SHORT NOTE

A method to partition the relative effects of evaporative cooling and shading on air temperature within vegetation canopy

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Abstract

The cooling effects of vegetation in urban areas are generally attributed to two distinct processes: shading by vegetation canopy and evaporative cooling (EC) by evapotranspiration. An important knowledge gap in using vegetation to moderate urban temperatures is the relative importance of these two processes at different spatial scales. Information is particularly limited at the individual tree level. The current state of knowledge prevents more informed decisions on the selection of trees species for more effective urban cooling. This paper reports on a method developed to evaluate the relative importance of shading versus EC on air temperatures within the canopy of small potted trees. A replicated field study was conducted to assess the relative effects of these two processes on a commonly used urban tree species in the tropics. By comparing temperature differences at different positions in the canopy, and controlling transpiration through withholding water and by severing stems of the trees, the study demonstrated a method to partition the effects of shading compared with transpiration. Both shading and EC effects peaked around midday when solar radiation was the highest. The latter effect was shown to contribute ~29% to the lower air temperature within the canopy compared with the temperature above the canopy. We suggest that the method reported in this study can be scaled up to larger specimens or replicated to other species to improve our knowledge of species differences in these two processes within canopies of urban trees.

Key words: evapotranspiration, shading, evaporative cooling, canopy microclimate, urban cooling

Introduction

The role of greenery in urban temperature mitigation is an area of active research because of the adverse consequences of high urban temperatures on human well-being, energy consumption and capacity of urban areas to support wildlife. There is strong empirical evidence that urban greenery provides significant cooling effects in built-up areas in different climatic zones (Wong and Yu 2005; Chow and Brazel 2012; Chen et al. 2014). Such a role of urban vegetation is generally attributed to two distinct mechanisms: shading and evapotranspiration (ET) (Oke et al. 1989). The former occurs through the interception of
solar radiation by vegetation canopy, which leads to reduction in heat gain, storage and emission of long-wave radiation by shaded built surfaces such as building walls and pavement. The latter arises from conversion of sensible heat to latent heat through combination of water loss from leaves during transpiration, and water loss from soil surfaces by evaporation. The change in phase of water leads to reduction in sensible heat and change in temperature above the canopy, what is the relative contribution of these two processes to urban cooling, and how this in turn, is influenced by factors such as climate, urban form, vegetation type and scale. Understanding scale effects seems particularly crucial in extending our knowledge to inform effective greening of cities for urban heat mitigation. At the global scale, the role of ET in regulating the global water and energy cycles is unequivocal. The combined volume of water moved by ET is more than 60% of global terrestrial precipitation (Hetherington and Woodward 2003; Fisher et al. 2017). Since the global water and energy cycles are closely coupled, ET also has a strong influence on the global surface energy balance, with more than half of solar radiation absorbed by land surfaces being used for ET (Jung et al. 2010), and this exerts a major influence on global surface temperatures (Shukla and Mintz 1982). At smaller scales from local to micro- and meso-scales in urban areas, however, there is a much larger variation in the role of ET in energy balance of urban areas. For instance, the ratio of latent heat to total solar radiation in urban areas ranges almost 10-fold from 0.04 to 0.37 across a range of climatic conditions (Cleugh and Grimmond 2012), which may in turn reflect differences in amount of vegetation, capacity of vegetation to transpire freely and provide EC, as well influence of climatic conditions between study sites. Coupled with this large variation in ET under urban conditions, there are very few studies which compared the effects of shading with ET by urban canopies in urban climate moderation. An early study by Huang et al. (1987) using models reported that savings in energy for cooling due to increase in canopy cover was mainly due to ET, compared with 10–30% due to shading. Another study, albeit at a smaller scale, suggests that the effect of ET in reducing temperature of urban wooded areas is low compared with shading, with the latter contributing more than 80% of the cooling effect (Shashua-Bar and Hoffman 2000). However, this study was conducted in an arid climate, where ET is expected to be low under non-irrigated conditions. A recent study using computational fluid dynamics showed that ET can reduce ambient temperature in a street canyon by a mean of 0.52°C and a maximum of 2.0°C, which are not insignificant (Gromke et al. 2015).

