Transpiration and cooling potential of tropical urban trees from different native habitats

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HIGHLIGHTS

- Assessed whole tree transpiration of tropical urban trees in replicated field studies
- Trees from seasonally dry forests transpired more than trees from aseasonal forests under cloudy sky.
- Transpiration was more dependent on solar radiation than vapor pressure deficit.
- Leaf stomatal conductance was a predictor of whole-tree transpiration.

GRAPHICAL ABSTRACT
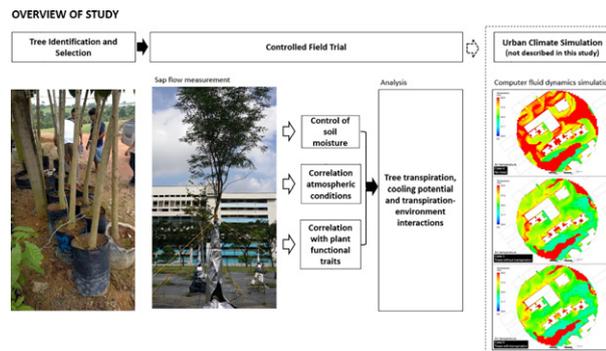
ABSTRACT

Urban trees are widely promoted as a solution to cool the urban environment because of shading and evaporative cooling provided by tree canopies. The extent to which the cooling benefits are realized is dependent not just on the genetically determined traits of trees, but also by their interactions with the atmospheric and edaphic conditions in urban areas, for which there is currently a paucity of information. We conducted a field experiment to compare whole-tree transpiration (E_t) of tropical urban species from seasonally dry forest (SDF) (*Tabebuia rosea, Lagerstroemia speciosa, Delonix regia, Caesalpinia ferrea, Dalbergia sissoo, Samanea saman*) and aseasonal evergreen forest (AEF) (*Peltophorum pterocarpum, Sindora wallichii*). We examined the dependence of E_t on atmospheric conditions (solar radiation (R_n) and vapor pressure deficit (VPD)), as well as on soil moisture level (θ_v). Daily E_t differences between species were large but not statistically significant overall: 2000–3200 g m^{-2} (leaf area) under sunny conditions and 980–2000 g m^{-2} under cloudy conditions. The led to a daily latent heat flux (LE) of 770 W m^{-2} between the species with the highest (2136 W m^{-2}) and lowest (1369 W m^{-2}) daily E_t. SDF species had higher daily E_t than AEF species, but the difference was only significant under cloudy condition. R_n had a slightly stronger role in influencing transpiration compared to VPD, and species responses to drought stress differed marginally between the two groups. We assessed if two plant functional traits, wood density

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(ρ_w) and leaf stomatal conductance (g_s), could be used to predict E_t. Only g_s was shown to be moderately correlated with E_t, but more studies are needed to assess this given the limited number of species used in the study.

1. Introduction

Urban trees form a key element of a city's green infrastructure because of the numerous social and ecological benefits they provide. A widely recognized benefit of urban trees is their ability to cool the urban environment (Erell, 2017). The cooling effects of trees can be attributed to two distinct mechanisms: evapotranspiration and shading (Oke et al., 1989). Evapotranspiration produces an evaporative cooling effect arising from the combined effects of evaporation from soil surfaces and transpiration from vegetation canopies (Akbari, 2002). It leads to conversion of radiant energy to latent heat rather than sensible heat, thereby reducing further increases in air temperature. The shading effect arises through interception of solar radiation by tree canopies, which leads to reduction in heat gain, storage, and emission of long-wave radiation by surfaces such as building walls and paved areas. Urban trees, either singly or in tree stands, thus generate cooler air within and under vegetation canopies, which through advection, produces an "oasis effect" or "cool island" (Hamada and Ohta, 2010; Taha et al., 1991) to adjacent built-up areas.

One important strand in current research on the cooling contributions of urban trees is to understand species differences in cooling capacity as a means towards selecting higher performing species. Studies by Armson et al. (2013), de Abreu-Harbich et al. (2015), Gillner et al. (2015), Lin and Lin (2010), Moss et al. (2018), Rahman et al. (2015), and Sanusi et al. (2017) all point to the potential of exploiting the physiological understanding of trees, their biophysical relationships with the environment, and canopy architecture to improve urban cooling by trees. Thus far, the evidence suggests that species differences in cooling effect can be large. For instance, Rahman et al. (2015) showed that there was a three to four-fold difference in daily cooling effect of about 2.2 kW per tree between temperate species. Gillner et al. (2015) showed that the air temperature difference between canopies of temperate urban trees and exposed reference sites differed by about eight times between species. More deliberate use of urban trees guided by an understanding of their physiological behavior thus appears promising as a strategy to improve the contributions of trees for urban cooling.

In this study, we assessed the transpiration of tropical urban trees and their interactions with the environment given its importance to the urban climate. Transpiration, as part of land evapotranspiration, is a critical component of energy and water budgets at global level (Jung et al., 2010) and at the city scale (Cleugh and Grimmond, 2012). Moss et al. (2018) recently demonstrated the role of E_t of urban trees in reducing energy consumption for cooling buildings. Despite its importance, there is a high level of uncertainty in estimating transpiration at the urban forest level (Litvak et al., 2017) and species level (Moss et al., 2018; Peters et al., 2010). There are also other important knowledge gaps.

First, there is a paucity of knowledge on transpiration of tropical urban trees. We are not aware of any published information which systematically compared transpiration of tropical tree species, except for the recent report by Edwards et al. (2016). The paucity of studies on tropical urban vegetation in relation to their benefits and ecological characteristics has also been highlighted recently (Song et al., 2017). This is an important knowledge gap, not the least because the different environmental challenges encountered in tropical urban areas should be used to prioritize the types of ecosystem services expected of urban trees (ibid), but also because climate has a marked influence on the primary mechanisms responsible for the cooling effects by trees.

Second, there is a need to improve our knowledge of the interactions between tree transpiration and environmental conditions in urban areas. Transpiration of trees is affected not just by genetically determined properties, such as stomatal control, wood anatomy and various leaf traits, but also by the vapor pressure of the air (which is in turn, dependent on solar radiation, temperature and relative humidity), as well as the level of soil moisture available to support transpiration (which is in turn, determined by precipitation and geological and topographical conditions). In other words, urban environmental conditions also influence the extent of transpiration and cooling provided by trees. This reciprocity, coupled with impending changes in urban conditions with climate change, implies that we need to have a better understanding of tree-environmental interactions under anticipated climate change scenarios for the contributions of trees to be sustained (McPherson et al., 2018). Given the influence of climate on urban environmental conditions, knowledge of tree-environment interactions need to be localized to specific climates. Knowledge of such interactions is highly limited in tropical urban areas.

Third, there is still a limited number of studies which adopt a more predictive approach towards tree selection. Many studies characterize differences in cooling effects between species, which although produces valuable knowledge, do not address the challenge of dealing with the large diversity in urban tree species worldwide. This large diversity makes it extremely resource-intensive to empirically determine the characteristics of all urban trees (Sanusi et al., 2017). For instance, in Singapore, there are >500 urban tree species (Tan et al., 2009), making it impractical to rank species based on their cooling properties through field measurements. Predicting which species tend to have higher cooling properties based on plant functional types, easily measurable traits, or using more readily available information should be more widely employed as a strategy. For instance, knowing evapotranspiration differences between plant functional types (evergreen or deciduous trees, and cool-season grass) seem adequate to predict evapotranspiration in temperate cities (Peters et al., 2011). O'Brien et al. (2017) showed that key plant functional traits such as wood density, tree size and growth have large influence on drought-induced mortality of trees across climate zones and can be used to select trees with higher drought tolerance.

