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Vertical air temperature gradients under the shade of two contrasting urban tree species during different types of summer days

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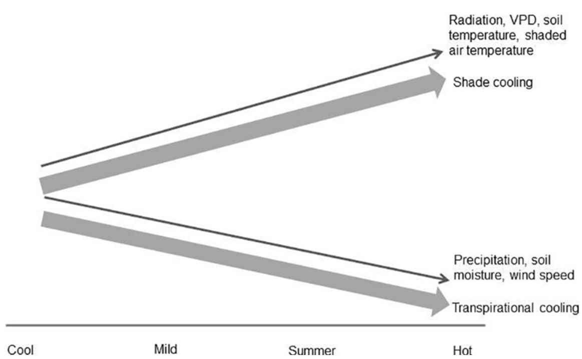
HIGHLIGHTS

- Below-canopy cooling benefits of tree species can vary depending on weather types.
- We studied air temperature from the tree canopies to the ground under tree shades.
- 20 *Robinia pseudoacacia* and *Tilia cordata* trees were studied during the summer 2016.
- Shading is the prominent cooling benefits when the days are very hot.
- Transpirational cooling from trees and grasses are prominent in mild or summer days.

GRAPHICAL ABSTRACT



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ABSTRACT

Moderation of thermal energy balance through the canopies of urban trees is well known. However, a more functional and quantitative view of the heterogeneous urban environment and their influence on the below-canopy vertical air temperature gradients is largely missing. Throughout the summer 2016 we continuously measured air temperature at three different heights (at 1.5, 3 and 4.5 m from the ground) under the canopies of two common but contrasting street tree species in respect of eco-physiology and morphology in Munich, Germany: *Robinia pseudoacacia* L. (ring porous) and *Tilia cordata* Mill. (diffuse porous). Along with air and surface temperature we also measured meteorological and edaphic variables and categorized summer time as cool, mild, summer and hot days. Global radiation, vapour pressure deficit and soil temperature increased as the days got warmer but precipitation, soil moisture and wind speed showed the reversed pattern. Overall, *T. cordata* trees with higher leaf area index and sap-wood area provided three times more transpiration than *R. pseudoacacia*. On an average air temperature gradient of outside to inside canopy dropped from 1.8 °C to 1.3 °C for *T. cordata* but from 1.5 °C to only 0.5 °C for *R. pseudoacacia* as the days got warmer. Vertical decline of air cooling effect was around 1 °C from canopy to the near-ground (1.5 m). Lower soil moisture but higher soil temperature suggested that cool air from the canopy mixed with a higher amount of sensible heat flux under the canopies of *T. cordata* compared to the *R. pseudoacacia* as the days got warmer. The study indicated a threshold for extreme hot days when grass surface evapotranspirational cooling will not be as effective and act like built surfaces rather deep shading from tree canopies will be important.

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1. Introduction

Over the last few decades numerous studies demonstrated that urban greenspaces can mitigate the negative effects of urban heat island mainly by changing the surface energy balance of the system both at micro and macro scale (Armson et al., 2012; Edmondson et al., 2016; Gill et al., 2007; Oke, 1989; Rahman et al., 2011; Zölch et al., 2016). Urban trees are particularly important to cool the surfaces underneath their canopies during the day via evapotranspiration, shading and also by increased albedo and reflection (Rahman et al., 2017a). Through the process of evapotranspiration urban trees can cool leaf surfaces and also ambient air temperature of the surrounding atmosphere as the radiative energy is stored as latent, rather than sensible heat (Brown and Gillespie, 1995). At the same time, grass surfaces were reported to be up to 24 °C cooler when compared to concrete (Armson et al., 2012) and consequently air temperature above the grass surfaces was cooler. Therefore, a combination of grass and trees in an urban area may further mitigate the higher air temperature, particularly near the ground surface (Edmondson et al., 2016).

The decrease of air temperature under tree canopies is caused by both shading and transpiration (Kong et al., 2017). However, in case of outdoor thermal comfort pedestrians have the highest benefit from below-canopy micro-climatic modifications by trees in hot summer days and in the midday to late afternoon when cooling are most needed. In forested areas below-canopy micro-climate may substantially differ from comparable open areas (von Arx et al., 2013) with gradients of temperature, humidity, wind and light. Moist soils underneath the tree canopies can further attenuate warming-up and lowering vapour pressure deficit (VPD) (Fischer et al., 2007). Therefore, the basic principles of forest micro-climate in relation to open-area are well established. However, the complex heterogeneity of urban landscapes (e.g., lawn, parking lot, road, building, and vegetation canopy) may exhibit unique radiative, thermal, moisture and aerodynamic properties (Shiflett et al., 2017) which contribute differentially to the warming of air parcels (Oke, 1978).