The examples above highlight that variations in the relative importance of ET and shading is likely to be scale-dependent. As scale decreases from global to meso-, micro- and local-scales in urban areas, other than climate of geographic region that dictates the general atmospheric conditions of the study site, a range of other factors comprising urban forms, urban microclimates, extent of vegetation cover, and types of vegetation collectively exert influence on energy fluxes, leading to larger variations in ET. At the smallest scale—the scale of the individual tree—the lack of empirical data on shading and EC is acute. Very few studies on canopy microclimate have been conducted to assess the relative roles of shading and EC in influencing within-canopy temperatures. Rahman et al. (2017) recently measured temperatures within and beneath tree canopies simultaneously with sap flow to evaluate the influence of latent heat fluxes and edaphic and atmospheric conditions on canopy temperatures of an urban tree species. The results showed that air temperature under canopy can be cooled by 0.85°C, and this air temperature reduction is largely explained by latent heat fluxes in the canopy. Such studies are, however, limited. Yet, a better understanding of the factors that influence within-canopy temperature of urban trees is useful, as within-canopy temperature has a direct influence on air temperature closer to the ground, and when aggregated to tree stands, cool air generated within canopies in a single tree essentially dictates the maximum EC potential that is produced by urban tree stands. Importantly too, a systematic understanding of the relative importance of evaporative and shading effects can also enable identification of species that can be preferentially used to provide more optimal cooling as dictated by site conditions. This need to focus on choice of species that have more optimal effects in urban cooling appears to be a consistent conclusion from recent studies, as suggested by Armaon, Rahman, and Ennos (2013), de Abreu-Haribich, Labaki, and Matzarakis (2015), Gillner et al. (2015), Lin and Lin (2010), Rahman, Armson, and Ennos (2015) and Sanusi et al. (2017).

The goal for improved selection of urban trees in practice is currently limited by the paucity of empirical results on the cooling properties of different species. A possible reason for this is challenges in conducting field studies, as methods used by Rahman et al. (2017) mentioned above, or those by Green (1999) who used a Whirligig device to measure the energy balance of a field grown tree are logistically demanding. Methodological challenges are also intensified by the need for studies to account for multiple confounding factors under the highly heterogeneous atmospheric conditions present in urban areas. In addition, as shading and EC are concurrent processes within the vegetation canopy during the daytime, and which cannot be easily separated in time, such as between daytime and night time (i.e. the extent of each process differs markedly between daytime and night time under the influence of solar radiation), a suitable method for partitioning shading and evaporative effects requires the manipulation of one over the other process under the same solar radiation levels.

The objective of the study is to determine how these two distinct cooling mechanisms stemming from the same plant canopy can be quantified independently. In this short note, we report a method developed for this purpose. The method was tested using a replicated experiment under open field conditions to assess the relative effects of shading compared with EC by transpiration within the canopy of small trees. By measuring air temperatures at different positions above and within the canopy and controlling the level of transpiration to manipulate level of evaporative cooling (EC), we assessed if the method could be used to partition the extent of air temperature reduction by shading compared with EC within the canopy. The results can then be used to answer this question: for every 1°C reduction of temperature within the canopy compared with the temperature above the canopy, what is the relative contribution by shading and EC through canopy transpiration.

Methods

Study site and plant materials

The replicated field study was conducted on a fully exposed rooftop of a university campus (1°17'49.6"N 103°46'14.2"E, 35 m ASL) from 8 December 2016 to 10 July 2017. Small plants of
Eugenia oleina (syn. Syzygium campanulatum, S. myrtifolium) can grow to a height of 20 m at maturity (Tee, 2009, p. 182). It is a common and fast-growing urban tree in tropical regions, which can grow to a height of 20 m at maturity (Tee, 2009, p. 182). It has a leaf area index (LAI) of 2.0–2.5 (Roseli, Tsan, and Ramlan 2012), reflecting a moderately dense canopy. It does not appear to be drought tolerant, as small trees are often seen to show signs of wilting during dry spells in Singapore. This suggests that drought can be induced relatively easily during our study, which is a useful characteristic for this study. The surface of the pot was covered with plastic sheets to reduce evaporation from the substrate, so that EC was solely due to transpiration.

The plants were irrigated two times daily at 6 am and 8 pm, which provided 18 l of water daily during the initial establishment phase over ~30 days to acclimatize the plants to the growing conditions of the roof. Plants were also spaced ~2 m apart to prevent mutual shading and placed away from shadow cast by adjacent buildings. There were three experimental treatments: well-watered (n = 3), water-withheld (n = 3) and stem-severed (n = 6). The well-watered plants received the same amount irrigation per day as during the establishment period. At the end of the water-withholding treatment, stems of all the plants were severed to fully stop transpiration.

