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Comparing the transpirational and shading effects of two contrasting urban tree species

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Abstract

Urban trees are getting increasing attention as a tool to mitigate urban heat island effects. A more functional and quantitative view of transpirational and shading effect, particularly the magnitude of both surface and air cooling potential can further strengthen motivations for urban tree planting. We investigated the transpirational and the surface cooling potential of two contrasting tree species in Munich, Germany: ring porous *Robinia pseudoacacia* L. and diffuse porous *Tilia cordata* Mill. Throughout the summer 2016 we monitored meteorological and edaphic variables and tree sap-flow along with the air temperature within and outside tree shade at different heights. With 30% higher leaf area index (LAI), double sap-flux density and sapwood area, *T. cordata* trees showed three times higher transpiration compared to the *R. pseudoacacia*. Consequently, *T. cordata* trees showed higher within canopy air cooling effect. Surface cooling (ΔT_{shade}) were higher under the denser canopies of *T. cordata* compared to *R. pseudoacacia* for asphalt surfaces but ΔT_{shade} for grass surfaces were not significantly different under the canopies of two species. Linear regression indicated a decrease in grass surface temperature of 3 °C with every unit of LAI but for asphalt, the reduction in surface temperature was about 6 °C. Additionally, higher water using efficiencies of *R. pseudoacacia* coupled with higher soil moisture and radiation probably increased the grass evapotranspiration and subsequently showed positive relationship with the near ground air cooling. Therefore, species with higher canopy density might be preferred over asphalt surfaces but low water using species with lower canopy density could be chosen over grass surfaces.

Keywords Urban heat island · Transpirational air cooling · Surface cooling · Leaf area index · Planting design

Highlights
- Species differences and growth conditions can influence tree cooling potential
- Higher water transpiring species provided higher air cooling at the canopy height
- Higher leaf area index (LAI) provided better surface cooling over built surfaces
- Lower LAI and water demand showed better grass surface and near ground air cooling

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Introduction

Creation of the urban heat island (UHI) (Wilby 2003), mainly due to the replacement of natural vegetative surfaces by built surfaces (Oke 1989), will be further intensified with ongoing climate change (Arnfield 2003). Therefore, urban green spaces are getting increasing attention for their important role in mitigating and adapting cities to climate change. The role of urban trees in mitigating UHI in particular has been highlighted (Gill et al. 2007; Rahman et al. 2011; Zölch et al. 2016). Urban trees can cool the local micro-climate by shading from direct shortwave radiation thus altering the surface energy balance and reducing the surface temperature underneath (Lindberg and Grimmond 2011). Trees can also cool down the air temperature through the process of evapotranspiration (Rahman et al. 2017a; Shashua-Bar et al. 2009; Zhao et al. 2014). Substantial work has been done regarding the thermal effects of urban vegetation both using modelling approaches and small scale field experiments which has been subjected to

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a meta-analysis by Bowler et al. (2010) and a review by Qiu et al. (2013). Urban vegetation has shown consistent reduction of air temperature between 0.5 and 5 °C, with time and magnitude for maximum influence depending on vegetation type, size, and climatic conditions. Similarly, Gill et al. (2007) and Armson et al. (2012) have shown that during hot summer days permanent tree shade can reduce surface temperatures by 12–20 °C. Yet, many questions remain unanswered such as the magnitude and pattern of air and surface cooling effects of urban tree species grown under different site conditions. Along with the micro-meteorological and edaphic factors (Rahman et al. 2017a) in highly heterogeneous urban environments, species selection can significantly alter the relative cooling effectiveness of urban trees (Rahman et al. 2015; Smithers et al. 2018; Vico et al. 2014).

Studies have shown that morphological characteristics of different tree species such as the tree shape, the canopy size, the canopy density, and the features of the tree leaves, can influence the resulting cooling effect (Georgi and Dimitriou 2010; Shahidan 2015). Among the morphological characteristics, canopy density showed the greatest effect in terms of both surface temperature reduction (Armson et al. 2013; Lin and Lin 2010) and evapotranspirational cooling (Rahman et al. 2015). For instance, as a measureable variable, the leaf area index (LAI) is widely used since it can reveal differences in spatial structure of vegetation in terms of light interception as well as transpiration and photosynthesis (Kong et al. 2016). Within the leaf, stomata and leaf hydraulic network control two distinct phases of water transport across the soil-plant-atmosphere continuum (vapour and liquid flux) (Simonin et al. 2015). Assuming similar evaporative demand and no water stress condition, plant transpiration is strongly constrained by the hydraulic architecture (Bush et al. 2008) that supplies water to leaves. Within angiosperms, xylem anatomy is broadly divided into plants with ring-porous versus diffuse porous vessel elements. Ring-porous species have a bimodal distribution of vessel diameter associated with wide, early season vessels and narrow late-season vessels, while diffuse porous species show little variation in diameter in early versus late wood (Tyree and Zimmerman 2002), consequently vessel diameters have significant impact on xylem conductivity. Bush et al. (2008); Peters et al. (2010) and Pataki and Oren (2003) all reported 2–3 times higher daily sap flux density from diffuse porous trees compared with ring porous species during June and July in different urban areas in the USA.

Shading by tree canopies can affect both soil and air temperature; however, the direct effect on below canopy air temperature appeared to be small compared to the effect on soil surface temperature (Armson et al. 2012), mainly because of the advection of air in urban conditions. Moreover, a more functional and quantitative view of urban street trees influencing the below-canopy microclimate is largely missing. Higher canopy density can potentially lead to lower light availability at the below-canopy surfaces (Katul et al. 2004). Using thermal satellite imagery Hardin and Jensen (2007) have shown that every unit in LAI reduces surface temperature by 1.2 °C or using thermal camera Gillner et al. (2015) showed a decrease in asphalt surface temperature of 4.63 °C for every unit increase in leaf area density (LAD).

Based on the grass evapotranspiration, surfaces reduce their surface temperature and the differences between sunny and shaded area are predicted to be smaller compared to the built surfaces. However, below-canopy meteorological and edaphic parameters along with tree transpiration measurements have not been investigated to our knowledge at least at urban micro scale. In particular, the decoupling of the intriguingly related shading and evapotranspirational cooling effect of urban trees remain unexplored. Given the numerous technical and logistical challenges to make physiological measurements on trees in an urban ecosystem, this is not surprising. With complex non-linear feedback loops between several processes in the soil-plant-atmosphere continuum (Banerjee and Linn 2018) low dimensional outlines must be developed to capture the essential variations between cooling efficiencies of contrasting species (Stratopoulos et al. 2018).

With high heterogeneity at small scale and harsh growing conditions in urban areas (Pauleit 2003; Rahman et al. 2011, 2013), it is very important to understand the responses of tree physiological processes such as hydraulic adjustment of urban trees to the local micro-climate (Savi et al. 2015). Considering the ecosystem services provided by urban trees and how they are altered by growing conditions, tree level transpiration might be the most significant measure of the ability to provide cooling (Vico et al. 2014). Significant transpiration-induced air temperature cooling has been reported (Lindén et al. 2016; Rahman et al. 2017b). However, simultaneous measurements of the energy fluxes under the canopies of different plant functional types over several growing seasons are required to understand the full potential of tree cooling effect. More realistically, investigating the energy loss in relation to its temperature differences and of shaded surfaces would be better in quantifying the cooling effects of different tree species in comparable conditions. Within the tree canopy, evaporative cooling is compensated by the heat transfer from the surrounding environment (Rahman et al. 2017b). Therefore, the balance between latent and sensible heat fluxes underneath the tree canopy can be estimated from the air and soil temperature within and outside the canopy along with bio-meteorological and physiological variables. We hypothesized that trees with higher LAI, sap velocity and sap wood area will have more canopy transpiration, consequently have higher shading and boundary layer air cooling effect.

