]. For each species, we selected three individuals with accessible canopy and containing relatively large number of healthy leaves. Then, we randomly chose three fully expanded and sunlit leaves from each tree [25]. To confirm if the gas exchange measurements were under light saturation, which would be assumed for sunlit leaves, we compared the PAR values during measurement days to a PAR value above which photosynthetic rates saturate in some tropical trees. A previous study showed that the PAR value at which photosynthetic rate in some tropical tree species reached saturation was approximately 800 μmol m^{-2} s^{-1} [26–28]. The result showed that PAR values on the measurement days were significantly higher than the PAR value for light-saturated photosynthesis ($p < 0.001$, one-sample t-test). Thus, our measurements on sunlit leaves were confirmed.

Leaf water potential was measured using a pressure chamber (PMS Instrument Company, Albany, OR, USA). Leaf gas exchange measurements were made using a portable photosynthesis system (TARGAS-1, PP Systems, Amesbury, MA, USA). All leaves covered the entire window area of the cuvette which was equal to 4.5 cm^2. The leaf gas exchange rates were recorded three times for each leaf and reported per unit leaf area. The flow rate was set to 250 ml min^{-1} (TARGAS-1 Portable Photosynthesis System Operation Manual Version 1.04 2018). Photosynthetically active radiation (PAR; μmol m^{-2} s^{-1}) inside the cuvette was set to 1,500 μmol m^{-2} s^{-1}, which corresponded to the light saturation ranges in tropical trees [26–28]. Atmospheric temperature, relative humidity and CO_2 concentration were not controlled and thus tracking ambient conditions. All study variables (i.e., Ψ_L, g_s, A_n) during midday were measured daily on 10 randomly selected days throughout the study period. Additionally, we performed three diurnal measurements of the leaf gas exchange rates to gain insight into physiological variations of both species throughout diurnal changes of environmental conditions. The diurnal measurement was done every two hours, starting from 700 to 1700 h [29].

4) Statistical analysis

We performed the analysis at tree level by taking averages of data from all leaves in each tree as the unit of analysis. This results in the sample size of 30 data points for each species. Regression analysis was used to analyze the relationships between variables in each species including the relationship between g_s and VPD_{LA}, the relationship between Ψ_L and θ, the relationship between g_s and Ψ_L and the relationship between g_s and A_n. Data analyses and visualization were performed in Rstudio, version 1.3.1073 (The R Foundation for Statistical Computing, http://www. R-project.org) and SigmaPlot 12.0 (Systat Software, Inc., San Jose, California, USA). In all statistical analyses, we used a significance level of 0.05.

Results and Discussion

Overall, the selected trees and palms were of similar size within group of each species. The average and one standard deviation of diameters at breast height (DBH) of *Ta* and *Pm* were 17.67 ± 5.69 and 6.32 ± 0.18 cm, respectively. This confirms that there was no potential confounding effect from variation in tree size [30]. For the measured variables, Table 1 shows their means and the corresponding one standard deviation values. The average leaf water potential values of *Ta* were within the ranges found in Oliveira et al. [31] who studied seedlings of *Tabebuia aurea*, a species of the same genus as *Ta*, under water stress. They reported that Ψ_L values of *T. aurea* varied between -0.5 and -2.5 MPa. The same study also reported initial values of g_s between 240 and 370 mmol m^{-2} s^{-1} and A_{net} between 8.0 and 9.9 µmol m^{-2} s^{-1}, which were higher than our measured values. Our average leaf water potential values of *Pm* were higher than those found in Suresh et al. (2010) who studied gas exchange and leaf water potential in oil palm seedlings (*Elaeis guineensis* Jacq.) under water stress. They showed that values of Ψ_L, g_s and A_{net} of oil palm were approximately -2.0 MPa, 1800 mmol m^{-2} s^{-1} and 6.10 µmol m^{-2} s^{-1}, respectively, in irrigated condition. Overall, our measured Ψ_L values were within the ranges found in previous studies, but our gas exchange rates of both species were lower than previously reported values. The different developmental stages of sampled trees may contribute to such difference.