The daily average difference between street air temperatures under tree shade as compared to an open area was 0.1 °C in Indiana, United States (Souch and Souch, 1993), up to 0.9 °C in Melbourne, Australia (Coutts et al., 2016), up to 1 °C in Munich, Germany (Rahman et al., 2017b) and 2.8 °C in South east Brazil (De Abreu-Harbicha et al., 2015). Both the micro-climatic shading and air cooling vary between species (Armson et al., 2013; Konarska et al., 2016; Rahman et al., 2015) owing to morphological characteristics (tree shape, canopy size, canopy density, and features of the tree leaves) (Georgi and Dimitriou, 2010; Shahidan et al., 2010) or plant hydraulic architecture (Bush et al., 2008) that supplies water to leaves. Among the parameters of different tree species leaf area index (LAI) is considered as a central parameter affecting light penetration and below canopy microclimate (Kong et al., 2017; Lin and Lin, 2010). von Arx et al. (2013) reported maximum air temperature reduction under the canopies of trees with high LAI. Under less dense canopies or when the soil was desiccated, the difference between below-canopy and open-area microclimate were levelled off. With variation in canopy light availability trees can modify their canopy temperature and humidity microclimate along a vertical gradient (Bauerle et al., 2007). Zweifel et al. (2002) reported about a 1 °C temperature decrease and 5% humidity increase approximately every 4 m from the upper to lower canopy over 22 m in a *Picea abies* L. forest. Rahman et al. (2017b) reported up to 3.5 °C temperature reduction within 4 m radius of canopies of *Tilia cordata* in Munich, Germany. With sparse tree canopy vertical air mass within and below-canopy can be readily mixed with ambient air and thus reduce the air cooling effect.

Although with the canopy insulating effect below-canopy evapotranspirative air cooling may become prominent (Geiger et al., 2009), with higher wind velocity mixing of hot air from the surrounding may result in a reduction of the cooling effect (Dimoudi and Nikolopoulou, 2003). In any case, the air cooling due to tree transpiration will gradually decrease along the vertical path downwards (Rahman et al., 2017b) whereas the conduction of heat or latent heat flux from the ground underneath depends on the paving surfaces, the amount of soil moisture and the penetration of solar radiation through the canopy (Rahman et al., unpublished results). Thus Baldocchi et al. (2000) reported that sparse canopies require accurate representations of energy exchange at the soil surface, where substantial energy exchange occurs. Due to boundary layer mixing cooling effectiveness of tree canopies along a vertical gradient Shiflett et al. (2017) reported a reduction of air temperature ranged from 6 to 3 °C at 0.1 and 2 m, underneath tall canopy compared to bare ground respectively. The partitioning of the turbulent heat fluxes is of particular interest when it comes to cooling processes of urban trees. The quantification of energy fluxes is a common approach to quantify the variability of soil heat flux for row crops particularly important in agronomy (Colaizzi et al., 2016) or in forestry such as investigating the differences between the biological and physical processes over different types of forests (Baldocchi and Vogel, 1996). However, due to higher heterogeneity this approach is difficult to conduct in an urban context and research is rare. Therefore, it is necessary to quantify temperature changes to understand the spatial dimension of turbulent fluxes in the immediate environment of trees. In this simple approach not all the energy fluxes are quantified, only the effects.

Thus, there is still a need to investigate temperature on a spatially explicit basis in urban settings and to describe the vertical temperature acclimation response (Bauerle et al., 2007). A more functional and quantitative view on how the properties of urban ecosystems influence the below-canopy microclimate is largely missing. The vertical profiling needs to be properly assessed to better understand the maximum vertical distance over which air cooling extends and the volume of air affected by different tree canopies and the underneath greenspaces. Moreover, weather conditions can affect the mediating effects of trees (Wang et al., 2015). During hot summer days intense solar radiation can promote radiative warming and thus evaporative cooling as long as water from surfaces below the tree canopy and plants are available (Fischer et al., 2007; Seneviratne et al., 2006). Therefore, investigating the magnitude of tree species to provide cooling benefits to residents and pedestrians under hot, sunny conditions would be extremely beneficial for tree selection and replacement (Sanusi et al., 2017). However, it is impossible to consider all the species commonly planted around the cities. One approach could be to understand the variations within contrasting species in terms of eco-physiology and morphology. In this study, we used a unique set-up for vertical stratification of below-canopy and open-area air temperature replicated under two contrasting tree species to investigate the influence of tree morphology, tree eco-physiology and edaphic variables on under-storey micro-climate. Specific research questions set for the experiment were: (1) what are the magnitudes of air temperature reductions under the shade of two contrasting tree species over grass surfaces under four types of summer days? (2) What are the key characteristics of the thermal regime at different heights and times of the day?