Fourth, the potential to use geographical origins of trees to select trees appears to be a promising approach. For instance, Kjelgren et al. (2011) suggested that the geographical origin of trees can be used to select trees better adapted to harsher urban conditions brought about by climate change. Recently, Stratópoulos et al. (2018) showed that the native habitats of temperate trees have distinct sap flow rates and growth rates. The impact of geographical origin of species is clear—between extreme climates, species from dry climate can be expected to have reduced transpiration compared to species from the humid or wet tropics as a water conservation strategy. Within tropical regions, there are also wide variations in ecohydrology of ecosystems. One example is the distinction between seasonally dry forests (SDF) and aseasonal wet evergreen forest (AEF) in the tropics, in which trees exhibit different physiological and phenological responses to seasonal changes in moisture availability (Ishida et al., 2006). In SDFs, dry seasons with high temperatures and high vapor pressure deficit (VPD) create conditions for rapid water loss and risk of tissue desiccation. Species in such conditions develop adaptations, such as leaf shedding (in drought-deciduous species), and maximizing stem storage and maintaining adequate carbon stores (in dry evergreen species) (Vico et al., 2015). Tropical deciduous trees from SDFs thus exhibit distinct periodicity in

growth and water use. When water supply is non-limiting, growth is rapid and transpiration is expected to be high; when water is limiting, leaves are shed to avoid drought stress. Such species also appear to be more tolerant of drought and higher temperatures than evergreen species (Kjelgren et al., 2011). Trees from AEFs on the other hand, invest less biomass for developing deep root systems because of the uniform availability of water year-round, are less tolerant of soil moisture deficit and atmospheric dryness, and appear to have higher stomatal control in response to increasing VPD (Baltzer et al., 2008; Kjelgren et al., 2011).

The study focuses on quantifying species differences in E_t of tropical urban tree species and assessing if E_t might be related to the geographical origin and functional traits of species. We are particularly interested in trees from SDFs as these species exhibit higher maximal stomatal conductance and wider vessels in the xylem than wet-evergreen species, indicating higher potential for sap-flow (Ishida et al., 2006). We test the hypothesis that dry deciduous trees from SDFs have higher transpiration rates when water supply is non-limiting compared to trees from AEF. In the wet tropics, moisture availability is non-limiting for plant growth throughout the year and the higher transpiration rates of SDF trees can potentially lead to a higher evaporative cooling potential in urban areas. Evaporative cooling potential can in turn be estimated from latent heat flux calculated from whole-tree transpiration. This study has three specific objectives: (1) to quantify whole-tree transpiration and the associated latent heat flux of SDF and AEF trees under the wet, humid conditions of tropical Singapore; (2) to evaluate responses of transpiration to key environmental variables, namely solar radiation, *VPD* and soil moisture; and (3) to examine if whole-tree transpiration can be predicted with two plant functional traits (wood density and leaf stomatal conductance).

2. Materials and methods

A controlled field experiment was conducted to characterize E_t of nine tropical species under two irrigation regimes: well-watered and water-withheld conditions. Atmospheric environmental variables and plant functional traits were simultaneously measured and correlated to E_t.

2.1. Experimental setup and species selection

A field experiment was set up in an open field (1°18′0.33″N, 103°46′10.79″E) in Singapore. The site was fully exposed and not under direct shadow of adjacent buildings or other structures. The turfed area was covered in heavy-duty canvas to reduce influence of evaporation from the turf on transpiration measurements. The study was conducted

over two phases: in Phase 1 (5 May 2016 to 30 September 2016) four species were studied: *Tabebuia rosea*, *Brachychiton acerifolius*, *Lagerstroemia speciosa*, *Delonix regia*, and in Phase 2 (13 January 2017 to 30 June 2017) five species were studied: *Caesalpinia ferrea*, *Dalberghia sissoo*, *Peltophorum pterocarpum*, *Samanea saman*, *Sindora wallichii* species (Table 1). Conducting the study in phases was necessary to achieve adequate replication per species within the space and with the equipment available. These nine species are currently used as urban trees in Singapore and in South-East Asia (Chong et al., 2011; Kjelgren et al., 2011). Of the nine species, two species are from AEF: *P. pterocarpum* and *S. wallichii*. *P. pterocarpum* has a wide distribution in the lowland humid tropics, including beach forests and mangroves (Orwa et al., 2009); *S. wallichii* is naturally distributed in the Malay Peninsula, Sumatra and Borneo, and tends to be associated with aseasonal evergreen forests (Baltzer et al., 2008). Both species are native to Singapore, which has a wet climate defined "tropical rainforest" (Af) in the Köppen climate classification. The remaining species are from SDFs, which are defined by distinct wet and dry seasons under the influence of episodic monsoonal rainfalls and are known to have deciduous or semi-deciduous leaf habit in their place of origin.

The tree specimens were purchased from commercial nurseries and selected to have as uniform dimensions (height, canopy size, and girth) as possible. The trees were 3–4 m in height and 6.5–9 cm in DBH and were potted in 144 l size pots. The soil was a soil mix of loamy soil, compost and washed sand in the volumetric ratio of 3:2:1 (CUGE, 2013). The tree specimens were acclimatized on site under well-watered conditions for 30 to 45 days prior to the commencement of measurements. Between three to four replicates were used per species, but due to equipment failure or poor tree growth for several species, data presented were means of two to four replicates.

In each phase, replicates were randomly placed in rows of four by five in the open field, and space 6 m apart from trunk to trunk. After the initial establishment period, measurements commenced on the trees, first over a well-watered period followed by a water-withheld period to induce drought conditions. During the establishment and well-watered periods, an automated irrigation system was used to water the plants twice daily for a duration of 10 min with 32 l of water each session. This provided a total of 64 l of water to each tree per day. During the water-withheld-period, irrigation was turned off for between three to eight days.

As transpiration of urban trees are known to be affected by solar radiation (Litvak et al., 2017), it is necessary to compare transpiration data collected over the two phases when solar radiation levels were approximately equivalent. Two types of sky conditions were used to compare transpiration among species: "sunny" sky condition (defined as a rain-

Table 1
Tree species used for the study. "Native" refers to species Singapore as native habitat (Reference: Chong et al. (2009)).

Scientific name	Geographical origin	Forest type	n[b]	Total leaf area (m²)/(LAI)[c]
Phase 1 (5 May 2016 to 30 September 2016)				
Tabebuia rosea (Tr)	Central America	SDF	4	2.0–3.9/(0.93–1.96)
	South America - North and South of Amazon			
Brachychiton acerifolius (Ba)[a]	North- Eastern Australia (Queensland)	SDF	4	1.7/(1.15)
Lagerstroemia speciosa (Ls)	India, Indochina	SDF	4	3.6–4.5/(1.50–2.49)
Delonix regia (Dr)	Central and South Africa, West Africa, West Madagascar	SDF	4	3.7–3.9/(1.76–1.77)
Phase 2 (13 January 2017 to 30 June 2017)				
Caesalpinia ferrea (Cf)	Central America	SDF	3	2.3–3.7/(1.46–2.13)
	South America - North and South of Amazon			
Dalberghia sissoo (Ds)	India, Indochina	SDF	3	1.6–3.5/(1.16–1.92)
Peltophorum pterocarpum (Pp)	Malay Peninsula, Sumatra, Borneo, Indo-China, Northern Australia	AEF (native)	3	2.0–2.9/(1.62–1.81)
Samanea saman (Ss)	Central America	SDF	3	1.8/(1.22)
	South America - North and South of Amazon			
Sindora wallichii (Sw)	Malay Peninsula, Sumatra, Borneo	AEF (native)	3	2.3–3.4/(1.86–2.20)

[a] *B. acerifolius* was observed to be highly sensitive to the heat application from sap flow and showed charred stems and very low sap flows as a consequence of impaired water movement. As such, results from this species were excluded from all analysis.