Figure 1 shows values of all environmental variables which were averaged during midday period (1000 to 1400 h), corresponding to the time of leaf measurements. During measurement days (Figure 1, red circles), atmospheric vapor pressure deficit averaged 2.01 ± 0.49 kPa (one standard deviation) and average PAR was 1,171.17 ± 221.56 µmol m^{-2} s^{-1} (Figure 1A, solid and dashed line, respectively). Due to the limited option for sensor installations, the measured PAR values were somewhat affected by the partial shading by the building in the afternoon because the values were not consistent with VPD as typically observed. However, this issue did not affect our measurements because we compared the PAR values during measurement days to the threshold at which leaf photosynthesis begins to saturate as previously explained the Methods section. The θ values of *Ta* and *Pm* plot were similar ($p = 0.98$), equally averaged 0.35 ± 0.08 m^3 m^{-3} (Figure 1B, solid and dotted lines; note that θ of both plots shared the same profile). To assess whether the *Ta* and *Pm* in the plots received sufficient water for growth, we compared the measured θ on measurement days to the wilting point of 0.150 m^3 m^{-3}, which was estimated from soil bulk density measured from the site [33]. The result showed that soil moisture in both plots were significantly higher than the wilting point (Figure 1B compare solid line to red dashed line; $p < 0.001$ for both plots, one-sample t-test). Therefore, both *Ta* and *Pm* received enough water through regular irrigation and never experienced water limiting conditions during the study period.

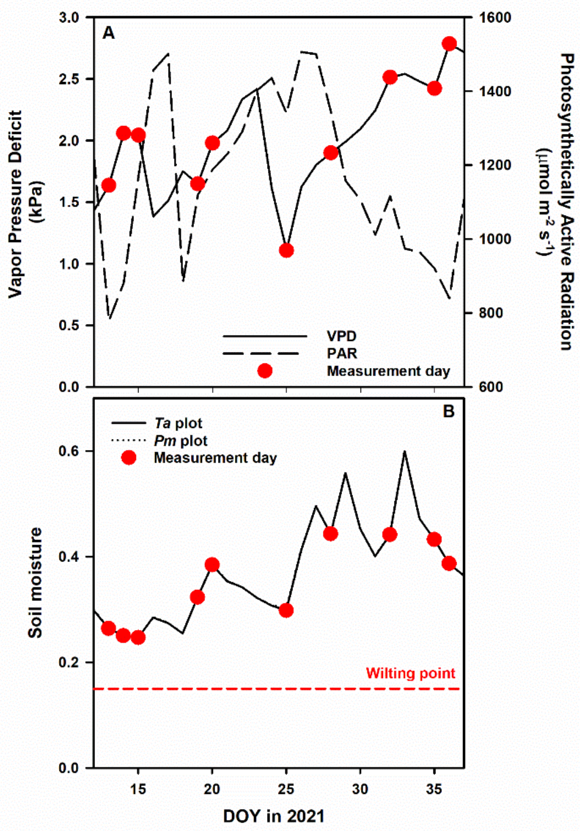

Figure 1 Environmental conditions during the period of data collection including (A) Atmospheric vapor pressure deficit (VPD in cm; solid line) and photosynthetically active radiation (PAR in µmol m^{-2} s^{-1}; dashed line) and (B) soil moisture in *Pm* (dotted line) and *Ta* (solid line) plots. Note that the soil moisture values of the two plots were similar so the two lines were exactly aligned. Values were averaged over midday period (1000 – 1400 h) when leaf measurements were taken. Red circles indicate the days of data collection.