The main aim of this study is to understand the cooling efficiencies of two ecologically contrasting species both in terms air and surface temperature in urban conditions. The study measured air and surface temperature differences below

and outside the canopy along with the tree transpiration rate of two common tree species with contrasting wood anatomy: *Robinia pseudoacacia* (ring porous) and *Tilia cordata* (diffuse porous) grown in two street canyons. The specific research questions posed for the experiment are i) Does street tree transpiration vary with xylem anatomy and if so, how much of the transpirational cooling effects near ground air temperature? ii) How to assess the relative strength of tree and below-canopy surface attributes for an integrated understanding of the thermal effects of urban street trees?

Methods

Study area

The study site was located in Munich, one of the biggest cities in Germany with a high population density (4700 people/km^2) (Xu et al. 2018). Munich has long been reported as a city with substantial effects of UHI with monthly mean UHI intensity up to 6 °C and increasing (Pongracz et al. 2010). The city is characterized by a warm temperate climate which is affected by its sheltered position due to the Alps. The annual mean temperature is 9.1 °C with a temperature range from −4 °C (January) to 24 °C (July) and an annual precipitation of 959 mm, the winter is comparatively dry (46 mm in January) but the summer is rainy (maximum of 125 mm in July) (DWD 2017). In Munich a number of green open areas can be found with presence of few taller buildings higher than 100 m (Pauleit and Duhme 2000).

Following a dedicated field campaign, the area of Messestadt Riem (48.14° N, 11.77° E, at 520 m asl) was selected within the eastern fringe of Munich. The area is a densely built residential and shopping district developed on the former airport area since 1992 (Baureferat München 2016) (Fig. 1). It should be noted that all the potential confounding variables while quantifying cooling benefits from different species in the urban settings are difficult to control. Therefore, selection criteria were set carefully: (1) to have two popular and commonly planted but ecologically contrasting species in a sufficient number and free from any visual decay or damage of similar age and planted on the same soil type, and (2) street trees planted in grass lawns that, however, also shade the nearby asphalt streets. Consequently, two nearby streets were selected with one plot of *Tilia cordata* and another of *Robinia pseudoacacia* at two sides of a big shopping center. The streets are comparable in terms of solar exposure, wind direction and public use. Both streets are located in a residential area with 2–3 storey perimeter blocks distributed in a regular configuration. The selected tree species have contrasting wood anatomy and water using behaviour. *T. cordata* is a diffuse-porous, anisohydric, shade-tolerant species with a low water use efficiency (Radoglou et al. 2009),

whereas, *R. pseudoacacia* is characterized as ring-porous, isohydric, light-demanding and highly water using efficient species (Keresztesi 1988; Roloff 2013). Both *R. pseudoacacia* (Vitkova et al. 2017) and *T. cordata* (Dahlhausen et al. 2016) are widespread in Central European cities. *T. cordata* alone was estimated to have a share of 35% of all street trees in Berlin (Dahlhausen et al. 2016). Trees are planted in grass lawns in both plots; however, in the case of the *T. cordata* plot, 10 trees are planted at one straight row (8 m distance between trees), 1.5 m away from the asphalt street. In case of *R. pseudoacacia* plot, 10 trees were selected in 2 rows of 5 trees (8 m distance between rows and between trees) and only 1 row of trees is 1.5 m away from an asphalt street (Fig. 1). There was no irrigation, mowing of grass or pruning of trees at both the plots over the experimental period. To have better estimates over the micro-climatic and tree variabilities, care was taken while choosing the controls such as shaded and sunny sites for surface temperature measurements; repetitive and continuous measurements of morphological, physiological, meteorological and edaphic variables from a comparatively large number of replicates.

Tree selection and morphological measurements

Both *T. cordata* and *R. pseudoacacia* are widespread throughout Europe and the dominant street trees in Munich. *T. cordata* trees are characterized by pyramidal to oval crown whereas *R. pseudoacacia* tree crowns are mostly of oval shape. They are commonly used in urban areas especially in sidewalks and in residential streets (Pauleit et al. 2002). Diameter at breast height (DBH) was measured using a diameter measurement tape at a height of 1.3 m. Tree height was calculated using a Vertex Forestor; crown radii were measured in eight intercardinal directions (N, NE,. .., NW) and crown diameter, crown projection area (CPA) as well as crown volume (cv) were calculated. LAI was derived from hemispherical photographs captured in July using a Nikon CoolpixP5100 camera with fisheye lens and Mid-OMount following Moser et al. (2017). Each tree was cored to the heart wood at two opposing directions (N-S) to estimate tree age according to Moser et al. (2017).

Meteorological data collection

Air temperature, air pressure, relative air humidity, precipitation, wind speed and direction, global radiation and PAR were measured by installing Vaisala Weather Transmitters WXT520 and CMP3 pyranometer and a PQS1 PAR sensors (Kipp & Zonen, Delft, The Netherlands) at the two plots. At the *R. pseudoacacia* plot, a meteorological station was mounted on top of a 3.3 m street lamp post (average height of the crown start) and 10 m apart from tree rows to avoid shade of the nearby trees and buildings. At the *T. cordata* plot the station was installed on top of a 3.5 m iron pole (average
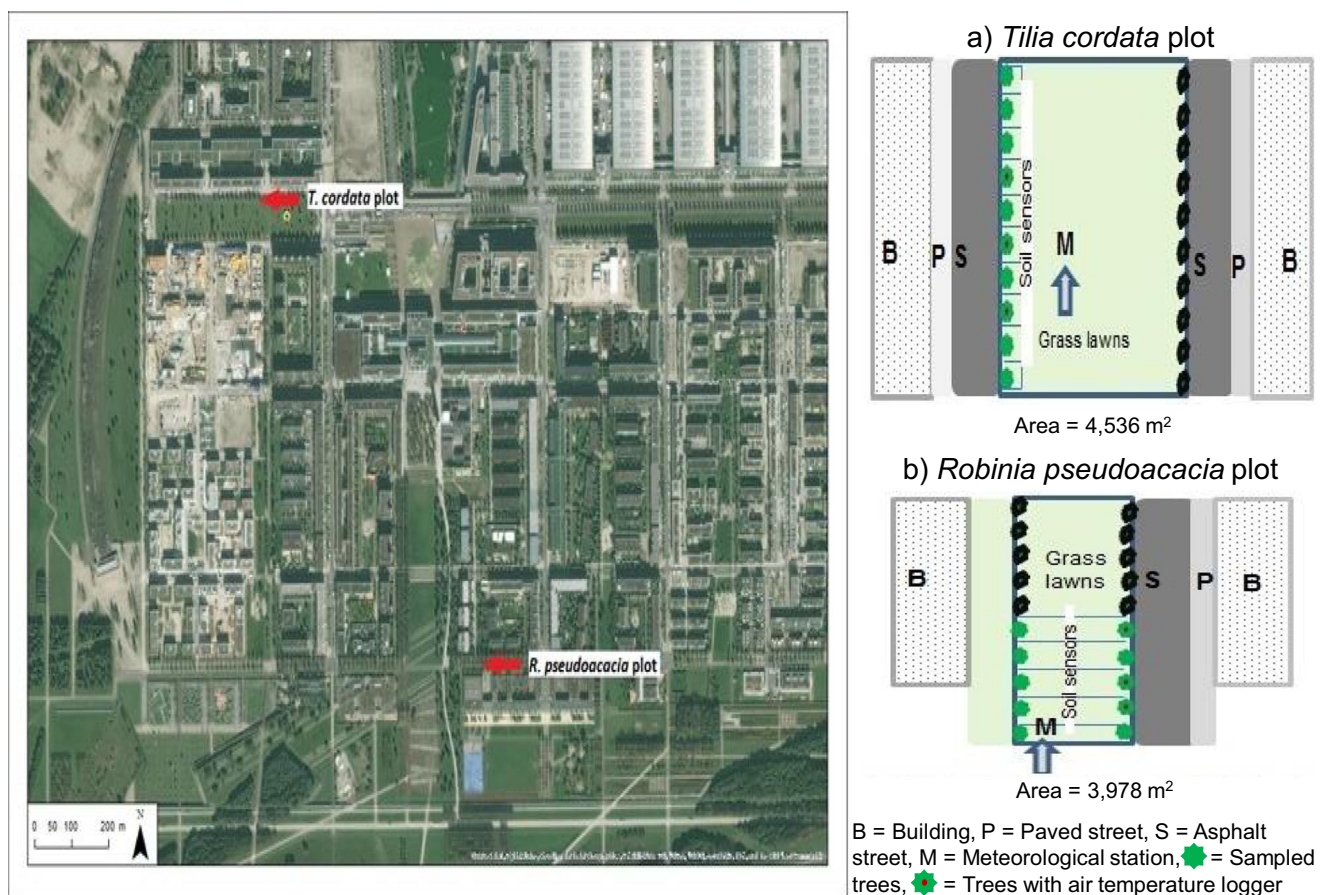
Fig. 1 Plan view of the two plots (left) (Source: Google image, 2018). Cross section of the street view (right) with sampled trees: **a**) *Tilia cordata* plot; **b**) *Robinia pseudoacacia* plot