2. Methods

2.1. Study area

The study was conducted in Munich, the 3rd largest but the most densely populated city in Germany (4500 people/km^2) (Bayerisches Landesamt für Statistik, 2016). The city is characterized by a warm temperate climate with substantial effects of urban heat island (UHI) with a monthly mean UHI intensity up to 6 °C which is still increasing (Pongracz et al., 2010). The annual mean temperature is 9.1 °C with a temperature range from −4 °C (January) to 24 °C (July). The mean maximum temperature in July is 25.3 °C. The annual precipitation amounts to 959 mm, the winter is comparatively dry (46 mm in January) but the summer is rainy (maximum of 125 mm in July (DWD, 2017)). There are a number of green open areas in Munich (Pauleit and Duhme, 2000) with presence of few taller buildings higher than 100 m (Jochner et al., 2013).

After 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 which was developed on the former airport area since 1992 (Baureferat München, 2016). Although the district is relatively new and still under construction the area is a densely built residential and shopping district (Fig. 1). The selection criteria involved were (1) to have two popular and healthy matured diffuse and ring porous species in a sufficient number and free from any visual decay or damage of similar age and similar branch free trunk height and planted on the same soil type (2) street trees grown in grass lawns situated near to asphalt streets, shading both surfaces during the day. Consequently, two nearby sites with east-west oriented streets were selected; one plot with *Tilia cordata* and another with *Robinia pseudoacacia* trees. The *T. cordata* site with an area of around 4500 m^2 contains 67 *T. cordata* trees planted in two rows at each site of the square. The *R. pseudoacacia* site with an area of around 4000 m^2 had three rows with a large number of *R. pseudoacacia* trees. Both sites were comparable in terms of precipitation, wind speed (WS), air temperature (AT), vapour pressure deficit (VPD) (Fig. 2 with small SE values) and public use and had 2–3 storey perimeter blocks distributed in a regular configuration along the North and South side of the streets. The *R. pseudoacacia* site was comparably more shaded although the sky view factor estimated at the middle of the asphalt street using a hemispheric camera showed no significant difference (ranging between 48 and 57%). The wind direction was mostly perpendicular to the axis of the street canyons in both the plots. We choose 10 *T. cordata* trees at one straight row (8 m distance between trees), 1.5 m away from the asphalted street. In case of the *R. pseudoacacia* site we choose 10 trees in 2 rows of 5 trees each (8 m distance between rows and between trees) and only 1 row of trees was 1.5 m away from an asphalt street. There was no irrigation, mowing of grass or pruning of trees at both the plots over the experimental period.

2.2. Tree selection and morphological measurements

Both *T. cordata* and *R. pseudoacacia* are commonly planted throughout Europe and the dominant street trees in Munich (Pauleit et al., 2002) but have contrasting life strategies. While *T. cordata* is a diffuse-porous, anisohydric, shade-tolerant species with less water using efficiencies (Radoglou et al., 2009), *R. pseudoacacia* is characterized as ring-porous, isohydric, light-demanding and highly water using efficient species (Keresztesi, 1988; Moser et al., 2016; Roloff, 2013). Among the tree morphological variables diameter at breast height (DBH) was measured using a diameter measurement tape at a height of 1.3 m, tree height using a TruPulse 200 Laser Rangefinder, crown radii were measured in eight inter-cardinal 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. (2015). Moreover, each tree was cored to the heartwood at two opposing directions (N-S) to estimate tree age.