Table 1 Average values and one standard deviation of tree size (e.g., diameter at breast height; DBH in cm) and leaf variables of Tabebuia argentea and Ptychosperma macarthurii that were selected for measurements. The measured variables include midday leaf water potential (Ψ_L; MPa), stomatal conductance (g_s; mmol m^{-2} s^{-1}) and net photosynthesis (A_n; μmol m^{-2} s^{-1})

Species	DBH (cm)	Ψ_L (MPa)	g_s (mmol m^{-2} s^{-1})	A_n μmol m^{-2} s^{-1})
T. argentea	17.67 ± 5.69	-0.69 ± 0.46	96.46 ± 60.78	6.48 ± 3.26
P. macarthurii	6.32 ± 0.18	-1.33 ± 0.22	65.06 ± 25.59	5.87 ± 1.57

First, we examined the dynamics of g_s under changes in atmospheric demand, represented by leaf-to-air vapor pressure deficit (VPD_{LA}) at daily and sub-daily timescales (Figure 2). The VPD_{LA} was measured concurrently with leaf gas exchange parameters using the TARGAS-1 machine. The analysis allowed us to validate whether our selected period for leaf measurements (i.e., 1,000 to 1,400 h) corresponded to high gas exchange rates. Leaf-to-air vapor pressure deficit indicates the difference between vapor pressure inside the leaf, which is under saturation [34], and that in the air. Thus, high VPD_{LA} is associated with dry air and high atmospheric demand for plants. Our data showed that g_s of both *Ta* and *Pm* decreased logarithmically with VPDLA (Figure 2A, Table 2 for regression statistics), indicating stomatal closure at high atmospheric demand [35–36]. The logarithmic function is of the form $g_s = m \times \ln(VPD_{LA}) + b$, where m and b represent the sensitivity of g_s to VPDLA and the maximum g_s at low VPD_{LA}, respectively [35]. Stomatal conductance of *Ta* decreased more rapidly as VPD_{LA} increased compared to that of *Pm* (Figure 2A, compare the m parameters in Table 2). High VPD_{LA} usually induces dehydration of plants, resulting in stomatal closure to reduce water loss [37-38]. For the sub-daily variations, g_s of both species varied following changes in VPD_{LA} (Figure 2B, compare each pair of solid and dashed lines). Note that the profile of VPD_{LA} differed from the commonly observed bell-shaped pattern in natural settings [39]. This is because locations of the sampled trees were close to a concrete wall which stores much heat during daytime and emits it in the late afternoon [40]. Consequently, we observed an increase in VPD_{LA} towards the end of the day, rather than near the midday period (Figure 2B, dashed lines).

For both species, g_s was low in the early morning (i.e., before 700 h) when it was limited by low light and low temperature [41]. After that, g_s increased and reached peaked values between 900 and 1,300 h (Figure 2B, solid lines). Then, in the afternoon, g_s decreased with increasing VPD_{LA} to prevent excessive water loss. Overall, the daytime patterns validated the selected measurement period between 1,000 and 1,300 as high g_s values were observed in both species. Nevertheless, our measured values collected after 1,300 were at least 65% of the maximum among all values for both species, thus validating our results. Additionally, the daytime variations of g_s showed more abrupt decrease as VPD_{LA} increased in *Ta* compared to *Pm*, similar to the result for the daily analysis (Figure 2A).