[b] n = number of replicates.

[c] Data for 28 Aug 2016 and 25 Feb 2017 for sunny conditions.

free day with peak R_n higher than 600 W m^{-2} and with R_n that was as symmetrical over the day as possible), and "cloudy" sky condition (defined as a rain-free day with peak R_n less than or close to 400 W m^{-2}). A sunny and a cloudy day were selected from each phase and corresponding the atmospheric and soil moisture conditions are shown in Fig. 1. Sunny days have T_a from 25 to 32 °C, and VPD from 0.14 to 1.6 kPa over the observation period, whereas the corresponding values for cloudy days were 25 to 31 °C and 0.12 to 1.3 kPa, respectively. Daytime variations of R_n, T_a and VPD generally showed similar pattern, but whereas peak values of R_n occurred between 12:00 and 13:30 on sunny days, T_a and VPD peaked between 14:30 and 17:00. θ_v was maintained between 0.28 and 0.34 cm^3 cm^{-3} in between the scheduled irrigation periods (well-watered period) within a day.

For the water-withheld treatment, the periods selected for comparison was 27 Sep to 30 Sep 2016 for *T. rosea* and *D. regia*, and 6 Apr to 11 Apr 2017 for *C. ferrea*, *D. sissoo*, *P. pterocarpum*, *S. saman* and *S. wallichii*. Sunny day data for 29 Sep 2016 and 11 Apr 2017 were used for the two batches of trees. The average θ_v of the preceding day was 0.21–0.24 cm^3 cm^{-3} whereas the corresponding values under well-water conditions for sunny days (26–28 Aug 2016, 23–25 Feb 2017) were 0.31–0.32 cm^3 cm^{-3}. At the lower θ_v, there was visible wilting of leaves, indicating that the trees were drought-stressed.

2.2. Measurement of whole-tree transpiration and other plant traits

2.2.1. Sap-flow measurements

Whole-tree sap flow was measured using Dynagage Sap Flow Sensor SGA70-WS (Dynamax Inc., Houston, USA), which is based on the stem heat-balance approach (Baker and Bavel, 1987; Sakuratani, 1981). The data were collected in the Flow32-1K Sap Flow Monitoring System (Dynamax Inc., Houston, USA). The heat-balance method has the advantages of being non-intrusive and not requiring the estimation of cross-sectional sap wood area. The sap flow sensors were installed on the main trunk of the specimens. To ensure good thermal contact between the stem and the thermocouples, the trunk was first smoothened with sand paper, and then applied with a thin layer of granola oil. The heating strips within the sensors were coated with a thin layer of silicone insulation material to prevent moisture from building up between the sensor and trunk. To reduce the influence of heat from the soil on the temperature measurements, sap flow sensors were placed as high up in the trunk as possible. The sensor was wrapped with two layers of reflective foil-faced bubble sheet to shield the trunk from external radiation and reduce heat gain from solar radiation. All pots were wrapped with plastic sheets to reduce soil evaporation. Water loss from the pot was thus mainly through transpiration.
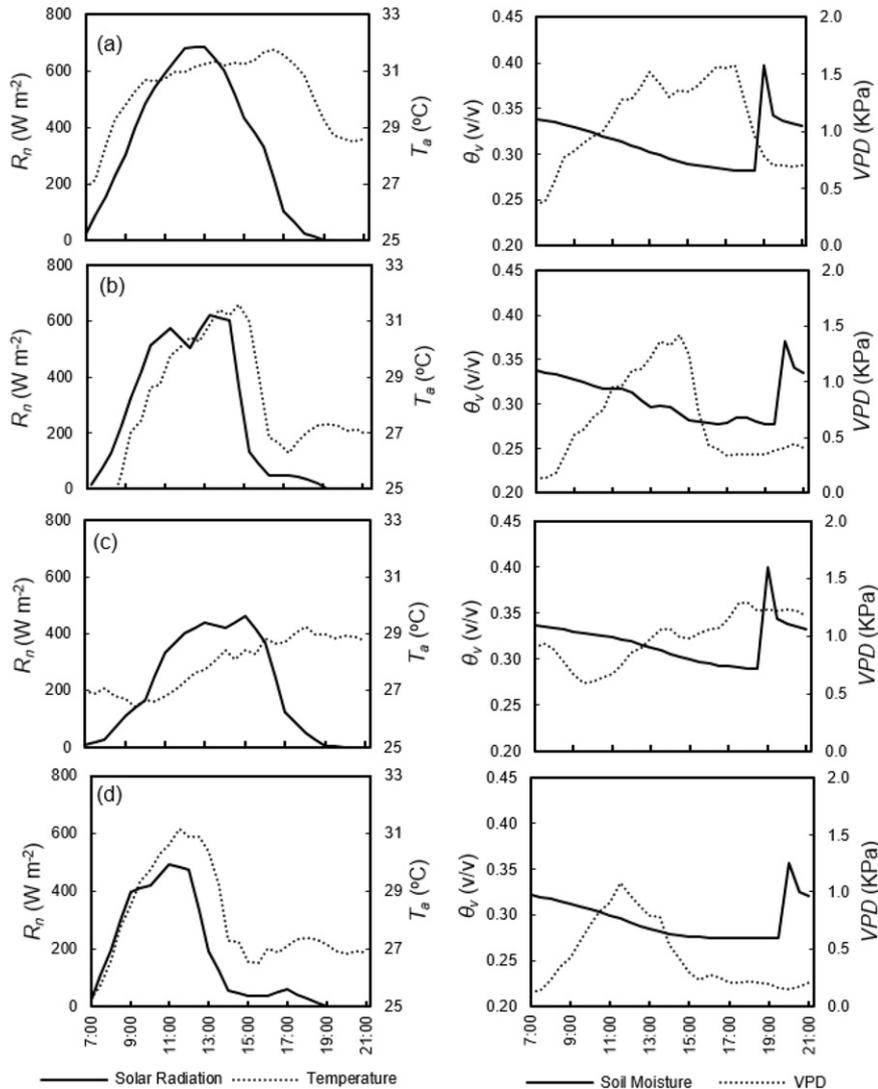
Fig. 1. Solar radiation (R_n), *VPD*, ambient air temperature (T_a) and volumetric soil water content (θ_v) for sunny days (a) Phase 1–28 Aug 2016, (b) Phase 2–25 Feb 2017; cloudy days (c) Phase 1–24 Aug 2016, (d) Phase 2–14 Apr 2017.

Sap flow data was logged every 30 min from 7 am to 9 pm. The sheath conductance which corresponds to zero sap flow was recorded and input into the programme each time the sensors were removed for maintenance and reinstalled. The zero sap flow values were obtained during predawn (from 4 am to 5 am) on the following day after installation.

To assess the accuracy of sap flow measurement, direct measurement of water loss was measured using a weighing balance which recorded weight continuously and simultaneously with sap flow measurements. Two sets of stainless steel weighing beams (PCE-SD 600B SST) (PCE Instruments, Meschede, Germany) were used to measure the weight of the pots and trees. Data was collected every 1 min and logged every 5 min, then aggregated to hourly averages. The weighing balance was rotated to different species in conjunction with sap flow measurements. The correlation between daily cumulative sap flow per tree and daily weight loss measured by the weighing balance for four species of trees produced a significant linear correlation ($p < 0.001$) and moderately high R^2 of 0.61.