height of the crown start) and 10 m apart from trees to represent outside-canopy measurements. All the data were recorded continuously at a 15-min resolution from June 2 to October 27, 2016 on enviLog remote data logger attached to one of our sampled trees.

Soil moisture potential and temperature measurements

Soil matric potential and temperature at both the plots were measured using Tensiomark (range pF0-pF7) (EcoTech, Bonn, Germany) installed within the grass lawns vertically through the soil profile to the depth of 30 cm. At the *T. cordata* plot the sensors were installed 4 m apart from the tree trunks between the trees and at the *R. pseudoacacia* plot they were installed in between the rows and trees (Fig. 1). Care was taken in selection of spots in installing tensiomarks to minimize the direct solar radiation.

Tree transpiration measurements

Tree transpiration was estimated from sap flux density (Js), measured continuously using thermal dissipation probes

(Ecomatik, Dachau, Germany) introduced by Granier (1987). Pairs of 20 & 10-mm long and 2.0-mm diameter heating probes were inserted in the stem sapwood of 10 sampled *T. cordata* and 10 sampled *R. pseudoacacia* trees respectively at the two plots after removing the bark. Sensors were inserted into the sapwood on the north side of the trunk at 3–3.5 m height from the ground to deter theft or vandalism. Considering the radial variations in the sapwood area (Cermak and Nadezhdina 1998) of the diffuse porous *T. cordata*, two pairs of longer needles were also installed at a xylem depth of 20–40 and 40–60 mm with identical heating and sensing devices having the same diameter as those drilled for the outermost (0–20 mm depth) sensors. Considerable radial variability in Js might also exist for ring porous *R. pseudoacacia* (Jiao et al. 2016b); however, due to logistical constraint we could not investigate the pattern. All sensors were covered with reflective foil to minimize the influence of solar irradiance. The temperature difference (ΔT) between upper and lower sensor probes was recorded every 30-s with a CR800 data-logger (Campbell Scientific, UK) equipped with Multiplexer, AM16/32B. Five-minute means were calculated from the 30-s readings and stored by the data-logger. Temperature differences were converted to sap flux densities

(Js; ml cm^{-2} min^{-1}) based on Granier's empirical calibration equation (Eq. 1, Appendix) (Granier 1987).

The same tree core samples used for age estimation were also used to visually determine the sapwood depth immediately after the cores were extracted. *T. cordata* trees showed a sharp decline of Js from outer 20 mm to inner xylem of 40 mm (55%) and then a gradual decline (49%). Considering this variability, the sap flow (SF) (ml tree^{-1} min^{-1}) for *T. cordata* (Eq. 2, Appendix) and *R. pseudoacacia* (Eq. 3, Appendix) were estimated by multiplying Js with sap wood area (SA) following Rahman et al. (2017a) .

SF were converted to daily values (average values between 9 am and 6 pm) and multiplied by the latent heat of vaporization L$_V$ which is 2.45 kJ g^{-1} to calculate the energy loss (W tree^{-1}) per tree (Eq. 4, Appendix).

Air and surface temperature measurements

Seven Newsteo LOP16 temperature datalogger (La Ciotat, France) were installed at each plot. Three of them were installed at 1.5 m height from the ground close to the tree trunks above grass surface and three at 4.5 m height within the lower part of tree canopies to measure air temperature at shade following Rahman et al. (2018). One logger was installed on the same pole where the weather station was mounted but at a height of 2 m from the ground to measure air temperature at open site. The temperature loggers were fitted with radiation shield and were calibrated before the monitoring programme began. Air temperature was recorded within the internal memory of the loggers every five minutes between June 23 and October 13, 2016.

Surface temperature of grass and asphalt surfaces were measured between 9 am and 6 pm based on at least 2 and maximum 6 inter-cardinal directions on 8 clear and warm days during summer 2016 using a laser gun (PTD 1, Bosch GmbH, Germany). The shaded location was always selected close to the tree trunk to ensure that the surface had as much time in the shade as possible to measure below-canopy surface temperature (T$_{shade}$) and the sunny location minimum 5 m away from the main canopy shade ensuring the area had never been in shade to measure outside-canopy surface temperature (T$_{sun}$). However, due to the orientation of the *R. pseudoacacia* trees on the north side of the asphalt street, asphalt surface temperature measurements were carried out only beneath 5 trees of similar morphological characteristics from the south side of the street (Fig. 2). Prohibition on hanging cables over streets did not allow us to include those five trees as sampled trees for continuous measurements. In both the cases, the sampled region was instantaneously shaded by the researcher during the reading to remove the calibration error that would have been caused by direct sunlight following Armson et al. (2013). The surface cooling temperature (ΔT$_{shade}$) was calculated from the difference between T$_{sun}$ and T$_{shade}$. At the same time, below-canopy wind speed was measured using a hand held anemometer PCE-THA 10 (PCE-Holding GmbH, Germany) at the point where T$_{shade}$ was measured.