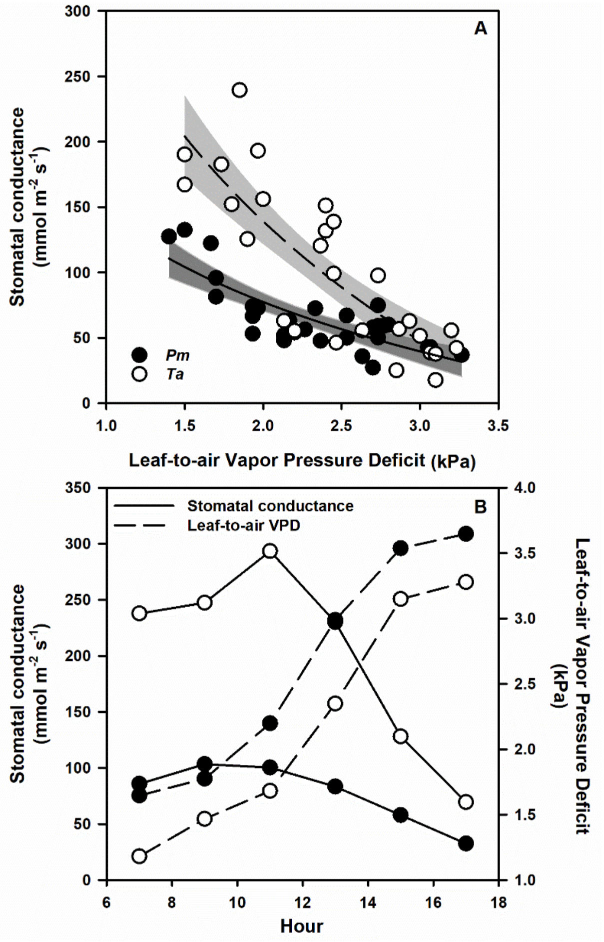

Figure 2 (A) Relationship between stomatal conductance (g_s) and leaf-to-air vapor pressure deficit (VPD_{LA}) of *Pm* (closed circles) and *Ta* (open circles). Gray shaded regions indicate 95% confidence intervals of the regression lines (B) Daytime profile of g_s (solid lines) and VPD_{LA} (dashed lines) of *Pm* (closed circles) and *Ta* (open circles). All measurements in (B) were taken every two hours during the period from 700 to 1,700 h, averaged for three days. Regression statistics are summarized in Table 2.

Table 2 Summary of regression statistics. g_s is stomatal conductance in mmol m^{-2} s^{-1}, VPDLA is leaf-to-air vapor pressure deficit in kPa, Ψ_L refers to leaf water potential in MPa and A_n is net photosynthesis in µmol m^{-2} s^{-1} r^2 and p are the coefficient of determination and *p* value for each regression result. The analyses were based on significance level of 0.05. n/a indicates no significant relationship was found

Figure	Species	Relationship	r^2	*p*
2A	*T. argentea*	$g_s = -225.66 \times \ln(VPD_{LA}) + 295.6$	0.64	<0.0001
	P. macarthurii	$g_s = -93.09 \times \ln(VPD_{LA}) + 142.01$	0.69	<0.0001
3	*T. argentea*	$\Psi_L = -46.72 \times \theta^2 + 34.01 \times \theta - 6.6$	0.84	0.002
	P. macarthurii	n/a	n/a	0.82
4A	*T. argentea*	$g_s = -114.31\ \Psi_L + 32.08$	0.58	<0.0001
	P. macarthurii	n/a	n/a	0.50
4B	*T. argentea* *P. macarthurii*	$A_n = 13.29 \times (1-e^{-0.009g_s})$	0.88	<0.0001

To understand how soil water availability influenced water status in these trees and palms, we investigated the relationship between Ψ_L and θ. Results showed that Ψ_L of *Ta* significantly varied with θ following a quadratic function, while no response was found in Pm (Figure 3, Table 2). Note that data points in Figure 3 correspond to the averages of all measured *Ta* or *Pm* for each measurement day (n = 10 for each species) because variations in soil moisture within a day were low (coefficient of variation was up to 0.3% within each measurement day for both plots). As soil moisture increased, Ψ_L of *Ta* increased until θ reached approximately 0.4 m^3 m^{-3} when it began to decline (Figure 3; solid line). Generally, increasing Ψ_L (less negative) in the beginning may be attributed to the increased water content in plant cells because of high soil moisture [42]. However, our results showed Ψ_L of *Ta* decreased at high soil water. High soil water may restrict water absorption by roots, leading to low plant water status [43]. In fact, a study reported reduced photosynthesis and stomatal conductance in *Tabebuia aurea*, a species of the same genus as *Ta*, under artificial flooded condition [44]. Additionally, based on our observation, the nearly flooded condition often occurred in this garden due to excessive watering in both plots. Unlike *Ta*, *Pm* maintained its leaf water status regardless of changes in soil moisture (Figure 3; closed circles). According to Rivera-Mendes et al. [41], oil palms (*Elaeis guineensis*) growing under partially flooded conditions showed similar leaf gas exchange parameters to those under the optimal soil moisture conditions. Nevertheless, the effect of excessive soil water on trees varies depending on the species, stage of development and duration and frequency of the event.