Sap flow data (g hr^{-1}) was converted to whole-tree transpiration per unit leaf area (E_t, g m^{-2} h^{-1}) by dividing sap flow with the estimated total leaf area per tree. Transpiration was also converted to latent heat flux using Eq. (1) (Allen et al., 1998):

$$LE = \lambda * Q \tag{1}$$

where:

LE = latent heat flux (MJ m^{-2} h^{-1})
λ = latent heat of vaporization (2.43 MJ kg^{-1})
Q = water flux (kg m^{-2} h^{-1})

LE was converted from MJ m^{-2} h^{-1} to W m^{-2} using conversion ratio of 3.6 MJ m^{-2} = 1000 W m^{-2}.

2.2.2. Leaf stomatal conductance and wood density

Leaf stomatal conductance (g_s) was measured with a steady state leaf porometer (Decagon Devices Inc., Washington, USA). Measurement was made on three sun-lit, youngest mature leaves per replicate. For *D. regia*, *C. ferrea*, *P. pterocarpum*, *S. saman*, g_s was not measured as the leaflets were too small to be measured within the chamber of the porometer. Wood density (ρ_w) was sourced from Desch and Dinwoodie (1996), Reyes et al. (1992) and World Agroforestry Centre (n.d.).

2.2.3. Total canopy leaf area

The total canopy leaf area was estimated to convert sap flow into transpiration per unit leaf area. It was estimated by multiplying the projected canopy area with the leaf area index (LAI). The former was estimated by mapping out the canopy area on ground level and latter was measured with the LI-COR LAI-2000 Leaf Canopy Analyzer (LI-COR, Nebraska, USA), following the steps described in Tan and Sia (2009, 14) using the procedure for measurement of solitary trees. Measurements were done under cloudy conditions to avoid direct sunlight on the sensor. The LAI-2000 was placed under the tree canopy about 0.3–0.4 m beneath the point where branches are attached to the trunk and view caps were used to block the view of obstruction by the trunk. Four readings taken in different directions 90° apart was used per tree whereas one reading for the fully exposed light condition outside the canopy was recorded simultaneously for comparison.

2.3. Micrometeorological and soil water data

2.3.1. Atmospheric data

Solar radiation (R_n), air temperature (T_a), relative humidity (RH), wind speed and rainfall were measured on site using a HOBO Weather Station (Onset Computer Corporation, Massachusetts, USA). All the data were recorded on one-minute interval and aggregated to half-hourly and hourly averages.

2.3.2. Vapor pressure deficit

Atmospheric vapor pressure deficit (VPD) is the difference between saturation and actual vapor pressure and is an indicator of the evaporative capacity of the air. VPD was derived using RH and T_a data collected from the weather station following Allen et al. (1998, 40):

$$VPD = e_s - e_a \tag{2}$$

where:

e_s = saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)

The saturation vapor pressure at air temperature was first calculated using:

$$e^o(T_a) = 0.6108 \exp\left[\frac{17.27 T_a}{T_a + 237.3}\right] \tag{3}$$

where:

$e^o(T_a)$ = saturation vapor pressure at air temperature T_a (KPa)
T_a = air temperature (°C)

Due to the non-linearity of Eq. (3), the mean saturation vapor pressure was computed using hourly maximum (T_{max}) and minimum (T_{min}) air temperatures:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{4}$$

The actual vapor pressure was derived from maximum and minimum relative humidity:

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \tag{5}$$

where:

$e^o(T_{min})$ = saturation vapor pressure at hourly minimum temperature (kPa)
$e^o(T_{max})$ = saturation vapor pressure at hourly maximum temperature (kPa)
RH_{max} = maximum hourly relative humidity (%)
RH_{min} = minimum hourly relative humidity (%)

2.3.3. Soil moisture and irrigation control

Volumetric soil water content (θ_v) was measured using ONSET 10HS Soil Moisture Smart Sensor (Onset Computer Corporation, Massachusetts, USA). One sensor was installed in one pot per species. The probes were inserted vertically such that the end of the probes was at a depth of about 5 cm beneath the soil surface. The accuracy of the instruments used in the study is shown in Table 2.

2.4. Statistical analysis

Non-parametric tests were used to compare species and group (AEF, SDF) differences. Normality of data was assessed using Shapiro-Wilk test and assessment of kurtosis and skewness. Overall species differences were tested using the Kruskal-Wallis H test, whereas differences between SDF and AEF trees were assessed using the Mann Whitney U test. Multiple linear regression was used to compare relative effects of R_n and VPD in influencing whole-tree transpiration, and linear regression was used to examine correlation between E_t, and g_s and ρ_w. All statistical analyses were conducted with SPSS Statistics 23 (IBM Corp,

Table 2
Measurement range and accuracy of equipment used.

| Variables	Equipment	Measurement range	Accuracy
Sap flow	Dynagage Sap Flow Sensor SGA70-WS	Depends on setting	dT $\pm$0.1 °C
	Flow32-1K Sap Flow System		$\pm$1μv
Weight	PCE Instrument stainless steel weighing beams PCE-SD 600B SST	Maximum 600 kg	$\pm$0.2 kg
Air temperature	Onset 12-bit Temperature/Relative Humidity Smart Sensor	$-40°$–75 °C	$\pm$0.21 °C (0° to 50 °C)
Relative humidity	Onset 12-bit Temperature/Relative Humidity Smart Sensor	0–100% RH	$\pm$2.5% (10% to 90% RH)
Soil moisture	Onset 10HS Soil Moisture Smart Sensor	0–0.570 m^3 m^{-3} (volumetric water content)	$\pm$0.033 m^3 m^{-3}
Solar radiation	Onset S-LIB-M003	0–1280 W m^{-2}	$\pm$10 W m^{-2} or $\pm$5%
Wind speed	Onset Wind Speed Smart Sensor, S-WSA-M003	0–45 m s^{-1}	$\pm$1.1 m s^{-1} or $\pm$4%
Rainfall rate	HOBO Rain Gauge Data Logger	Maximum 12.7 cm h^{-1}	$\pm$1.0%
Stomata conductance	Decagon SC-1 Porometer	0–1000 mmol m^{-2} s^{-1}	$\pm$10%
Leaf area index	LI-COR LAI-2000 Leaf Canopy Analyzer	320–490 nm	

Armonk, NY, United States). For *S. saman*, as data was only available for one specimen due to poor growth of other replicates after transplanting from the nursery, it was excluded from all statistical analyses. We provide additional information on *S. saman* in Appendix 1 given that it is the species with the highest population in urban plantings in Singapore (Tan et al., 2009).

3. Results

3.1. Transpiration under sunny and cloudy atmospheric conditions

Transpiration over a day generally reflected diurnal patterns of R_n and *VPD* both on sunny and cloudy days. This was particularly clear on 25 Feb 2017 when the dip in solar radiation around 13:00 was mirrored by dips in hourly E_t for *C. ferrea* and *D. sissoo*. Peak E_t generally occurred between 11:00 am and 1:30 pm over sunny and cloudy days, and different species showed peak E_t over different times over this period (Fig. 2). Differences in peak hourly E_t were marginal among species. Most species had equivalent peak hourly E_t of 400–600 g m^{-2} on sunny days, and 200–400 g m^{-2} on cloudy days, with the exception of *L. speciosa*, which had peak hourly E_t at 700 g m^{-2}.