**Measurements**

**Air temperature**

Air temperature and relative humidity (RH) were recorded using HOBO U23 Pro v2 External Temperature/Relative Humidity Data Logger (Onset Computer Corporation, Massachusetts, USA). The sensors were placed above, within and below the canopy (Fig. 1), and data logged hourly. It is assumed that the sensors at the top, placed within 2–3 cm above the tip of the canopy, measured air temperature primarily that is influenced by EC through transpiration; sensors within the canopy, placed in the middle of the canopy (~0.6–0.7 m above ground) and roughly mid-point between the stem and outer edge of the canopy measured air temperature cooled through transpiration and shading; sensors below the canopy, placed ~5–8 cm above the plastic covering the pots, measured air temperature cooled through shading and possibly some transpiration. We also expect that there is a vertical air temperature gradient, with temperature at the roof being higher than the air temperature above the canopy. This might influence the temperature recorded at the bottom and top sensors over and beyond effects of EC and shading. To determine shading compared with EC effect, we used temperature differences rather than absolute temperatures to reduce the influence of this vertical temperature gradient. Temperature differences were calculated from air temperature differences recorded between 13:00 and 15:00, which covered the period when solar radiation is the highest (see ‘Partitioning EC and shading effect’ section).

**Soil moisture and control of transpiration**

Volumetric soil moisture content for each replicate was recorded using ONSET 10HS Soil Moisture Smart Sensor (Onset Computer Corporation, MA, USA). The soil moisture probe was inserted vertically such that the top-end of the probe was ~1–2 cm beneath the soil surface. All plants were well-watered for 2 months during the establishment period, following which transpiration was manipulated by two methods: control of irrigation and excision of stems. In the first treatment, irrigation was stopped for the water-withheld treatment for between 5 and 8 days (8–15 December 2016 and 12–17 January 2017, respectively). Irrigation was then resumed and plants allowed to fully recover between each water-withheld period. The changes in soil water content over these periods are shown in Fig. 2. At the peak drying period, soil water content in the water-withheld treatment was ~70% that of well-watered (~22–0.23 cm³ cm⁻³ in water-withheld compared with 0.31–0.32 cm³ cm⁻³ in well-watered treatment).

In the last phase of the study from, stems of all plants were severed to stop sap flow completely. Data were collected from 30 June 2017 to 7 March 2017. The stem of the plants was cut in the segment just above the soil surface, and then secured tightly to the lower part with wooden stick supports and cable ties. Maintaining the upright position of the shrub ensured that the sensors were exposed to similar levels of shading by the leaves before and after cutting the stem. The leaves shrivelled and wilted within 3 days and it was assumed that transpiration...
has ceased. Care was taken to ensure the sensors measured temperature at the positions that were intended. Any temperature differences between the positions within the canopy were assumed to be due to shading effect only. As several replicates had stems tilted by wind after severing the stems, eventually only three replicates were used for the analysis.

**Leaf stomatal conductance**

A steady state leaf porometer (Decagon Devices, Inc., Washington, USA) was used to measure leaf stomatal conductance. Three youngest mature leaves per tree were selected per plant, and measurements were done on non-rainy days. Measurements were done between 11:00 and 13:00.

**Atmospheric data**

A HOBO Weather Station (Onset Computer Corporation, MA, USA) was used to record the solar radiation, air temperature, RH, wind speed and rainfall during the experiment. All the data were recorded on 1-min interval and aggregated to half-hourly and hourly averages. Figure 3 shows the solar radiation, ambient air temperature wind speed for the days of data collection. Wind speed was highly variable over the study period and was generally in the range 1–3 m s\(^{-1}\), which is considered as ‘light breeze’ in the Beaufort wind scale, and close to the prevailing mean surface wind speed in Singapore (http://www.weather.gov.sg/climate-climate-of-singapore/), accessed 1 March 2018). Solar radiation was also variable over the data collection periods, particularly during 12–17 January 2017 and 30 June 2017–3 July 2017. Ambient air temperature generally followed the pattern of solar radiation. The equipment used, and the measurement range, sensitivity and accuracy are shown in Table 1.