To gain insights into how leaf gas exchange, which represents plant functioning, responded to soil moisture, we further assessed the relationship between g_s and Ψ_L (Figure 4A) and another one between A_n and g_s (Figure 4B). Results indicated that g_s of *Ta* significantly decreased with increasing Ψ_L whereas no response was discerned in *Pm*. Normally, increased plant water potential results in high water content in guard cells, inducing stomatal opening and thus high stomatal conductance [18]. However, neither *Ta* nor *Pm* exhibited such behavior. The reverse pattern of gs in *Ta* may be attributed to the limited root space for trees in this garden. Because the roots cannot grow freely, they consistently experience well-watered condition under frequent irrigation [47].

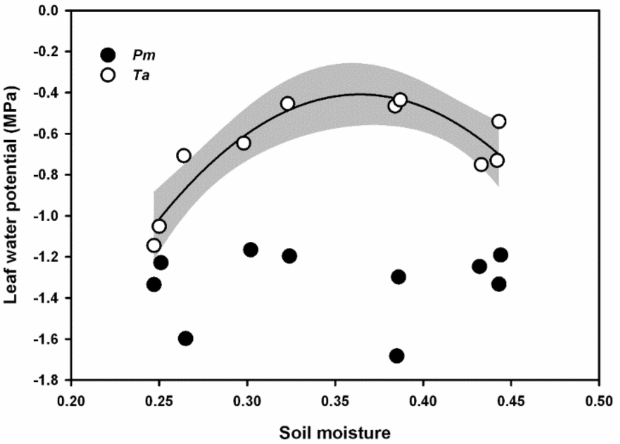

Figure 3 Relationship between midday leaf water potential (Ψ_L) and soil moisture (θ) of *Pm* (closed circles) and *Ta* (open circles) which are reported as the average of all sampled trees or palms during each measurement day. Result of regression is shown in Table 2. Gray shaded region indicates 95% confidence intervals of the regression line.

Consequently, g_s of the trees responded more strongly to VPD_{LA} (Figure 2) than to soil moisture (data not shown, *p* = 0.2833). As shown in Figure 1, during the days with relatively low soil moisture (e.g., the first three measurement days), which would correspond to low leaf water potential (based on the relationship in Figure 3), VPD was relatively lower than other days (e.g., the last three measurement days). Since VPD was highly correlated with VPD_{LA} in this site ($p \leq 0.014$ for both species), the low VPD conditions translated to the high stomatal conductance (Figure 2A). Therefore, gs of *Ta* was high when Ψ_L was low (Figure 4A; solid line). For *Pm*, as previously discussed, high water storage in palms help maintaining transpiration and gas exchange rate, thus allowing consistent g_s across changes in leaf water status [48] (Figure 4A; closed circles).