Statistical analysis

The software package R, version 3.2.1 (R Core Team 2015) was used for statistical analysis. To investigate the difference between means, both spatially and temporally, we used Two Sample t-tests. In all the cases the means were reported as significant when $p < 0.05$. Pearson correlation coefficient was calculated to determine the association between outside-canopy minus below canopy air temperature (ΔAT) and below-canopy surface temperatures (T$_{shade}$); leaf area index (LAI) and surface temperature reduction (ΔT$_{shade}$).

Fig. 2 Experimental set up - *T. cordata* plot (left) and *R. pseudoacacia* plot (right). Shading effect on asphalt was estimated from five *R. Pseudoacacia* trees located on the south of the street

Table 1 Average morphological characteristics of trees and open grass surface area (OSA) of two plots (CPA = crown projection area; AS = degree of asphalt surface within CPA; CR = crown radius; CV = crown volume; LAI = leaf area index; SWD = sapwood depth; SWA = sapwood area)

Species	Age (years + SE)	CPA (m² + SE)	OSA (m² + SE)	AS (% + SE)	CR (m + SE)	CV (m³ + SE)	DBH (cm + SE)	Height (m + SE)	LAI (+ SE)	SWD (cm + SE)	SWA (cm² + SE)
T. cordata	36 + 0.4	35 + 1.03	203 + 0.27	36 + 5	3.32 + 0.05	250 +12	23.7 + 1.04	10.6 + 0.20	3.64 + 0.41	7.15 + 0.28	364 + 8.3
R. pseudo-accacia	32 + 1.2	52 + 3.78	198 + 3.6	44 + 10	4.03 + 0.15	460 +51	27.4 + 1.18	12 + 0.36	2.61 + 0.21	1.82 + 0.09	155 + 5.5

Results

Tree morphological characteristics

R. pseudoacacia trees were younger with significantly smaller LAI, sapwood depth and area but had significantly higher crown projection area, crown radius, crown volume, height and DBH, than *T. cordata.* The open grass surface area and the degree of asphalt surface within CPA at both plots were not significantly different (Table 1). The average height of the branch-free trunk was about 3.30 and 3.50 m for *R. pseudoacacia* and *T. cordata* respectively.

Micro-climatic differences between the two plots

Meteorological variables measured over time were almost identical at two plots except for wind direction. At the *R. pseudoacacia* plot the wind direction was mostly perpendicular to the axis of the street canyons, whereas at the *T. cordata* plot it was more parallel to the street with evidence of isolated roughness flow (Fig. 3).

The global radiation (I_{tot}) peaked to 21 MJ m^{-2} day^{-1} with mean PAR value of 128 W m^{-2} on June 22, and then gradually declined towards September and October, 2016. High I_{tot} and PAR were in good agreement with high vapour pressure deficit (VPD) and air temperature (AT) indicating warm sunny days (Fig. 4). Total amount of rainfall between June and October, 2016 was about 412 mm which was
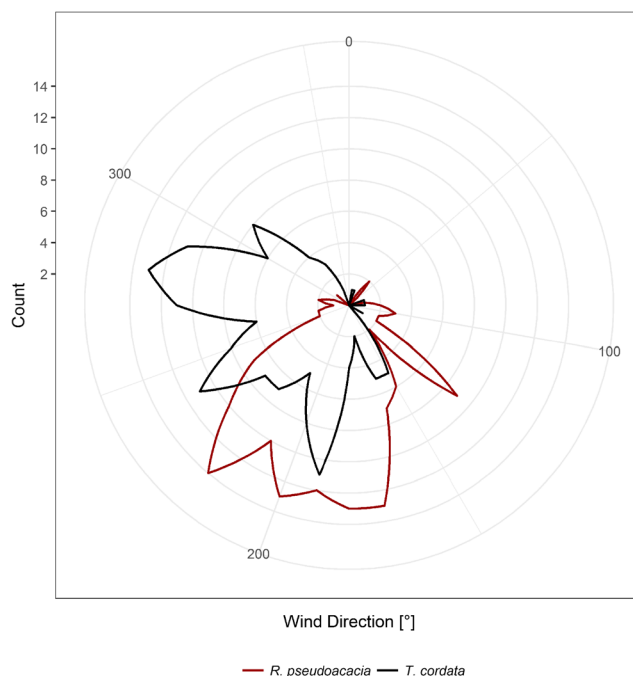
Fig. 3 Average daily wind direction counts of two plots with *R. pseudoacacia* and *T. cordata* (0° starts from North direction) between June 06 and October 26, 2017

Fig. 4 Average daily totals of global radiation (I_{tot}) and mean daily photosynthetically active radiation PAR; precipitation and air temperature (AT); wind speed (WS) and vapour pressure deficit (VPD) of two plots between June 6 and October 26, 2016 (missing values for radiation are due to vandalism)
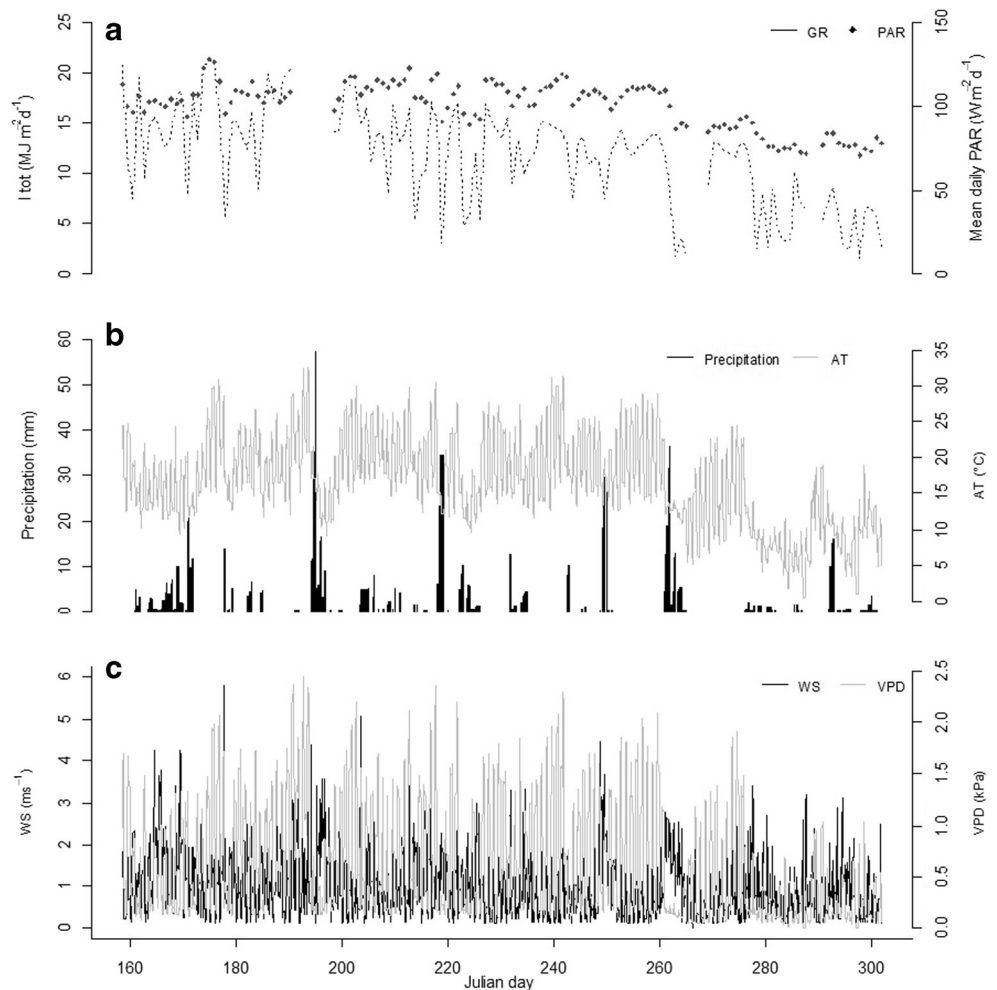

spread over the whole season except few heavy rainy days exceeding 20 mm on days 194, 218 and 261 (Fig. 4). Compared to the long term meteorological data (DWD 2017) the summer of 2016 was a typical one; maximum air temperature more than 30 °C reached on around 10 days. Wind speed was mostly below 2 m s^{-1} with occasional gust of 4 m s^{-1} or more. The below canopy wind speed was two-thirds to half of the canopy level wind speed at both sites (Fig. 5). Nonetheless, below-canopy wind speed at the plot with *T. cordata* trees was comparatively higher than at the plot with *R. pseudoacacia* trees.