**Partitioning EC and shading effect**

The air temperature data collected from different canopy positions of the two phases with different moisture regimes (well-watered, water-withheld and severed stem conditions) were compared with estimate the relative cooling effects induced by EC from transpiration and shading. These data used were average of hourly readings recorded between 13:00 and 15:00, which was selected to coincide with the period of peak solar radiation. With reference to Fig. 1, the following assumptions were made:

1. Air temperature above the plant, as measured by the sensor above the canopy, is influenced by EC from transpiration. While it can also be influenced by the bulk air temperature above the canopy, this was minimized by placing the sensor very close to the tip of the canopies (Point C).
2. Temperature measured by sensor within the canopy is influenced by a combination of EC by leaves around the sensor and shading by portion of the canopy above the sensor (Point D).
3. By withholding water, transpiration is reduced and hence EC is reduced (Points A and B).
4. Severing the stem cuts off transpiration completely and EC is absent (Points E and F).

Therefore, the shading effect and EC effect under the three conditions can be estimated by the difference in air temperatures:

\[
\text{Shading effect} = A-B \text{ or } E-F
\]

Evaporative cooling effect above canopy (EC\(_{wa}\)) = A-C or E-C or E-A

Evaporative cooling effect within canopy (EC\(_{wo}\)) = B-D or F-D or F-B.

The different EC effects are dictated by the extent to which transpiration is reduced compared to well-watered plants. We should expect that temperature difference using stem-severed treatment (E–C and F–D) to be larger than the other temperature differences. As the extent of exposure to solar radiation is an important determinant of transpiration (Konarska et al. 2016), under well-watered conditions in which transpiration was active, C–D was not used to estimate shading effect given that transpiration above the canopy (at C) could be higher than transpiration in the middle of the canopy (D).

**Results**

**Canopy Air temperature and influence of atmospheric conditions**

Air temperature at the top of the canopy was always higher than temperature in middle of the canopy in all treatments (Table 2), illustrating the effect of shading on temperature within the canopy. Air temperature below the canopy was also higher than within canopy temperature in all treatments. This was possibly due to the proximity of the sensor to the soil and roof which acted as heat sources. In addition, temperature below the canopy under well-watered condition was also higher than the temperature in water-withheld treatment, indicating the presence of an additional heat source, such as irrigation water which has high thermal capacity than soil. This effect, was however variable when compared with the stem-severed treatment. For these reasons, comparison with the temperature below the canopy was omitted from subsequent analyses.

The temperatures at all three positions showed a strong linear relationship with solar radiation, both under well-watered and water-withheld conditions (Fig. 4). In contrast, the relationship with wind speed was much more variable. Even for temperature above the canopy, which is expected to be subjected to stronger influence wind movement than those within and below the canopy, no clear pattern was visible.

**Canopy microclimatic conditions under different treatments**

Withholding irrigation reduced mean soil volumetric water content to ~70% of well-watered treatment. This in turn, was correlated with mean leaf stomatal conductance, which was reduced by ~75% from 118 mmol m\(^{-2}\) s\(^{-1}\) under well-watered conditions to 31 mmol m\(^{-2}\) s\(^{-1}\) (data not shown). Water withholding did...
Figure 3: Hourly atmospheric conditions over a day during the three data collection periods (8–15 December 2016 and 12–17 January 2017 for water-withholding treatment and 30 June 2017 to 7 March 2017 for stem severing treatment: (a)–(c) for solar radiation; (d)–(f) for ambient air temperature; (g)–(i) for wind speed. Data points are mean of all measurements at the respective positions. Note that partial data were available for 30 June 2017 and 3/7/2017 and these 2 days were excluded from analyses.