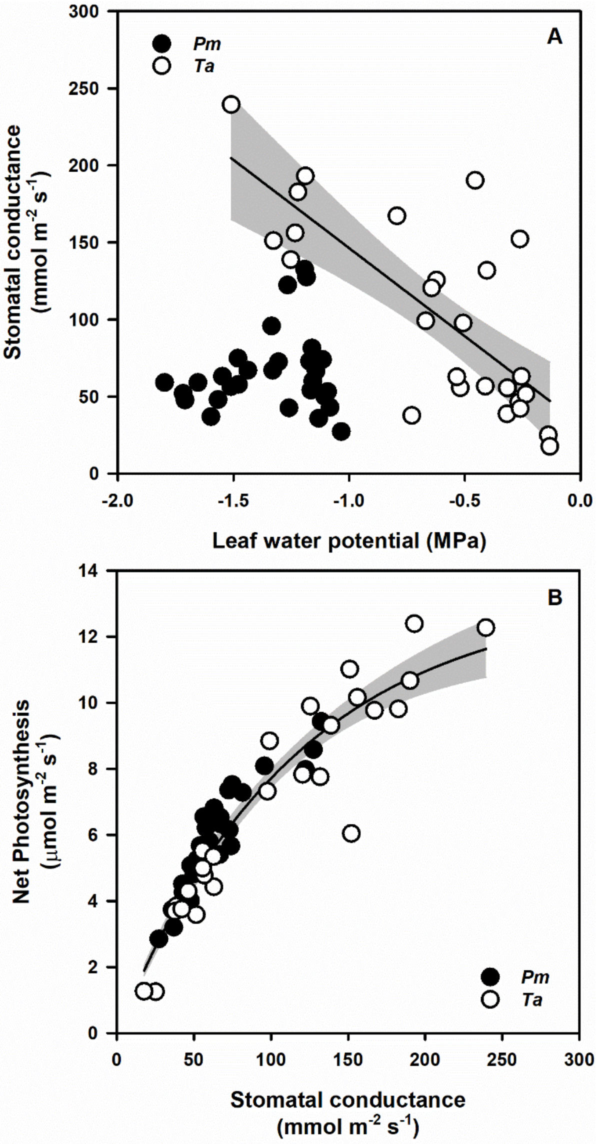

Figure 4 (A) Relationship between stomatal conductance (g_s) and midday leaf water potential (Ψ_L) and (B) between net photosynthesis (A_n) and gs of Pm (closed circles) and *Ta* (open circles). Regression statistics are shown in Table 2. Gray shaded region indicates 95% confidence intervals of the regression line.

Considering the relationship between A_n and g_s, both species displayed similar pattern. Net photosynthesis initially increased with gs and became saturated when g_s exceeded approximately 200 mmol m^{-2} s^{-1} (Figure 4B). This result indicates that both *Ta* and *Pm* have the same stomatal regulation for growth and the absorption of atmospheric carbon dioxide, which may be related to their adaptation to the environments of this garden [49]. Clearly, these results showed that *Ta* was more sensitive to environmental conditions than *Pm* in this roof garden. Comparing our results with a previous study that examined water-use characteristics of *Ta* and *Pm* in this roof garden [33], we found the similar pattern that *Ta* being more sensitive to environmental conditions than Pm on rain-free days. Specifically, based on our measurements under rain-free conditions, *Ta* should be irrigated during daytime, especially when atmospheric VPD 2.6 kPa, to maintain stomatal opening and thus allowing high photosynthesis and transpiration for cooling the leaves. Additionally, *Pm* can be irrigated less frequently to avoid overloading effect on the roof, thereby saving water, and still maintain water status and productivity of the palms.

Conclusions

In this study, we presented a simple investigation of how urban tree (*Tabebuia argentea*; *Ta*) and palm (*Ptychosperma macarthurii*; *Pm*) species, growing in the same tropical roof garden, responded to environmental changes, provided normal irrigation during rain-free period. Specifically, we measured leaf water status and leaf gas exchange parameters, representing plant growth and function, and analyzed their relationships with soil and air humidity. Results indicated that *Ta* was more sensitive to changing atmospheric and soil moisture than *Pm*. Because net photosynthesis was significantly related to stomatal regulation in both species, careful maintenance by considering the different behaviors of these species is needed. Our data suggested that, for this roof garden, the trees (*Ta*) should be irrigated during daytime when atmospheric vapor pressure deficit is below 2.6 kPa to allow high photosynthesis and evaporative cooling of the leaves. Additionally, the palms (*Pm*) may be watered less frequently to avoid excessive loading of the roof and save water. Our results serve as an initial investigation of how irrigation practice could be adjusted to maximize plant growth and optimize water use in urban settings, especially in highly polluted cities such as Bangkok. Nevertheless, we warrant a comprehensive study including multiple temporal and spatial scales to fully confirm these results.

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