A couple of dry spells showed significant impact on soil moisture status especially during the middle of August (227) to early September, 2016 (253) (Figs. 4 and 6). However, soil moisture potential was significantly higher at the *T. cordata* plot (mean = 0.20 MPa) compared to the *R. pseudoacacia* plot (mean = 0.03 MPa) (t = −85.24, df = 14,901, $p < 0.001$) (Fig. 6). Soil temperature was also significantly higher at the *T. cordata* plot (mean = 17.99 °C) compared to the *R. pseudoacacia* plot (mean = 16.20 °C) (t = −49.86, df = 26,242, $p < 0.001$) (Fig. 6).

Sap flux density (Js) and transpirational cooling

Average Js of *T. cordata* trees (0.09 ml cm^{-2} min^{-1}) was significantly higher compared to *R. pseudoacacia* (0.05 ml cm^{-2} min^{-1}) (t = − 65.94, df = 65,242, $p < 0.001$) over the entire measuring period. Maximum Js of *T. cordata* trees reached 0.36 ml cm^{-2} min^{-1} (Fig. 7a) around days 176 to 210 but showed large decline afterwards. On the other hand, Js of *R. pseudoacacia* trees peaked up to 0.18 ml cm^{-2} min^{-1} at around days 207 but showed constant values throughout the season until the beginning of October, 2016 (Day 275). Subsequently, average daily energy loss (between 9 am and 6 pm) through tree transpiration was significantly higher for the *T. cordata* trees (1.9 kW tree^{-1}) compared to *R. pseudoacacia* (600 W tree^{-1}) (t = 21.29, df = 179, $p < 0.001$) (Fig. 7b). In terms of diurnal pattern, the energy loss peaked during the late morning for *T. cordata* up to 4 kW tree^{-1} and during late afternoon for *R. pseudoacacia* up to 1.3 kW tree^{-1}.
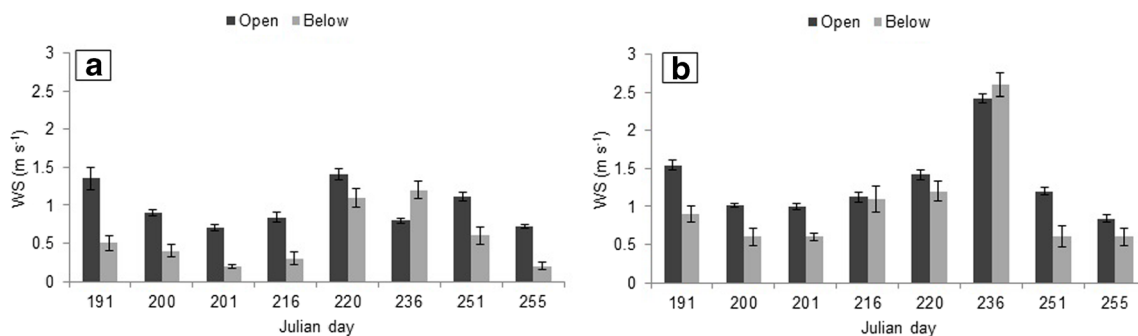
Fig. 5 Average day time wind speed (9 am to 6 pm) of sampled days at below canopy and open sites at a) *R. pseudoacacia* plot b) *T. cordata* plot

Within canopy air temperature reduction (ΔAT $_{canopy}$) and relationship with meteorological and edaphic variables

Overall ΔAT_{canopy} during the day time (9 am – 6 pm) was significantly lower within the tree canopies of *R. pseudoacacia* (mean $\Delta AT = 0.9$ °C) than the *T. cordata* (mean $\Delta AT = 1.6$ °C) (t = 43.64, df = 7769, p < 0.001). ΔAT_{canopy} of the *T. cordata* peaked in the morning (9 am) but showed a depression during the mid-day following an increase in the GR and VPD. Towards the later afternoon, ΔAT_{canopy} of the *T. cordata* canopies increased slowly.

However, ΔAT_{canopy} of the *R. pseudoacacia* canopies were less responsive to the VPD condition and kept transpiring at an increasing rate to show higher ΔAT_{canopy} towards the late afternoon. Starting from 15 h there were no significant differences in ΔAT_{canopy} between the species (Fig. 8).

On an average ΔAT_{canopy} for both the species were not significantly different at night (18–09 h) (0.4 °C and 0.3 °C for the *R. pseudoacacia* and the *T. cordata* respectively). With more stable wind speed and absence of solar radiation and transpiration, AT_{canopy} were close to the outside canopy air temperature.