Table 1: Equipment used in the study

| Variables             | Equipment                                             | Measurement range                  | Accuracy            |
|-----------------------|-------------------------------------------------------|------------------------------------|---------------------|
| Air temperature       | HOBO U23 Pro v2 External Temperature/Relative Humidity | −40°C to 70°C                      | ±0.21°C from 0°C to 50°C |
| RH                    | HOBO U23 Pro v2 External Temperature/Relative Humidity | 0 to 100% RH                      | ±2.5% from 10 to 90% |
| Soil moisture         | 10HS Soil Moisture Smart Sensor                       | 0 to 0.570 m³ m⁻³ (volumetric water content) | ±0.033 m³ m⁻³      |
| Solar radiation       | Onset S-LIB-M003                                      | 0 to 1280 W m⁻²                   | ±10 W m⁻² or ±5%   |
| Wind speed            | Onset Wind Speed Smart Sensor, S-WSA-M003             | 0 to 45 m s⁻¹                     | ±1.1 m s⁻¹ or ±4%  |
| Rainfall rate         | HOBO Rain Gauge Data Logger                           | Maximum 12.7 cm h⁻¹               | ±1.0%              |
| Stomatal conductance  | Decagon SC-1 Porometer                               | 0 to 1000 mmol m⁻² s⁻¹            | 10%                |
not lead to full stomatal closure, but nevertheless, the large re-
duction was assumed to have reduced transpiration within and
above the canopies. This was reflected in the reduced RH at
Position A compared with C, and to a smaller extent between
Positions B and D (Table 3). Withholding irrigation and severing
the stem increased temperatures above and within the canopy
compared with well-watered conditions (Table 2). The tempera-
ture differences were most apparent during daytime, peaking
within 1–2 h around midday, when hourly temperature differ-
ences at equivalent canopy positions were compared across the
days of measurements (Fig. 5). Temperature differences during
night time generally fluctuated around zero. The influence of
solar radiation was further shown when temperature difference
between above and within canopy (A–B) under the water-
withheld treatment was compared with solar radiation, wind
speed and RH (Fig. 6). Whereas there was a strong linear rela-
tionship between temperature difference and solar radiation,
only a very weak relationship was visible for wind speed, and
no clear relationship with RH was observed.

Relative effect of EC to shading on air temperature
in canopy

The differences in canopy temperature in different treatments
were used to derive EC and shading effect. Data for these peri-
dods were used: 9–15 December 2016 and 12–17 January 2017 for
well-watered and water-withheld treatments, and 1–2 July 2017
for stem-severed treatment. Data omitted were for 3 days with
data anomaly (8 December 2016, likely due to wrong label of file
at time of data download) and incomplete data (30 June 2017
and 3 July 2017).

The effects of reduced transpiration on reduced EC can be
determined from temperature difference between above the
canopy (A–C, E–C, E–A) and within the canopy (B–D, F–D, F–B)
(Table 3; Fig. 7). ECa was on average almost twice higher than
ECw (Table 3). We also compared EC effects between water-
withholding treatment and stem-severed treatment, in which
the latter showed a predictably higher effect in reducing ECa
(E–C) and ECw (F–D) compared to water-withholding treatments
ECa (A–C) and ECw (B–D), respectively.

The shading effect can be determined from difference above
canopy and within canopy temperatures under water-withheld
and stem-severed conditions. This effect ranged from 0.85 to

Table 2: Air temperature above, within and below the canopy in
well-watered and water-withheld treatments

| Air temperature (%C) | Above | Within | Below |
|----------------------|-------|--------|-------|
| Well-watered         | 32.85 ± 0.52 | 31.83 ± 0.35 | 32.57 ± 0.37 |
| Water-withheld       | 33.13 ± 0.52 | 32.28 ± 0.35 | 32.42 ± 0.36 |
| Stem severed         | 34.09 ± 0.26 | 32.54 ± 0.17 | 33.65 ± 0.24 |

Values are mean ± standard deviation (SD) of daily figures between 13:00 and
15:00 for period 9–15 December 2016 and 12–17 January 2017 for well-watered
and water-withheld treatments, and 1 and 2 July 2017 for stem-severed
treatment.

Figure 4: Air temperature above, within and beneath the canopy compared to solar radiation for (a) well-watered plants, (b) water-withheld plants and compared with
windspeed for (c) well-watered plants; (d) water-withheld plants. Data points are means of hourly temperature for all replicates for data between 08:00 and 18:00 col-
lected over the period 9–15 December 2016 and 12–17 January 2017.
1.55°C, with an average of 1.20°C. Within the canopy, the EC effect ranged from 0.26 to 0.72°C, with an average of 0.48°C. Therefore, the shading effect was ~2.5 times higher than EC effect within the canopy. For every 1°C temperature reduction within the canopy compared to above the canopy, 71% was from shading and 29% was from EC within the canopy.

**Diurnal variations in shading and cooling effect**

Shading and EC effects showed contrasting diurnal patterns over multiple days of monitoring (Fig. 8). While both shading and EC generally had positive effects during day time, with shading having a higher effect than EC, the pattern was reversed during night time. At night, EC effect dropped to zero, while shading effect was negative, indicating that the temperature within the canopy was higher than temperature above the canopy. In addition, both shading and EC effect, particularly the former, followed closely the diurnal pattern of solar radiation.