2.3. 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 (EcoTech, Bonn, Germany) and CMP3 pyranometers and PQS1 PAR sensors (Kipp & Zonen, Delft, The Netherlands) at the two plots. At the *T. cordata* plot the station was installed on top of a 3.5 m iron pole, 10 m apart from trees to represent reference measurements while at the

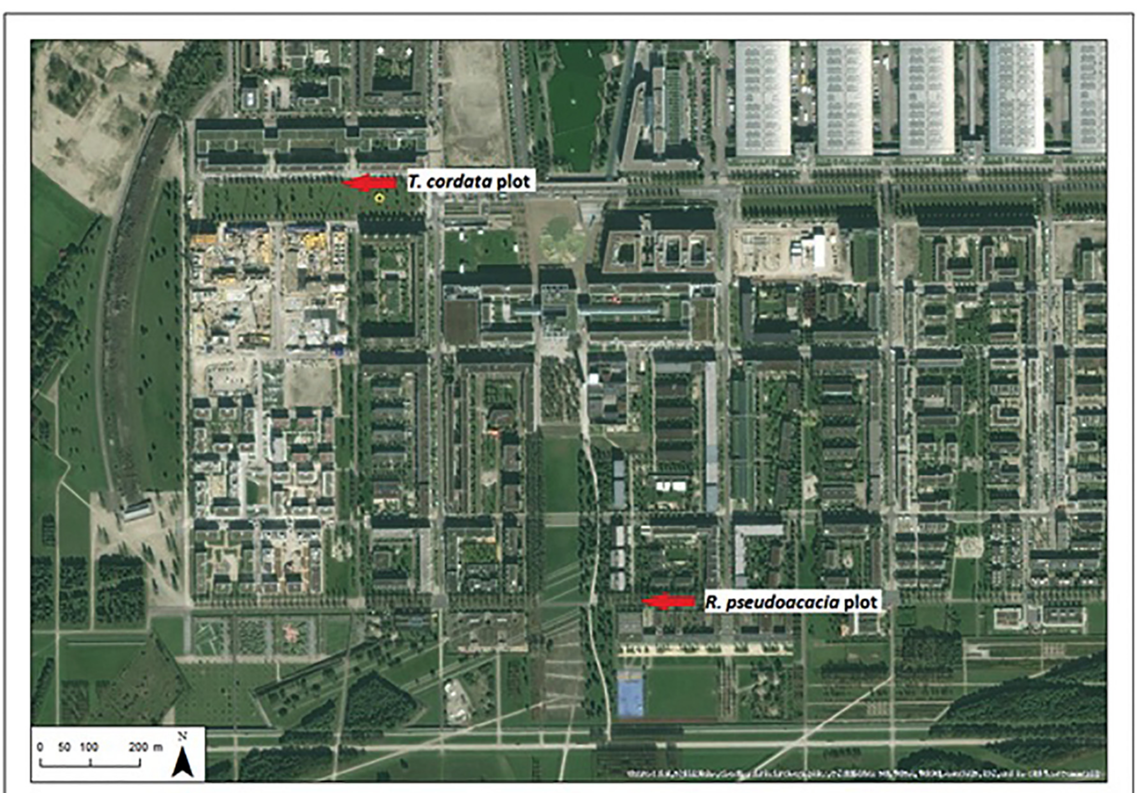

Fig. 1. Plan view of the two plots (Source: Munich city council) with *Tilia cordata* plot on the top and *Robinia pseudoacacia* plot at the bottom.