Fig. 6 Soil moisture potential (SMP) (**a**) and soil temperature (**b**) of two plots between June 6 and October 26, 2016 (missing values are due to vandalism)
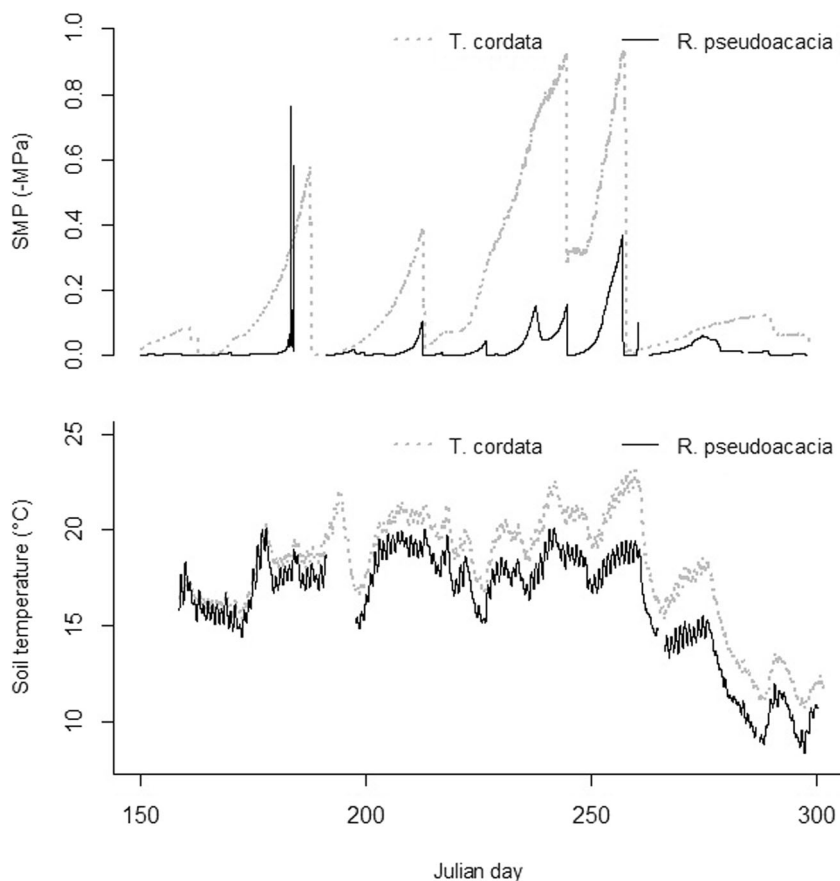
Fig. 7 a) Sap flux density (Js) and b) average energy loss per tree of *T. cordata* and *R. pseudoacacia* trees between May 13 and October 13, 2016 (missing data represent days when equipment failed owing to vandalism and power interruptions)
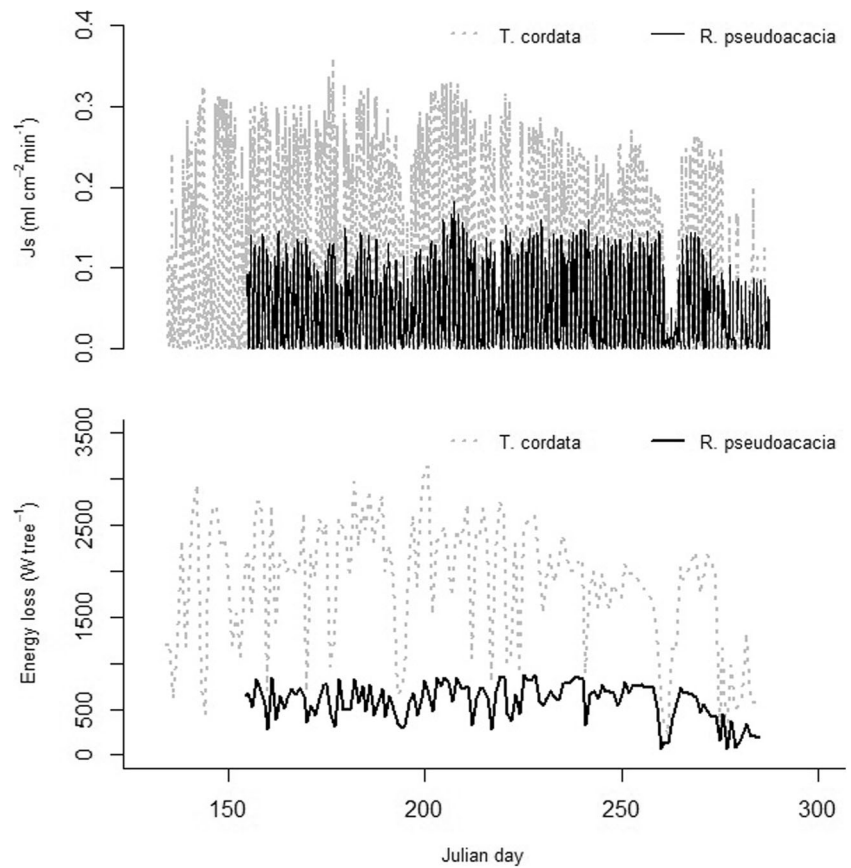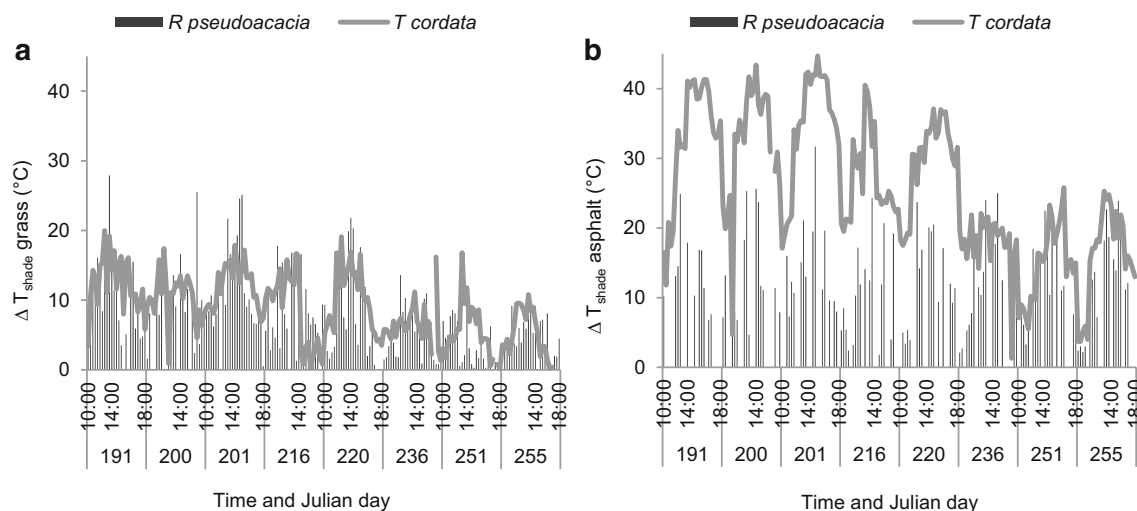

Surface temperature and relationship with LAI

The overall surface temperature reduction (ΔT_{shade}) was significantly higher for asphalt surfaces compared to grass surfaces under the shade of both the species. But ΔT_{shade} asphalt was more than double under the shade of *T. cordata* than *R. pseudoacacia* (25.59 °C and 12.71 °C respectively).

However, ΔT_{shade} grass was not significantly different between the species (9 °C and 8 °C for *T. cordata* and *R. pseudoacacia* respectively) (Fig. 9).

Surface cooling of both the grass and asphalt surfaces was strongly correlated to LAI (Fig. 10). However, the relationship was stronger over the asphalt surfaces compared to the grass surfaces.
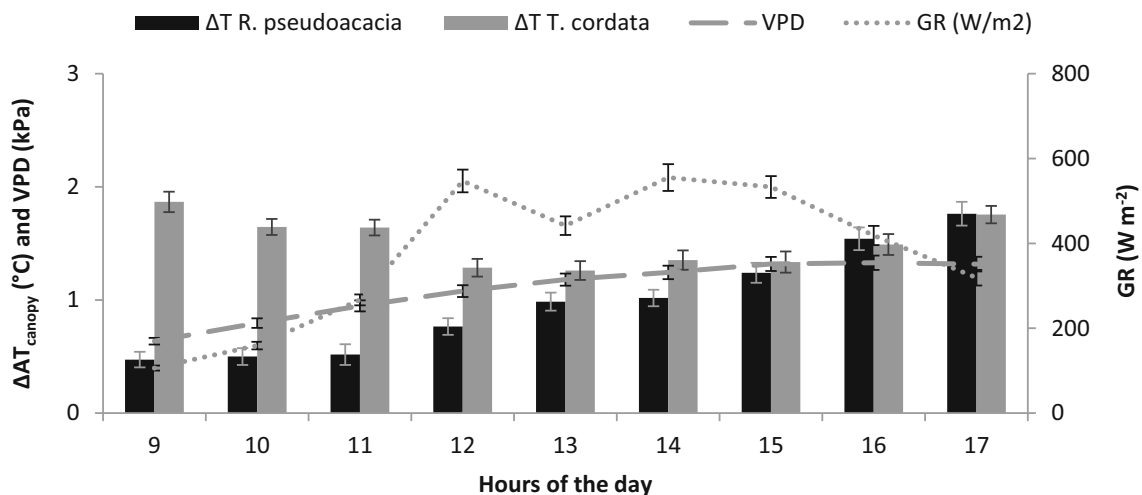
Fig. 8 Average hourly air temperature differences between open and within canopy (ΔAT_{canopy}) of *T. cordata* and *R. pseudoacacia* trees, vapour pressure differences (VPD) and global radiation (GR) between 9 am and 6 pm during June, July and August, 2016