We also computed the contribution of ECw to temperature within the canopy for each of the days in Fig. 8. Over the study period, the contribution of ECw to the temperature within the canopy ranged from 0.1 to 0.67, with a mean of 0.33 (SD = 0.14). With the progressive reduction in soil moisture from the start of water withholding over the two periods, the magnitude of ECw increased (comparing the first period to the second period) (Table 4). In other words, compared to well-watered condition, EC effect was progressively reduced (magnitude of ECw increased) as moisture stress developed in the water-withholding treatment.

**Discussion**

**Ability of method to partition within canopy shading and EC effects**

The cooling effect of vegetation is commonly attributed to the combined effects of shade and transpiration. The objective of this study is to determine how these two distinct cooling mechanisms stemming from the same plant canopy can be quantified independently. Using a relatively simple experimental setup, we demonstrated a method to estimate the relative effects of shading compared to EC from transpiration within the vegetation canopy. Overall, transpiration appeared to have a comparatively smaller effect than shading in determining the temperature within the vegetation canopy. EC effect was also higher above the canopy than within the canopy, possibly because of higher transpiration due to more sunlit leaves on the outer than inner canopy.

The relative contribution of EC to temperature within the canopy in our study is close to the quantum demonstrated in other studies. These studies evaluated the contribution of EC under different circumstances but are nevertheless useful to provide some comparison. For instance, Hoelscher et al. (2016) showed in their study in which water was withheld to estimate effects of shading compared with EC effect of creepers on building wall, that shading effect was dominant on sunny days (more than 80%). Koyama et al. (2015) also assessed the contribution of creepers to reduction in interior wall temperature by severing stems to stop transpiration and reported that transpiration accounted for ~10% of the temperature reduction of interior wall. These results and ours suggest that EC is comparatively smaller compared than shading in producing cooling effects under the study conditions. However, the importance of climate and vegetation types in determining EC effect is still largely unknown.

In addition to partitioning shading versus EC effect within the canopy, our method also seemed capable of detecting changes in relative EC and shading effects with the change in water status of the plants. The magnitude of ECw reduced (compared with well-watered conditions) with increasing number of days from withholding water, indicating that this method was sensitive to detect changes in EC with progression of soil moisture deficit and plant water stress. This was also demonstrated when comparing the ECw effect between the water-withheld

**Table 3: Air temperature and corresponding RH and derived mean shade and evaporative cooling effect**

| Measurement points | Air temperature (°C) | RH (%) |
|--------------------|----------------------|-------|
|                    | Mean ± SD            | Mean ± SD |
| Water- withheld    |                      |       |
| A                  | 33.13 ± 1.23         | 58.67 ± 6.92 |
| B                  | 32.28 ± 1.11         | 62.54 ± 6.19 |
| Well-watered       |                      |       |
| C                  | 32.85 ± 1.20         | 59.75 ± 6.68 |
| D                  | 31.83 ± 0.96         | 63.69 ± 5.93 |
| Stem-severed       |                      |       |
| E                  | 34.09 ± 0.26         | 65.59 ± 3.25 |
| F                  | 32.54 ± 0.17         | 65.58 ± 3.59 |

**Shading/evaporative cooling effects [air temperature difference (° C)]**

|                  | A-B                 | E-F |
|------------------|---------------------|-----|
| **Shading effect**|                     |     |
| A-B              | 0.85 ± 0.31         |     |
| E-F              | 1.55 ± 0.09         |     |
| **Mean Shading effect** | 1.20 ± 0.49 |     |

|                  | A-C (above)         | E-C (above) |
|------------------|---------------------|-------------|
| **Evaporative cooling (EC) effect** |                     |             |
| A-C              | 0.27 ± 0.26         |             |
| E-A              | 1.24 ± 0.26         |             |
| E-A              | 0.96 ± 0.26         |             |
| B-D              | 0.45 ± 0.29         |             |
| F-D              | 0.72 ± 0.17         |             |
| F-B              | 0.26 ± 0.17         |             |

|                  | Mean ECw effect (above) | Mean ECw effect (within) |
|------------------|-------------------------|--------------------------|
|                  | 0.82 ± 0.50             | 0.48 ± 0.23              |