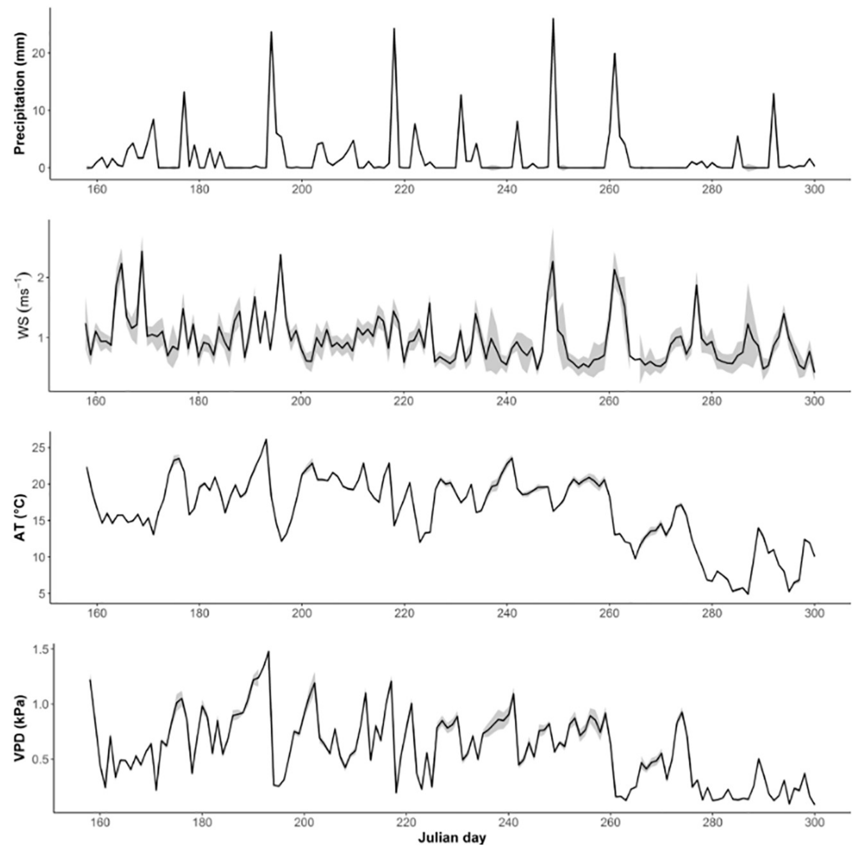

Fig. 2. Average rainfall, wind speed (WS), air temperature (AT) and vapour pressure deficit (VPD) of the two plots between June 6 and October 26, 2016 with SE of mean (gray shaded area).

R. pseudoacacia plot, the meteorological station was mounted on top of a 3.3 m street lamp post 10 m apart from tree rows by a 3.5 m cross arm, 2 m outward from the lamp to avoid influence of lamp and shade of the nearby trees and buildings. All the data were recorded continuously at a 15-min resolution from June 6 to October 13, 2016 on enviLog remote data logger attached to one of our sampled trees.

The diurnal variations of all the measured variables were analyzed for four different types of summer days, which were determined via the maximum average air temperature per day of both the weather stations. According to the definition of the German Meteorological Service, the measurement days were categorized in 'summer days' (AT max ≥ 25 °C < 30 °C) and 'hot days' (AT max ≥ 30°) (DWD, 2017). In addition, a third and fourth category was introduced, the 'mild days' (AT max ≥ 20 °C < 25 °C) and "cool days" (AT max ≤ 20°).

2.4. Vertical air temperature measurements

To better understand air temperature changes vertically due to the upward and downward energy fluxes we installed 9 Newsteo LOP16 temperature data loggers (La Ciotat, France) on three trees and one as a reference measurement point at each site. Three of them were installed at 1.5 m height, three at 3 m and the rest 3 at 4.5 m from the ground close to three tree trunks above grass surface and insulated against direct radiation to measure air temperature in the shade. The reference logger was installed at the same pole where the weather station was mounted but at a height of 2 m from the ground (to reduce the effect of ground surfaces) to measure air temperature at open site (Fig. 3). Air temperature was recorded within the internal memory of the loggers every 5 min and was downloaded using radio signal every week between June 23 and October 13, 2016.

2.5. Below-canopy air, surface temperature and wind speed measurements

Surface temperatures (T_s) of grass and asphalt surfaces and air temperature (T_a) at 1.5 m height were measured between 9 am and 6 pm based on at least 2 and maximum 6 inter-cardinal directions on eight warm and clear days using a laser gun (PTD 1, Bosch GmbH, Germany). The shaded surface temperature was measured close to the tree trunk to ensure that the surface had as much time in the shade as possible and the sunny surface temperature minimum 5 m away from the main canopy shade ensuring the area had never been in shade. The surface cooling temperature (ΔST) was calculated from the difference between sunny and shady surface temperatures. 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 and height where T_a was measured. Then, the sensible heat flux (H) was estimated using the following equation (Eq. (1)) after (Oke, 1989):

$$H = \rho_a C_p (T_s - T_a)/r_a \quad (1)$$

where ρa is the density for damp air, C_p is the specific heat of air at a constant pressure, T_s is the shaded grass surface and T_a is the air temperatures at 1.5 m height and r_a is the aerodynamic resistance. r_a *was estimated* as follows (Eq. (2)):

$$r_a = \ln((z_u - z_d)/z_{0m}) \ \ln((z_h - z_d)/z_{0h})/(k_2 u) \quad (2)$$

where u is the wind speed at height z_u, z_u is the height above the surface where the wind was measured (=1.5 m), z_d is the zero plane displacement (=0.067), z_{0m} is the roughness length governing momentum transfer (=0.01), z_{0h} is the roughness length governing the transfer of