E_t under cloudy conditions was significantly reduced compared to sunny conditions (Table 3). The change in sky conditions affected species differently, from 16% in *T. rosea* to 56% in *P. pterocarpum*. The average reduction was 42% (s.d. = 18%) (data not shown).
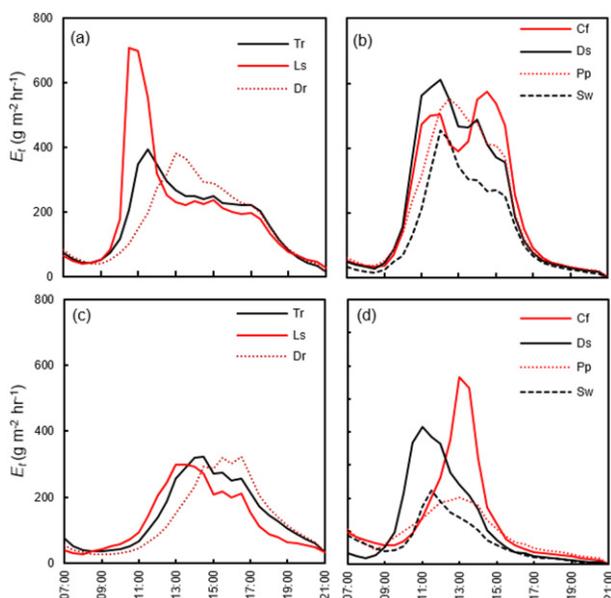
Fig. 2. Hourly E_t (g m^{-2} (leaf) hr^{-1}) on sunny days (a) on 28 Aug 2017 (b) 25 Feb 2017; cloudy days (c) on 24 Aug 2017, (d) 14 Apr 2017.

3.2. Transpiration and latent heat flux differences among species

Daily E_t translates to 1400–2100 W m^{-2} of *LE* under sunny conditions and 900–1400 W m^{-2} under cloudy conditions. Under sunny conditions, the highest difference in E_t between species was 56% (between *S. wallichii* and *C. ferrea*) (Table 3). Under cloudy conditions, the differences were also high but much reduced compared to sunny conditions.

Average E_t was similar between AEF and SDF species under sunny conditions, but significantly higher in SDF species under cloudy conditions (Table 4). Peak hourly LE was also higher in SDF than AEF species, but the difference was not statistically significant.

3.3. Responses to environmental variables

3.3.1. Vapor pressure deficit

For all species, there was a moderately strong to strong linear relationship between E_t and hourly atmospheric *VPD* under sunny conditions (Fig. 3a). The strength of the relationship was reduced under cloudy conditions. Overall across species, the sensitivity (taken as the gradient of the linear lines) of species to *VPD* was reduced under cloudy conditions. The mean sensitivity to *VPD* of AEF species (374 $\pm$ 94) was comparable to SDF species (325 $\pm$ 137) under sunny conditions; under cloudy conditions, sensitivity was higher in SDF (377 $\pm$ 70) than AEF species (170 $\pm$ 10) under cloudy conditions, but this was not statistically significant (Mann-Whitney *U* test, $p = 0.333$) (data not shown).

3.3.2. Solar radiation

Similar comparison was made between hourly E_t and hourly R_n (Fig. 3b). As for correlation with *VPD*, the linear relationship of E_t to R_n was generally moderately strong to strong under sunny conditions and was reduced under cloudy conditions for all species. The sensitivity of hourly E_t to R_n was higher under sunny than cloudy conditions. Sensitivity was also higher in SDF species (0.333 $\pm$ 0.024) than AEF species (0.145 $\pm$ 0.004) under cloudy conditions, but this was not statistically significant (Mann-Whitney *U* test, $p = 0.083$, data not shown). Overall, the general sky conditions affected the correlation between E_t and R_n more than between E_t and *VPD*.

3.3.3. Responses to drought

E_t under drought and well-watered were compared under sunny days. E_t was markedly reduced by drought. The reductions ranged between 92% in *T. rosea* to about 43% in *D. sissoo* (Table 5). There were no consistent responses of E_t to drought compared to daily or peak hourly E_t for the different species (in Table 3). AEF and SDF species did not show significant differences under drought, with average reduction of 36% and 33%, respectively (Mann-Whitney *U* test, $p = 0.683$) (data not shown).

Table 3

Daily transpiration and daily and peak hourly latent heat flux for selected days. (n1, n2) indicates number of replicates used in the analysis for sunny and cloudy sky, respectively. Numbers are mean $\pm$ standard deviation (sd). (*p* values) indicate statistical significance for Kruskal-Wallis H Test between species in the respective columns. All z-scores for skewness and kurtosis were all lower than the threshold of 1.96, except for z-score for kurtosis for E_t for Pp and Tr (data not shown).

Species	E_t (daily transpiration) mean $\pm$ sd (g m^{-2})		LE (daily latent heat flux) mean $\pm$ sd (W m^{-2})		Peak LE (latent heat flux) mean $\pm$ sd (W m^{-2})	
	Sunny ($p = 0.479$)	Cloudy ($p = 0.438$)	Sunny ($p = 0.479$)	Cloudy ($p = 0.438$)	Sunny ($p = 0.171$)	Cloudy ($p = 0.742$)
Caesalpinia ferrea (Cf) (2,3)	3164 $\pm$ 300	1835 $\pm$ 1042	2136 $\pm$ 203	1239 $\pm$ 703	462 $\pm$ 105	389 $\pm$ 292
Dalbergia sissoo (Ds) (3,3)	3150 $\pm$ 64	1656 $\pm$ 404	2126 $\pm$ 43	1118 $\pm$ 272	451 $\pm$ 43	311 $\pm$ 120
Delonix regia (Dr) (2,2)	2382 $\pm$ 100	1917 $\pm$ 291	1608 $\pm$ 68	1294 $\pm$ 197	295 $\pm$ 68	218 $\pm$ 18
Lagerstroemia speciosa (Ls) (2,4)	2833 $\pm$ 577	1861 $\pm$ 476	1912 $\pm$ 390	1256 $\pm$ 321	537 $\pm$ 244	235 $\pm$ 45
Peltophorum pterocarpum (Pp) (3,1)	2931 $\pm$ 600	1302	1978 $\pm$ 405	879	390 $\pm$ 162	135
Sindora wallichii (Sw) (2,2)	2028 $\pm$ 959	981 $\pm$ 284	1369 $\pm$ 647	662 $\pm$ 192	306 $\pm$ 93	170 $\pm$ 121
Tabebuia rosea (Tr) (4,3)	2450 $\pm$ 795	2054 $\pm$ 536	1654 $\pm$ 536	1386 $\pm$ 362	272 $\pm$ 80	218 $\pm$ 37

3.3.4. Multiple linear regression model for transpiration

A multiple linear regression was used to assess the degree to which hourly E_t is explained by R_n and VPD using data from for sunny and cloudy conditions. Volumetric soil moisture content was excluded given the lack of linear correlation with hourly E_t (data not shown). ANOVA showed that the multiple linear regression model was statistically significant at $p < 0.001$ (Table 6). The Variance Inflation Factor of 1.478 indicates that collinearity between the two independent variables was not a problem. The standardized coefficients showed that R_n has marginally higher effect than VPD on the total variance in E_t.

3.4. Correlation of transpiration with wood density and stomatal conductance

Daily E_t over the full measurement periods of the two phases of measurements was compared to wood density (ρ_w). *C. ferrea* with a very high ρ_w of 1.17 g cm^{-3} was a statistical outlier and was excluded from the regression, and so data from only six species was used. There was only a weak linear relationship (R^2 = 0.172, $p = 0.413$) (data not shown). Hourly E_t was correlated with g_s using the sap flow data of the same hour during which g_s was measured. The linear regression between the two variables was statistically significant ($p < 0.001$) and the R^2 was moderately high (Fig. 4).