Fig. 9 Surface temperature reduction (ΔT_{shade}) between 9 am and 6 pm on sampled days a) grass surfaces b) asphalt surfaces

Near ground air temperature and relationship with shaded grass surface temperature

The relationship between $\Delta AT_{1.5\ m}$ above grass surface and below-canopy grass surface temperature (T_{shade}) was significant ($p < 0.001$). It was positive for *R. pseudoacacia* (Pearson correlation coefficient, r = 0.55), i.e. air temperature reduction was positively influenced by the increasing surface temperature and indicated the fact that the extra energy was used for below-canopy latent heat exchange from the grass. Whereas it was negative for *T. cordata* (Pearson correlation coefficient, r = −0.42) i.e. extra energy increases the soil heat storage and ultimately the sensible heat flux (H) from the grass surfaces underneath the canopy.

Discussion

Our study showed that canopy density, sap flow and soil moisture interact in a complex way that depends on the tree functional type and planting design to provide a distinctive cooling effect. Diffuse-porous *T. cordata* despite having smaller crown projection area, and growth rate compared to the ring-porous *R. pseudoacacia*, showed higher transpiration rate due to the higher sap flux density (Js) and sapwood area. Additionally, *T. cordata* with higher LAI also allowed less short wave radiation to penetrate thus provided better surface cooling. With 412 mm of rainfall during the summer 2016, the overall microclimatic conditions provided a good opportunity to test how differences in angiosperm xylem anatomy dictate the transpiration rate in
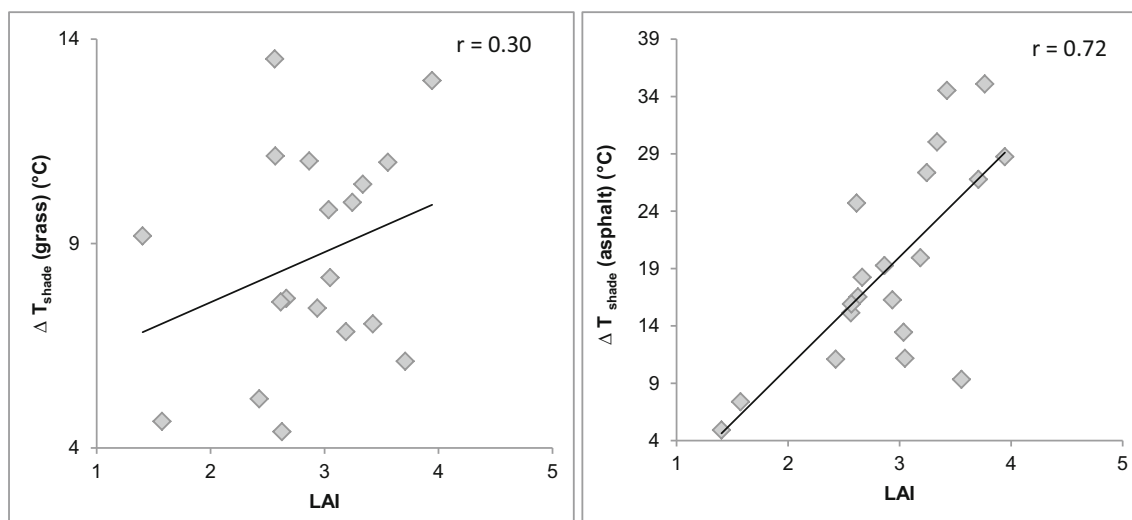
Fig. 10 Relationship between the surface temperature differences (ΔT_{shade}) between the sunny and shaded surface a) Grass b) Asphalt and leaf area index (LAI) (r = Pearson's correlation coefficient)

moist soils but in a relatively high VPD environment. However, less water demand and the sparse canopy of *R. pseudoacacia* was followed by higher soil moisture and lower soil temperature. Consequently, the near ground air temperature differences over-grass compared to the open site ($\Delta AT_{1.5 m}$) were higher under *R. pseudoacacia* than *T. cordata* trees.

Transpirational cooling

Our result of high daily Js but large declines towards the later part of the growing season for *T. cordata* and low but consistent daily Js for *R. pseudoacacia* agrees with previous research such as Bush et al. (2008) and Peters et al. (2010). Previous studies have shown that the diffuse porous species have more than double the density of vessels than the ring porous species (Atkinson and Taylor 1996). Our estimate of Js of *R. pseudoacacia* trees which peaked at 0.18 ml cm^{-2} min^{-1} is low compared to the values reported by Kume et al. (2012) at 0.3 ml cm^{-2} min^{-1}. However, they reported the values for a natural forested area with lower atmospheric demand and soil temperature as well as higher soil moisture than the urban setting. In contrast, some studies have shown that street trees might have higher transpiration rates compared to tree clusters or forested sites (Close et al. 1996; Pataki et al. 2011; Rahman et al. 2011). In case of *T. cordata*, peak value of Js of 0.36 ml cm^{-2} min^{-1} is comparable to previous studies carried out in the centre of Munich during a comparatively dry year of 2015 (Rahman et al. 2017a, b). During the night, significantly reduced energy loss from the tree canopy (20% of the day time value for *T. cordata* and 25% for *R. pseudoacacia*) along with reduced re-radiation of longwave radiation from the ground due to tree canopies can explain reduction in air cooling within the canopy at 4.5 m height.

T. cordata with higher LAI transpire more water and, therefore, deplete soil moisture faster than *R. pseudoacacia* (von Arx et al. 2013). Our data revealed that the air temperature underneath the tree can also be higher than the open grass surfaces if the warming effect from the ground cancels out the latent heat effect from the top. Despite higher solar radiation underneath the canopies of *R. pseudoacacia*, the soil temperature was significantly lower compared to *T. cordata* (Fig. 6). Probably this indicates higher latent heat exchange from the grass surfaces underneath canopies of *R. pseudoacacia*. Indeed this has been already shown for thinner canopy trees of arid, xerophilic vegetation (Renaud and Rebetez 2009). Moreover, Renaud and Rebetez (2009) reported even up to 1 °C warming effect below canopy temperature within a forested site in Switzerland when comparing the air temperature below canopy and open sites during the heatwave of 2003.