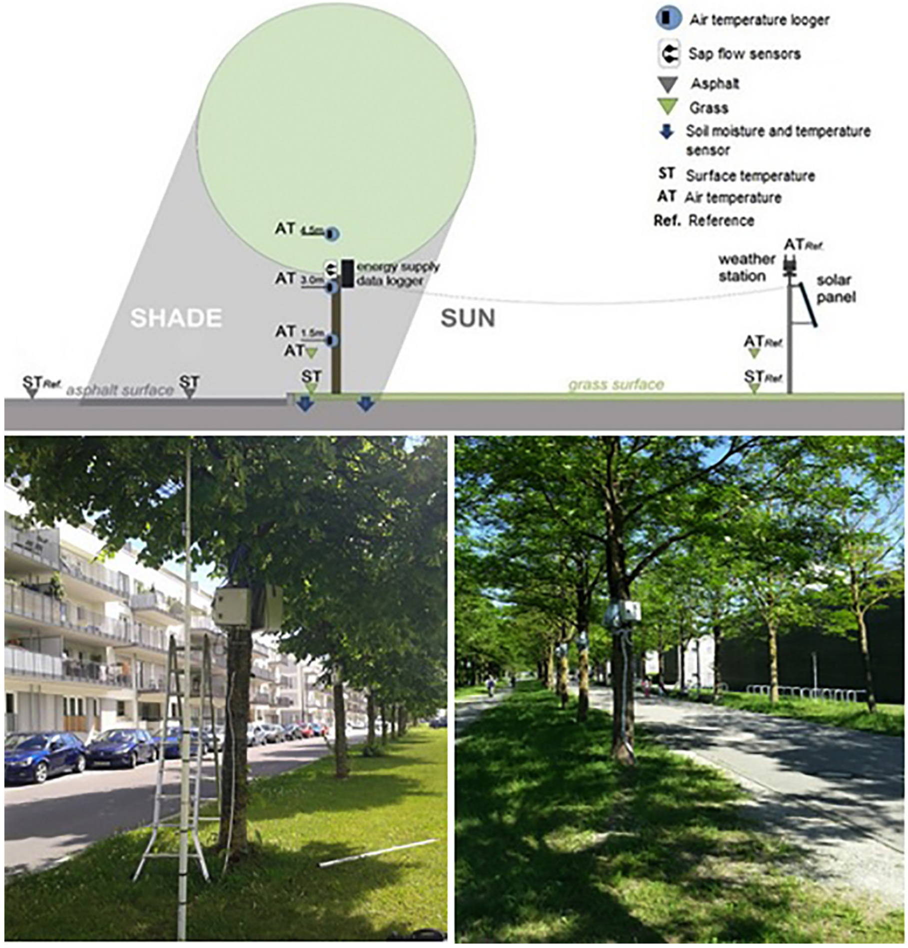

Fig. 3. Experimental set up: (top) Schematic diagram of a tree with measuring devices and measurement points, (bottom) *T. cordata plot* (left) and *R. pseudoacacia* plot (right).

heat and vapour was approximated as 1/10 of the roughness length governing momentum transfer (=0.001) (Allen et al., 1998), z_h is the height above the surface where the air temperature was measured (= 1.5 m) and k is the von Karman's constant (=0.41) (Allen et al., 1998).

2.6. Soil moisture potential and temperature measurements

Soil matric potential and temperature at both plots were measured using Tensiomark (4244/1, range pF0–pF7) (EcoTech, Bonn, Germany) installed within the grass lawns at an angle of 45° through soil profile to the depth of 30 cm. At the *T. cordata* plot two sensors were installed for each tree 4 m apart on both sides of tree trunk and at the *R. pseudoacacia* plot one sensor was installed in between the rows and another in between the trees. Care was taken in selection of spots in installing tensiomarks to minimize the direct solar radiation.