Values are mean ± standard deviation (SD) of daily figures between 13:00 and 15:00 for period 9-15 December 2016 and 12-17 January 2017 for A, B, C, D and 1 and 2 July 2017 for E, F. As these are not strict replicates (means of repeated measures over multiple days), statistical tests were not conducted.
versus stem-severed treatment, in which EC was shown to be higher (i.e. higher reduction of EC) in the latter. This was to be expected as transpiration will have ceased with the stem-severed treatment, whereas water-withholding may not have reduced transpiration completely. However, it should be noted that this comparison was made with data well-watered and stem-severed treatments collected under different ambient conditions, which could have affected the magnitude of the difference we observed. Nevertheless, we have shown that solar radiation has the strongest effect on temperature difference between canopies, and average solar radiation between 13:00 and 15:00 over these two periods were at the similar levels (506.8 ± 172.3 W m⁻² for period 9–15 December 2016 and 12–17 January 2017; 562.9 ± 315.2 W m⁻² for period 1–2 July 2017) (data not shown).
at night time because of warmer canopy temperatures that reverses the oasis effect of vegetation during daytime (Taha, Akbari, and Rosenfeld 1991). However, it is also useful to note that Konarska et al. (2016) in contrast, reported that night time transpiration by seven urban tree species, rather than daytime transpiration, was more effective in producing a cooling effect under tree canopies. These results suggest that canopy microclimate is complex, and is influenced by species characteristics, edaphic factors and microclimatic conditions around the trees. To unpack these complexities to identify suitable tree species, we suggest that a good starting point is to have consistent methodologies for studying canopy microclimate. The understanding that is developed from assessment of individual canopy microclimate and that of tree stands in relation to the urban surroundings can provide important insights on the use of urban vegetation for more effective cooling both during the day and night.

**Limitations and areas for future research**

We highlight several limitations in this study, which we hope can be used to guide future work in this area. First, improvements in the experimental design and data collection can be made. The study was not able to account for shading effect under the canopy because of the soil and roof surface acting as heat sources, and the unexpected higher temperature in well-watered conditions which we suspect could be due to irrigation water as an additional heat source. Further improvements can also be made to the experimental method. For instance, a set of air temperature sensors could be used to concurrently measure the vertical temperature gradient from the floor to air so as to account for its influence on temperature differences at different positions in the canopy. Plants could also be placed in elevated positions such that the influence of heat from the roof is reduced. Another control could also be used concurrently to account for possible effects of irrigation water on the results. In the stem-severed treatment, a well-watered control group could also be used so that comparison between stem-severed and well-watered measurements is made under the same ambient conditions.

Second, given that temperature differences between canopies are small, higher precision instruments with low error range and higher frequency of logging will be desirable. It will also be desirable to install more measurement points to capture spatial variation within the canopy. The extent to which different instruments and measurement points affect the study results remains to be shown. For this purpose, three-dimensional distributed sensors have been used at very fine spatial scales to capture high resolution temperature dynamics in different kinds of fluids (Hilgersom et al. 2016), and can be used to capture more measurement points above, within and below the canopy. However, there will be trade-offs between the ability to deploy sensitive and expensive instruments and achieving adequate number of replications to account for inherent variations in experimental systems. For trees with a wide canopy, in addition to capturing the vertical gradient from the top to the middle of the canopy, it is also possible to place temperature and RH sensors to capture data along a horizontal profile from the stem to the edge of the canopy.

Third, we assumed that temperature at D is a combination of shading effect, measured by (E–F) and EC within the canopy in the vicinity of D \( (E_{Cw}) \), measured by (F–D). However, it is also possible that under well-watered conditions, EC above the canopy at point C \( (E_{Ca}) \), measured by (E–C) can partially influence the temperature conditions.

In addition, it was also possible to use this method to assess diurnal changes in shading versus EC effects. During night time, EC by transpiration was shown to be minimal within the canopy, and the shading effect was negative, indicating that it is warmer within the vegetation canopy than above the canopy. This is likely due to the lack of turbulent mixing of air within the canopy, as well as the overall effect of leaves and branches in retaining heat. The exact reasons cannot be determined from our results, but we suggest that this is an important observation that have implications on formation of ‘nocturnal heat islands’
at D through cooler air generated above the canopy. We have assumed that cool air generated by transpiration at the top of the canopy is influenced by bulk air movement under the more exposed conditions, and therefore has less effect on temperature within the canopy. In the absence of finer scale data, we cannot ascertain this assumption. If ECw also influences within canopy temperature, the within canopy EC effect would have been underestimated. This uncertainty is an interesting and relevant area for research that can be addressed in future studies. The knowledge gained can contribute to our understanding of heat balance within canopies which should in turn, exert influence on physiological processes within the canopy.