Below canopy air and surface temperature

Numerous research has shown that characteristics of tree species such as tree morphological characteristics including tree shape, canopy size, canopy density as well as features of tree leaves can influence the tree cooling effect (Kong et al. 2016; Rahman et al. 2015; Shahidan 2015; Smithers et al. 2018). Increasing the leaf surface area and density is the major factor for optimizing the shading effect; however, relating the effect of transpirational cooling to tree features is more complicated since not only the morphology which governs the cooling but also physiological processes play a significant role along with the atmospheric demand (Rahman et al. 2017a). Our study showed that with higher LAI, *T. cordata* trees provided better surface temperature reduction (Fig. 9) both over grass and asphalt surface. However, from the slope of the regression line in Fig. 10 it can be calculated that every unit of increase in LAI happened to increase the surface cooling of about 3 °C for grass surface but for the asphalt surface it was about double. Given that the open asphalt surface received all the direct solar radiation with no evaporation, the magnitude of surface temperature reduction potential compared to grass surface was much higher for both the species. Similar to our study, Lin and Lin (2010) showed grass surface temperature reduction under tree canopies up to 8 °C compared to an open grass area inside a park in Taipei City, Taiwan. This suggested that grass surfaces are very important since impervious surfaces can be regarded as "heat sources" (Yang and Zhao 2016).

Further to this, how much air cooling is possible in presence of tree shade depends on the influence of latent heat (LE) fluxes from the tree and grass canopies. Grass evapotranspiration can be significant as shown in forest conditions (Baldocchi and Vogel 1996). In urban conditions, Gill et al. (2013) showed that without water stress grass actual evapotranspiration (eta) can be close to the potential evapotranspiration (PET) in fully sun exposed condition. Whereas in the permanent shade of a maple tree (with LAI 3), eta was reduced to only 1/3 of PET. On the contrary, in the current research when we estimated the PET using FAO (2009), we found the average transpiration rate of *T. cordata* and *R. pseudoacacia* were only around 39% and 15% of the PET respectively. Therefore, having a grass surface beneath the canopy must have played a significant role in determining the near ground air temperature. With two-thirds to half of the wind speed beneath the tree canopies compared to the open areas (Fig. 5) transpirational cooling from tree canopies are expected to be more effective towards the ground than other immediate surroundings. Simultaneously, comparatively higher below-canopy wind speed under the canopies of the *T. cordata* than the *R. pseudoacacia* might have also affected the warm air advection from the ground. However, sensible heat flux

was not measured in our experiment rather soil and below-canopy surface temperature was used as an indicator. Therefore, future measurements including radiation fluxes (long wave in and out, short wave in and out) from different directions, wind speed, air temperature and humidity, globe temperature along with the edaphic variables beneath different urban street tree species will be beneficial to more precisely understand their cooling potentials.

Effects of species and ground conditions on cooling

Although we did not measure all the water budget components, in a concurrent study Moser-Reischl et al. (2019) showed that the water using efficiencies (WUE) of isohydric *R. pseudoacacia* was 8.11 g L^{-1} compared to only 1.30 g L^{-1} for anisohydric *T. cordata* trees. Soil evaporation (Es) and grass LE possibly accounted for a significantly larger role in the total energy budget in the case of *R. pseudoacacia* below canopy air temperature, as shown by previous research carried out in forest conditions with *R. pseudoacacia* (Jiao et al. 2016a; Zhang et al. 2007). Moreover, this is in accordance with the findings of Jiao et al. (2016b) who reported *R. pseudoacacia*'s transpiration accounts only 5.3% of the total precipitation in a stand of 27 years old plantation in China. Moreover, the surface energy balance is modulated by soil moisture content and leaf area index of trees of other species present within the canyon (Lee and Park 2008).

The present study is a pioneering attempt to understand the differences of contrasting plant functional types over two common urban grounds (grass and asphalt) by investigating the micro-climatic regulation focusing on surface and air temperature. Consequently, we discussed the perspective of where and how the species studied could be integrated in the urban fabric with regard to human thermal comfort. Our results showed that strategic selection of tree species considering individual site conditions can significantly affect the human thermal comfort. Selection criteria in urban tree planting is frequently based upon aesthetics and origin rather than on the tolerance to stresses by the built environment or perceived co-benefits (Staas et al. 2017). *T. cordata* with lower water use efficiencies showed better below-canopy surface cooling over hard surfaces and may also provide better boundary layer air cooling given that the soil moisture is not limited. On the other hand, *R. pseudoacacia* with higher water use efficiencies showed better integrated human thermal comfort potential over grass lawns. Urban planners while considering species attributes and climate tolerance to use location-specific factors for optimal plant selection thus should also consider the soil and moisture availability. In our experiment, one row of *Robinia pseudoacacia* trees of 5 trees were comparatively further away from the buildings (18 m) and asphalted street

(9.5 m) compared to *T. cordata*. This might cause a small bias in terms of net radiation balance as well as convective heat transfer from the nearby buildings and asphalt streets. Moreover, with two rows of *R. pseudoacacia* the surfaces underneath were more sheltered and stable compared to *T. cordata* below-canopy surfaces. At the same time, owing to the orientation of the streets, we only measured asphalt surface temperature under five *R. pseudoacacia* trees. This might also cause small bias in the estimation of surface cooling. However, because of the minimal variations within the variables measured for *R. pseudoacacia* trees it is plausible that the below-canopy air and surface temperature was mainly affected by the tree attributes.

Our study showed that both surface type and shade greatly affect surface temperatures. However, when it comes to keeping air temperature down it is more important to have permeable water retaining surfaces such as grass lawns which can both evaporate and transpire in case all the soil moisture is not used by the tree to transpire. In places where soil water is not an issue we can still recommend ring porous species with lower LAI such as *R. pseudoacacia* to maximize the cooling benefit. In accordance with earlier studies our results do not support the fact that shading is the most important contributor to the cooling effect in the relatively high thermal urban environment during the daytime (Kong et al. 2016). Rather, the study suggests that the cooling effect is much more species and planting design specific. Overall, less water using species with less canopy density and area might provide lower below-canopy air temperature over grass or other water permeable surfaces as there is the potential for evapotranspiration from the ground as long as the soil is moist. However, where these surfaces are impractical and hard built surfaces are the only option, the governing factor should be both increasing tree canopy area and depth along with selection of higher water using species which can have two effects – maximum surface and air cooling. Incorporating structural soil (Bartens et al. 2009) and rainfall runoff collecting surfaces might also be helpful to maximize the benefits. Especially with ongoing climate change plans to use trees as green infrastructure to manage urban hydrological processes, an appropriate selection of species with special care given to the permeability of the surfaces could contribute strengthening mitigation strategies. However, additional measurements in a broader range of species and climates are needed to confirm the generality of these results as well as to investigate the overall effect on human comfort indices.

Appendix

Equation 1 Granier's empirical calibration equation (Granier 1987)

$$Js = 0.714\left[\frac{\Delta TM - \Delta T}{\Delta T}\right]^{1.231} \tag{1}$$

where ΔTM is the maximum temperature difference when sap flow is assumed to be zero.

Equations 2 and 3 the sap flow (SF) (ml tree^{-1} min^{-1}) for *T. cordata* (Eq. 2) and *R. pseudoacacia* (Eq. 3) were estimated by multiplying sap flux density (Js; ml cm^{-2} min^{-1}) with sap wood area (SA) following Rahman et al. (2017a)

$$SF = Js^*SA/2 + Js^*0.50^*SA/2 \tag{2}$$

$$SF = Js^*SA \tag{3}$$

Equation 4 SF were converted to daily values (average values between 9 am and 6 pm) and multiplied by the latent heat of vaporization L_V which is 2.45 kJ g^{-1} to calculate the energy loss (W tree^{-1}) per tree according to Eq. (4)

$$\text{Energy loss tree}^{-1} = SF \times L_V \times 60 \times 9 \tag{4}$$

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