2.7. Sap flow measurements and below-canopy grass evapotranspiration

Tree transpiration was estimated from sap flux density (Js), measured continuously between June 23 and October 13, 2016 using thermal dissipation probes (Ecomatik, Dachau, Germany) introduced by Granier (1987). The sensors were installed on the north side of the trunk at 3–3.5 m height. In the sapwood of each tree a pair of heating probes encapsulated in aluminum tubes was inserted after removing the bark. In case of *T. cordata*, the heating probes were 20-mm long with 2.0 mm in diameter, whereas, for *R. pseudoacacia* they were 10-mm-long with 2.0-mm in diameter. With a heating power of 0.2 W and an electric current of 0.12 A, the upper probe was constantly heated. On the contrary the lower probe was unheated and recorded the reference temperature of the wood. To avoid thermal interference, the two sensor probes were positioned 15 cm apart from each other (Rahman et al., 2017a). A CR800 data logger (Campbell Scientific, U.K.) equipped with Campbell Logger Multiplexer, AM16/32B, recorded the temperature difference (ΔT) of the two sensors every 30 s. From these readings five-minute means were calculated and logged. Based on Granier's empirical calibration equation (see Eq. (3)), the temperature differences were transformed to sap flux densities (Js; ml cm^{-2} min^{-1}) (Granier, 1987).

$$\mathrm{Js} = 0.714\left[\frac{\Delta\mathrm{TM}-\Delta\mathrm{T}}{\Delta\mathrm{T}}\right]^{1.231} \tag{3}$$

where Δ*T*M is the maximum temperature difference when sap flow is assumed to be zero.

Considering the radial variations in the sapwood area of the diffuse porous *T. cordata* (Cermak and Nadezhdina, 1998), two pairs of longer needles were also installed at a xylem depth of 20–40 and 40–60 mm of similar diameters as the previous sensors. Considerable radial variability in Js might also exist for ring porous *R. pseudoacacia* (Jiao et al., 2016); however, due to logistical limitation we could not investigate the pattern. We insulated all probes with reflective foil, to avoid the influence of air temperature and solar radiation. With visually derived sapwood depth from increment cores, the total sap flow was calculated. *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 from 40 mm to inner 60 mm (49%). Considering this variability, the total sap flow (SF) (ml tree^{-1} min^{-1}) for *T. cordata* was estimated by dividing the sapwood area into two sections (the average sap wood depth of ten trees was 71.5 mm) and multiplying Js with sap wood area (SA) following Rahman et al. (2017a) (Eq. (4)). SF of *R. pseudoacacia* was estimated by multiplying Js with sap wood area (SA) (the average sap wood depth of ten trees was 18.2 mm) (Eq. (5)).

$$SF = Js\_20/40 * SA/2 + Js\_40/60 * 0.50 * SA/2 \quad (4)$$

$$SF = Js * SA \quad (5)$$

Below-canopy grass potential evapotranspiration (PET) was estimated following FAO (2009) accounting for light attenuation [assuming a LAI = 6 as 100% shade (Asner et al., 2003), amount of radiation fell under the canopy of *R. pseudoacacia* as 56.5% and under the canopy of *T. cordata of as* 39%] and soil moisture status [assuming soil moisture at field capacity (≤0.05 MPa) for *R. pseudoacacia* and 40% of the field capacity for *T. cordata*] [based on the assumptions of Garg et al., 2015]. The daily PET values were multiplied by the latent heat of vaporization (2.45 kJ g^{-1}) to calculate the latent heat flux (LE) per unit area.

2.8. 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, two-sampled *t*-test and analysis of variance (ANOVA) with Tukey's HSD test were used. In all the cases the means were reported as significant when $p < 0.05$. Simple linear regression analyses were performed to determine the relationship between surface temperature difference (ΔST), leaf area index (LAI) and sap flow (SF). Moreover, linear regression analyses were performed to determine the relationship between air temperature (AT) at different height under the tree shade and each of the meteorological variables and finally, scatter plots based on the sap flow (SF) and surface temperature as dependent variable.

3. Results

3.1. Tree morphological characteristics

R. pseudoacacia trees were younger with significantly smaller LAI and sap wood area but had significantly higher crown projection area, crown radius, crown volume, height and DBH, when compared to *T. cordata* trees (Table 1). The average height of the branch-free trunk was about 3.30 and 3.38 m for *R. pseudoacacia* and *T. cordata* respectively.

3.2. Meteorological and edaphic variables

Global radiation (GR) varied significantly ($F (1, 100) = 80.4$, $p < 0.001$) between four categories of days. Further Tukey's post hoc analysis showed that GR on cool days (mean = 5.59 MJ m^{-2}) were significantly lower than on mild, summer or hot days. Hot days also showed significantly higher radiation (mean = 16.78 MJ m^{-2}) than mild days (mean = 12.55 MJ m^{-2}) and summer days (mean = 14.04 MJ m^{-2}) (Fig. 4).