4. Discussion

4.1. Transpiration and evaporative cooling differences among species

Overall, the tropical urban species studied had daily E_t of 2000–3200 g m^{-2} (leaf area) under sunny conditions. Under cloudy conditions, this was reduced by between 16 and 56% (980–2000 g m^{-2}). Given Singapore's equatorial location with a high cloud cover, and pervasive presence of shade in the built environment (Tan and Ismail, 2015), E_t under cloudy conditions is probably more representative of transpiration level in trees under the local sky conditions. Even under cloudy conditions, E_t represents a significant amount of water lost by urban trees. These values were substantially higher compared to those reported by Edwards et al. (2016), which were the

most directly comparable results to our study as both studies were conducted in Singapore. In their study, daily E_t was 580–1000 g m^{-2} for five tropical urban trees species. There reasons for this difference are not clear but might be related to the differences in water supplied to trees during measurement period (10 l compared to 64 l in our study), species differences, or methodological differences, e.g. in sap flow measurement techniques.

The high E_t reported in our study is, however, not unusual. For instance, in the review by Wullschleger et al. (2000), daily E_t among species was 390–8500 g m^{-2}. Most tropical species have daily E_t in excess of 1000 g m^{-2} per day (e.g., *Anacardium excelsum*, *Eucalyptus camaldulensis*, *Ficus insipida*, have E_t of 3900, 5800, 3300 g m^{-2}, respectively). Barradas (2000) reported daily transpiration of 1500 g m^{-2} per day for *Fraxinus uhdei* in Mexico City. During the dry season in a forest in Cambodia, E_t of 600–2500 g m^{-2} was reported for *Eucalyptus camaldulensis*, *Shorea roburghhii* and *Dipterocarpus obtusifolius* (Miyazawa et al., 2014). Even for temperate trees, E_t of 640–3900 g m^{-2} was reported for poplar (Zhang et al., 1999), and 2900–3500 g m^{-2} for *Carya illnoensis* (in Wullschleger et al. (1998)). The validity of our results was also further verified by direct weight loss measured simultaneously with sap flow.

With the exceptions of *L. speciosa*, species did not show clear midday stomatal depression. Midday depression in the gaseous change between leaf and the air is commonly reported in tropical trees and is attributed to high leaf-to-air VPD encountered during midday (Kosugi et al., 2009). *L. speciosa* also showed the largest decline in transpiration in response to soil moisture reduction, suggesting a higher level of stomatal regulation. The absence of visible midday stomatal depression for the other species is a useful property of the trees to mitigate higher urban temperatures encountered during midday.

Given the high E_t recorded in this study, latent heat flux is also high. On average, the species studied had an average daily LE of about 1800 W m^{-2} and peak hourly LE of 390 W m^{-2}. Among species, the maximum difference in daily LE was about 760 W m^{-2}, representing a difference of 56% between the species with the lowest and highest values. On a per tree level, the difference will scale with total leaf area, which was in the range 1.7–4.1 m^2. The difference in total LE among trees was thus large. The difference in peak hourly LE was also high, with a 97% difference between the highest and lowest. Large species

Table 4

Daily transpiration and daily and peak hourly latent heat flux for selected days between AEF and SDF trees. Numbers are mean of species $\pm$ sd. (*p* values) indicate statistical significance for Mann-Whitney U test between AEF and SDF species in the respective columns. Shapiro-Wilk test for normality showed that all variables were normally distributed (data not shown).

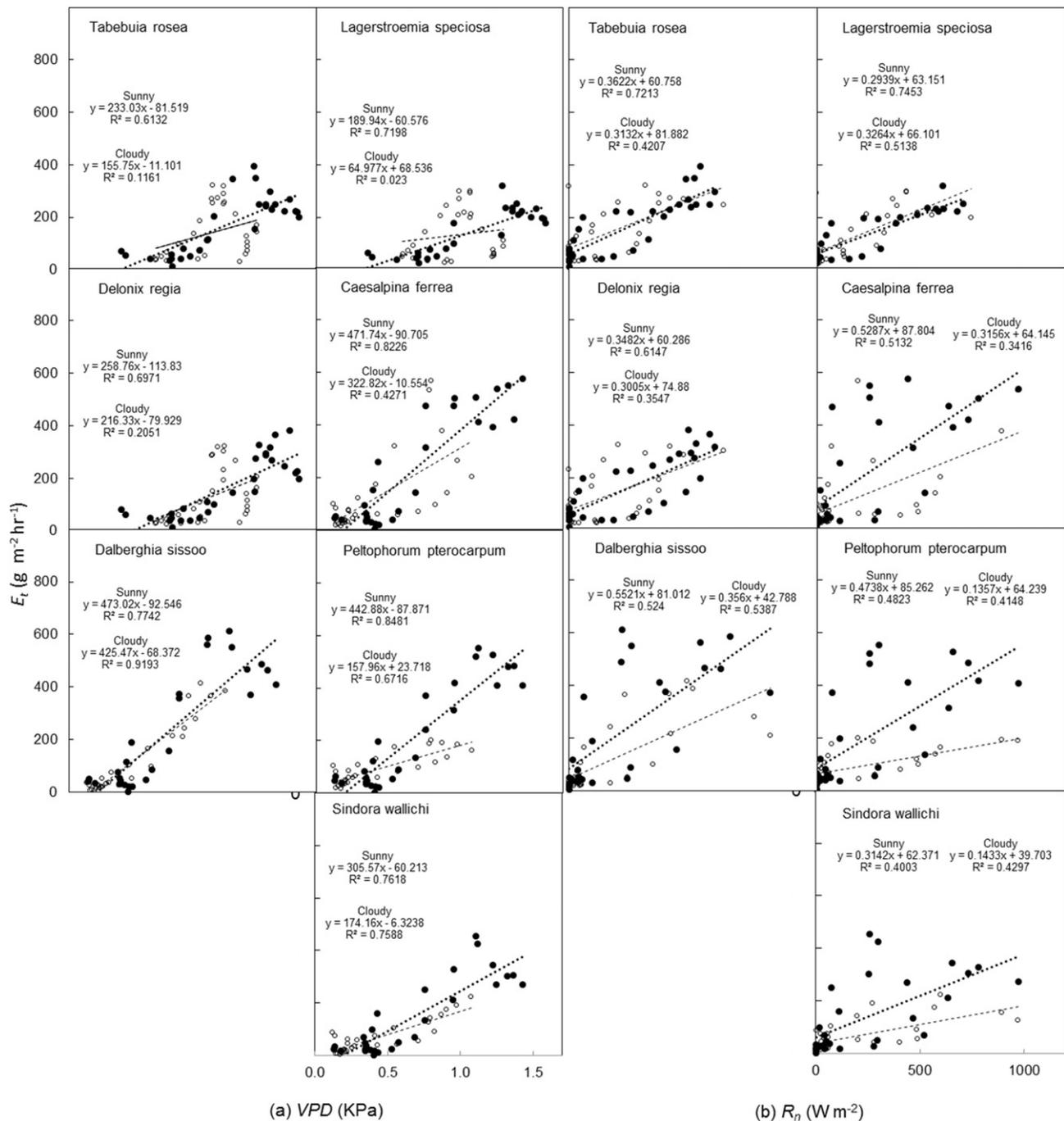|	E_t (daily transpiration) mean $\pm$ sd (g m^{-2})		LE (daily latent heat flux) mean $\pm$ sd (W m^{-2})		Peak LE (latent heat flux) mean $\pm$ sd (W m^{-2})	
	Sunny ($p = 0.805$)	Cloudy ($p = 0.028$)	Sunny ($p = 0.805$)	Cloudy ($p = 0.028$)	Sunny ($p = 0.621$)	Cloudy ($p = 0.166$)
AEF	2630 $\pm$ 786	1088 $\pm$ 273	1775 $\pm$ 530	735 $\pm$ 184	362 $\pm$ 139	159 $\pm$ 88
SDF	2774 $\pm$ 564	1861 $\pm$ 549	1873 $\pm$ 381	1256 $\pm$ 364	398 $\pm$ 156	279 $\pm$ 144