We also highlight that our results may be specific to the species we have used. In fact, one important knowledge gap in this area is the magnitude of species differences between urban trees in canopy microclimate, particularly on relative roles of shading and EC in influencing temperatures above, within, beneath and around the canopies. We could expect large variations in canopy characteristics and transpiration capacity between species within the large diversity of urban trees in the tropics. For instance, Rahman, Armson, and Ennos (2015) and Peters, McFadden, and Montgomery (2010) showed that transpiration rates per unit canopy area of evergreen trees are almost double that of deciduous trees due to higher LAI and longer growing seasons. Trees also exhibit a wide range of LAI, and LAI has been shown to exert a significant influence on the shading potential of trees (de Abreu-Harbich, Labaki, and Matzarakis 2015). Sanusi et al. (2017) recently demonstrated that differences in Plant Area Index of species led to differences in their ability to cool pedestrian walkways. Gillner et al. (2015) showed that temperate urban tree species have high leaf area density and leaf transpiration rates were more effective in reducing air temperature around and beneath tree canopies. There could thus be large, but yet unknown differences between species in transpiration and shading potential, considering the large diversity of tree species that are used in cities worldwide. There is very little information on these properties of urban trees currently. Therefore, the smaller role of transpiration compared with shading in explaining within canopy temperature of E. oleina shown in this study should thus not be taken as a universal phenomenon of urban trees until more empirical data is available.

Further investigations can use the method demonstrated in our study. When replicated to other species, information on species differences can be built up over time. It is also important to relate such differences to functional traits of species, as it is practically impossible to study all species. The assessment of functional traits in such studies, such as LAI, growth form (canopy architecture and aspect ratio), leaf traits such as leaf area density, specific leaf area, leaf inclination etc., might provide the ability to generalize from functional traits to canopy microclimate.

The method could also be scaled up to trees in situ, such as in courtyards, along roadside planting verges, or rooftop gardens, as a limitation of the current study is the use of small trees in pots, which may not fully represent canopy structure of larger trees. However, a particular difficulty to be overcome is that field experiments on urban sites are confounded by other factors such as anthropogenic heat sources, variations in solar radiation and wind exposure, all of which may affect transpiration differentially. Another added challenge is the control of soil moisture under such conditions. Careful site selection, relatively large samples and long-term monitoring over wet and dry periods will be needed to identify species differences. In this study, we also did not attempt to partition solar radiation fluxes into sensible heat compared to latent heat. Rahman et al. (2017) showed that through deployment of solar radiation and air temperature sensors above and within the canopy, as well as assessment of whole-tree transpiration, estimates of sensible and latent heat fluxes may be obtained.

Table 4: Ratio of ECw to total temperature reduction within canopy

| Date             | Ratio ECw/Total Reduction |
|------------------|---------------------------|
| 9 December 2016  | 0.26                      |
| 10 December 2016 | 0.38                      |
| 11 December 2016 | 0.33                      |
| 12 December 2016 | 0.45                      |
| 13 December 2016 | 0.41                      |
| 14 December 2016 | 0.67                      |
| 15 December 2016 | 0.36                      |
| 12 January 2017  | 0.17                      |
| 13 January 2017  | 0.26                      |
| 14 January 2017  | 0.24                      |
| 15 January 2017  | 0.23                      |
| 16 January 2017  | 0.10                      |
| 17 January 2017  | 0.36                      |
| Mean             | 0.33                      |
| SD               | 0.14                      |
Conclusion

Canopy microclimate studies of urban trees for improving species selection to achieve more effective urban cooling are still limited, even though an increasing number of studies now highlight the potential for more deliberate selection of trees to improve their use in cooling urban areas. In this short note, we described a method that can be used to delineate shading versus EC effect within vegetation canopies. The method can be used on other species to develop better understanding of species differences in canopy microclimate. For E. oleina, EC by transpiration was comparatively smaller than shading effect of vegetation canopy in explaining air temperature within the canopy. Night time temperature within the canopy was also higher than air temperature above the canopy. However, current state of knowledge does not allow conclusion on whether this is a universal phenomenon. Further studies are recommended.

Supplementary data

Supplementary data are available at JUECOL online.

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