Fig. 3. Correlation between hourly transpiration E_t and (a) VPD and (b) R_n, under sunny (closed circles) and cloudy (open circles) conditions.

differences have also been reported. For instance, Rahman et al. (2015) reported a three to four times difference in latent heat flux among five species of temperate urban trees, with up to 2200 W m^{-2} per tree for the species with highest transpiration. Litvak et al. (2017) assessed transpiration difference at the stand level for 14 temperate urban tree species and reported a large difference in daily transpiration of between 0.06 mm and 2.59 mm per day between lowest and highest transpiration, which translates to hourly heat flux difference of 140 W m^{-2}. This study and others confirm the large differences in E_t inherent among species (Wullschleger et al., 1998) and provides additional support that large species differences in transpiration can be exploited to improve evaporative cooling by urban trees.

Trees from SDF and AEF as predicted, also showed significant differences in E_t, but only cloudy conditions. The influence of sky conditions

on E_t reflects the strong role of solar radiation (further discussed in Section 4.2 below). The largest difference in daily transpiration was recorded between an AEF species (S. wallichii) and a SDF species (T. rosea). Between the two AEF species, P. pterocarpum has much higher E_t than S. wallichii, which could be due to the more limited distribution of the latter in aseasonal evergreen forests (Baltzer et al., 2008). Variations in E_t between SDF and AEF trees have been suggested to arise from different water use strategies necessitated by seasonal availability of water. For instance, deciduous species in seasonal dry climate tend to have high transpiration rates to maximize primary productivity during the wet season, and shed leaves during the dry season to reduce chances of xylem embolism and desiccation (Kjelgren et al., 2011; Vico et al., 2015). Evergreen species tend to have more conservative water use, leading to lower transpiration because of lower peak stomatal

Table 5
Ratio of daily transpiration under water-withheld compared to well-watered conditions. For *L. speciosa*, transpiration on 30 Aug 2016 was used, as data for 29 Sep 2016 was not available.

Species	Ratio of daily E_t under water-withheld to well-watered conditions
Tabebuia rosea (Tr)	0.08
Lagerstroemia speciosa (Ls)	0.16
Delonix regia (Dr)	0.57
Caesalpinia ferrea (Cf)	0.33
Dalbergia sissoo (Ds)	0.52
Peltophorum pterocarpum (Pp)	0.35
Sindora wallichii (Sw)	0.36
AEF	0.36
SDF	0.33

conductance (Ishida et al., 2006; Vico et al., 2015). The transpiration difference between trees from these two types forests have also been shown among three species of tropical trees (Kjelgren et al., 2013). Our results provided additional empirical support for E_t differences between trees from these two forest types, and that SDF trees can have higher potential for evaporative cooling. In addition, it is useful to note that the two AEF are native to Singapore, whereas the SDF species are non-native. Therefore, while native trees are often promoted in urban areas for ecological reasons, they could have a weaker role in urban cooling.

4.2. Sensitivity of E_t to environmental variables

Under conditions where soil moisture does not limit transpiration, many studies show that the control of transpiration is primarily influenced by two factors: the radiative load from solar radiation which provides the energy to drive vaporization, and the extent of atmospheric dryness (*VPD*), which determines driving force between leaf surface and the bulk air above the leaves (Litvak et al., 2017; Wullschleger et al., 2000; Zhang et al., 1999). The relative influence of R_n and *VPD* depends on the extent to which the canopy of the vegetation is "coupled" to the air above the canopy. Uneven canopies, such as those of single trees in urban areas, or canopies of mixed species with uneven height and canopy characteristics, tend to experience higher level of atmospheric turbulence, more mixing of air between leaves and the atmosphere and hence stronger dependence on *VPD* of the atmosphere in controlling transpiration. Vegetation with a more uniform canopy, such as agriculture plantations or grasslands, tends to have canopies that are more separated from the bulk air above. Transpiration is then more dependent on the radiative load. Several studies on trees point out the strong influence of *VPD* on transpiration of temperate urban trees (Chen et al., 2011; Green, 1993; Litvak et al., 2017; Zhang et al., 1999). Other studies show more mixed results, with R_n also exerting varying degrees of influence compared to *VPD* (Wang et al., 2011;
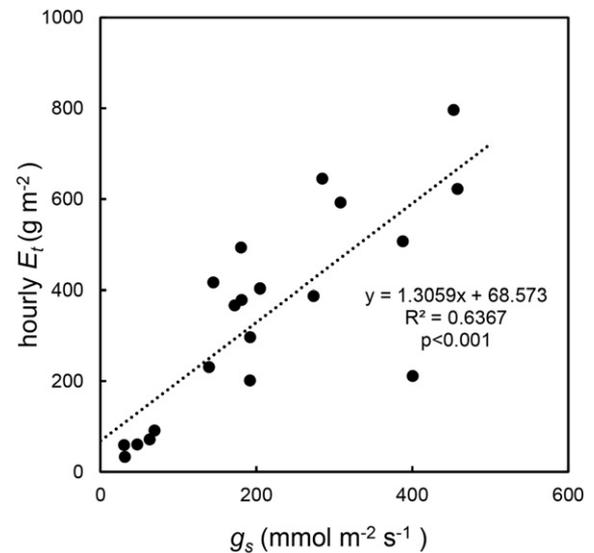
Fig. 4. Linear regression between leaf stomatal conductance (g_s) and whole-tree transpiration (E_t) measured within the same hour.

Wullschleger et al., 2000). Our results show the dual influence of R_n and *VPD*, but with R_n having a marginally stronger effect than *VPD*. In addition, the linear relationships between E_t and R_n showed larger differences between sunny and cloudy sky conditions than between E_t and *VPD*, further supporting the observation that R_n has a stronger influence than *VPD* on E_t. These results show that the environmental control of transpiration in urban trees cannot be generalized easily, and one large unknown is the effect of climatic differences in regulating the extent of coupling to the bulk air above tree canopies. In the tropics where high humidity tends to result in lower *VPD* than in a drier climate, the effects of *VPD* on controlling transpiration may be diminished as our results suggest, but this needs to be validated through more studies.

Deciduous species from SDFs are expected to respond to drought through several mechanisms: shedding leaves at the onset of dry period in conjunction with other environmental cues such as photoperiod or temperature to avoid drought, or a decrease in stomatal conductance, particularly in response to high leaf-to-air *VPD* (Vico et al., 2015). In contrast, evergreen species in seasonally wet forests are less drought-tolerant; such trees also reduce transpiration with water-stress, but the reduction is lower than would be observed in dry deciduous trees (Ishida et al., 2006; Kjelgren et al., 2013). Trees from both types of forest are however, known to exhibit isohydric stomatal behavior to regulate internal water status (Kjelgren et al., 2013). Our results show that under drought, AEF species maintained equivalent level of transpiration (36%) relative to well-watered conditions compared to the SDF species (33%). There were also large species differences within each group. It was therefore not possible to draw conclusions on the level of drought tolerance between species from each forest type. In a recent review of

Table 6
Multiple linear regression between hourly E_t and R_n and *VPD*.

ANOVA	Sum of squares	df	Mean square	F	Sig.
Regression	6,224,219	2	31,121,010	155.016	<0.0001
Residual	8,672,831	432	20,076		
Total	14,897,051	434			

	Unstandardized coefficients		Standardized Coefficients	t	Sig.	Collinearity statistics	
	B	Std. error	Beta			Tolerance	VIF
(Constant)	−7.311	13.959		−0.524	0.601		
R_n	0.296	0.032	0.418	9.358	<0.0001	0.677	1.478
VPD	137.949	19.857	0.310	6.947	<0.0001	0.677	1.478

Dependent variable: E_t
Predictors: (Constant), *VPD*, R_n.

isohydricity on global scale, Konings and Gentine (2017) showed that isohydricity may not be easily generalized based on land cover or eco-system types, as both seasonally dry and aseasonal evergreen forest species all exhibit isohydric behavior. Our results are consistent with this global synthesis.

4.3. Plant traits to predict transpiration of trees

Edwards et al. (2016) suggested that rate of plant growth can be used to selection of trees with higher transpiration rate. Our study showed that in addition to growth rate, instantaneous g_s can also be used to predict transpiration of the species. There was a moder-ately strong and statistically significant relationship between E_t and g_s (Fig. 4). This is despite challenges in scaling g_s to canopy conduc-tance. A possible reason for this result is that g_s and E_t both data sets were obtained within the same hour of measurement. This mir-rors the conclusion that instantaneous leaf of water use efficiency is a reasonable proxy for whole-tree water use efficiency (McCarthy et al., 2011). Nevertheless, because of the limited number of species used in our study, empirical data for more species should be col-lected to further validate and improve the robustness of the relation-ship obtained.

The linear relationship between E_t and ρ_w has been demonstrated in several studies. For instance, Gao et al. (2015) showed a strong negative relationship between sap flow and ρ_w of seven sub-tropical trees. While there was a visible linear relationship between ρ_w and E_t in our results, the correlation was weak and non-significant. This might be because of a small number of species assessed in our study. We highlight that more work should be focused in this area given the potential usefulness of ρ_w in understanding the physiological responses of trees. For instance, Bucci et al. (2004) assessed the correlation between ρ_w and a wide range of plant functional traits for six Brazilian tropical species in sea-sonally dry savanna and reported strong negative linear correlation be-tween daily transpiration and ρ_w. In addition, ρ_w predicted saturated water content of sapwood, midday leaf water potential, stomatal con-ductance, etc., leading to the suggestion that ρ_w was an integrator of trade-offs between wood production, wood hydraulic architecture and resource allocation. Wood density has also been shown to be a good predictor of growth responses to water balance in deciduous species of tropical dry forests (Mendivelso et al., 2013).

Finally, we highlight the usefulness of predicting E_t from plant traits. The use of a predictive equation for E_t can circumvent costly and time-consuming methods to estimate whole-tree transpiration. For instance, the linear regression equation (in Fig. 4) developed in this study from the field measurements can be used to predict whole-tree transpiration of tropical urban trees from leaf stomatal conductance using a hand-held porometer, and this in turn, be used to estimate species-specific daily LE for application in urban climatic or hydrological models. For in-stance, LE of trees from this study was used in a computation fluid dy-namics model and predicted air temperature reduction of 0.3 °C arising from a single tree in an urban area (Wong et al., n.d.). Moss et al. (2018) also used E_t rates to estimate energy reduction from evap-orative cooling of urban trees. Another potential use of this equation is for estimating "potential transpiration" of trees. Litvak et al. (2017) re-cently proposed an empirical model to estimate transpiration of urban trees in a stand, in which transpiration is the multiple of the fraction cal-culated from the combined effect of R_n and VPD on transpiration and a reference transpiration determined from sapwood area of a tree stand. We suggest that this model can be modified to take into account the ge-netically determined capacity for transpiration represented by ρ_w (which may be denoted as "potential transpiration"). Estimated transpi-ration is then the product of potential transpiration and the environ-mental control of transpiration exerted by atmospheric conditions represented by the equation in Litvak (2017). More studies are sug-gested to assess the validity of this suggestion.

5. Conclusion

The main objectives of this study were to assess whole-tree transpi-ration differences among tropical trees from SDFs and AEFs, and how transpiration may be correlated with plant traits, and atmospheric and edaphic conditions. The results highlight significant differences among urban trees in transpiration and environmental regulation of transpira-tion. Overall, daily E_t was 2000–3200 g m^{-2} under sunny conditions, and 980–2000 g m^{-2} under cloudy conditions. These rates fall within the wide range of tree transpiration documented in other studies. The differences in transpiration among species are translated to latent heat flux of 770 W m^{-2} between species with the highest and lowest E_t. E_t coincided with the period of peak R_n, highlighting an important role these species play in mitigating urban temperature when solar radiation load is the highest in the tropics. There are clear differences in daily E_t between species from SDF and AEF under cloudy conditions, indicating the potential of SDF trees to provide higher level of evaporative cooling under the predominantly cloudy conditions in Singapore. The two spe-cies of AEF trees are also native, whereas the five species from SDF are exotic. From the objective of improving urban cooling by trees alone, there is thus a clear role for the use of exotic trees. Understandably, tree selection cannot be purely based on heat mitigation role and other objectives need to be considered.

Both R_n and VPD are important determinants of E_t, with R_n playing a marginally stronger role. This contrasts with the other studies which show a stronger influence of VPD because of the close coupling between tree canopies and the bulk air above. This may reflect the generally lower VPD in humid tropics, but empirical studies need to be conducted to validate this suggestion. We did not observe clear differences be-tween AEF and SDF species when they were subjected to drought stress, but species which have higher daily E_t tend to also show highest decline in transpiration, demonstrating higher level of stomatal regulation in these species. The results clearly demonstrated the control of transpira-tion by genetically determined tree traits, atmospheric and soil dryness.

It is challenging to conduct empirical studies such as this to charac-terize transpiration of urban trees, not only because field studies are re-source demanding, but also because of the large number of species used as urban trees worldwide. Methods for predicting trees with high tran-spiration based on plant traits are thus useful. We showed in our study that g_s is potentially useful plant trait for this purpose.

There are, however, limitations in our study. A key limitation is that because of the logistical difficulties of undertaking simultaneous field measurements of large specimens, we were only able to collect ade-quate data for seven species, which also had uneven number of replica-tions due to equipment faults and poor plant growth. The analyses were also constrained by the need to compare species under two types of sky conditions, which required comparability within one type of sky condi-tion, and adequate differences between the two types of sky conditions. Although we feel that these conditions were achieved, particularly be-tween the two sky conditions, and hour-to-hour variation mitigated by using cumulative daily transpiration for comparison, the atmo-spheric environmental variables were nevertheless, not identical be-tween the days selected for assessment. This led to additional variation in the comparison, which might have masked inherent species differences. The small number of species could also be a reason why we not able to detect a significant relationship between transpiration and wood density.

More studies should be conducted to build up a stronger knowledge base on transpiration of tropical urban trees with the objective of guid-ing species selection to achieve more effective urban cooling. We also highlight here that urban cooling by urban trees is complex, as it not just influenced by evaporative cooling, but also by shade provided by tree canopies, and the effects of trees on mean radiant temperature, wind speed and relative humidity. Our study nevertheless provides ev-idence that significant differences exists in the potential of trees to pro-vide evaporative cooling.

Declaration of competing interest

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135764.

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