VPD was significantly different ($F (1, 112) = 243$, $p < 0.001$) between the four categories of days. Tukey's post hoc analysis showed that VPD significantly increased as the days got hotter (Fig. 4). Average

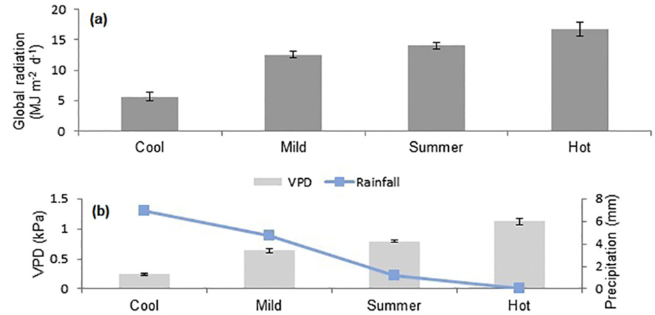

Fig. 4. a) Global radiation and b) average vapour pressure deficit and rainfall during four types of days over the experimental period (±SE of mean days).

rainfall was significantly higher during cool and mild days (7 and 5 mm d^{-1}) compared to only 1 mm d^{-1} during summer days and almost no rainfall event during hot spells (Fig. 4).

A two way ANOVA showed significant differences between species in terms of soil temperature ($F (1, 11{,}149) = 1153$, $p < 0.001$) and between the four different summer spells ($F (1, 11{,}149) = 7435$, $p < 0.001$) both during day and night time ($F (1, 7781) = 2354$, $p < 0.001$ and $F (1, 7781) = 5381$, $p < 0.001$ respectively). Interestingly, there was significant interaction between species and categories of day during the day time ($F (1, 11{,}149) = 788$, $p < 0.001$) which signifies that the soil temperature varies differently depending on the radiation interception for the two species. Generally soil temperature increased as the days became hotter both during day and night. However, there were no significant differences regarding the soil temperature between summer and hot spells under the canopies of *T. cordata*; between mild and summer spells under the canopies of *R. pseudoacacia* trees during day time. At night, during mild, summer and hot nights there were also no significant differences in terms of soil temperature under the canopies of both *T. cordata* and *R. pseudoacacia* trees (Fig. 5). The soil moisture potential under the shade of *T. cordata* trees was significantly more negative than under *R. pseudoacacia* trees both during day and night [$F (1, 12{,}968) = 3902$, $p < 0.001$) and $F (1, 7782) = 2234$, $p < 0.001$) respectively]. Post hoc tests confirmed that the soil moisture potential for both species were significantly higher during summer days and nights compared to cool, mild and hot days and night (Fig. 5).

Wind speed at the *T. cordata* site was significantly higher on all four different summer spells both during day [$F (1, 13{,}013) = 427$, $p < 0.001$] and night [$F (1, 7799) = 198$, $p < 0.001$]. Post hoc analysis resulted in a significant reduction of the wind speed as the days gradually got warmer both during day and night time. However, the difference between summer and hot spells was not significant during day time.

3.3. Tree transpiration on different types of days

A one way ANOVA showed that average sap flow rates of *T. cordata* were significantly higher compared to the rates of *R. pseudoacacia* trees ($F (1, 13{,}264) = 4645$, $p < 0.001$) (Fig. 6). Moreover, there was a significant difference between different categories of days for both the species [($F (1, 6773) = 1538$, $p < 0.001$) and ($F (1, 6489) = 1113$, $p < 0.001$) respectively]. Post hoc test confirmed that sapflow rates were significantly higher for both the species as the days got warmer.

Table 1
Average morphological characteristics of trees of two investigated species (CPA = crown projection area; CR = crown radius; CV = crown volume; LAI = leaf area index; SWA = sap wood area).

Species	Age (years ± SE)	CPA (m^2 ± SE)	CR (m ± SE)	CV (m^3 ± SE)	DBH (cm ± SE)	Height (m ± SE)	LAI (±SE)	SWA (cm^2 ± SE)
T. cordata	36 ± 0.4	35 ± 1.03	3.32 ± 0.05	150 ± 6	23.7 ± 1.04	10.6 ± 0.20	3.64 ± 0.41	364 ± 8.3
R. pseudoacacia	32 ± 1.2	52 ± 3.78	4.03 ± 0.15	223 ± 17	27.4 ± 1.18	12 ± 0.36	2.61 ± 0.21	155 ± 5.5

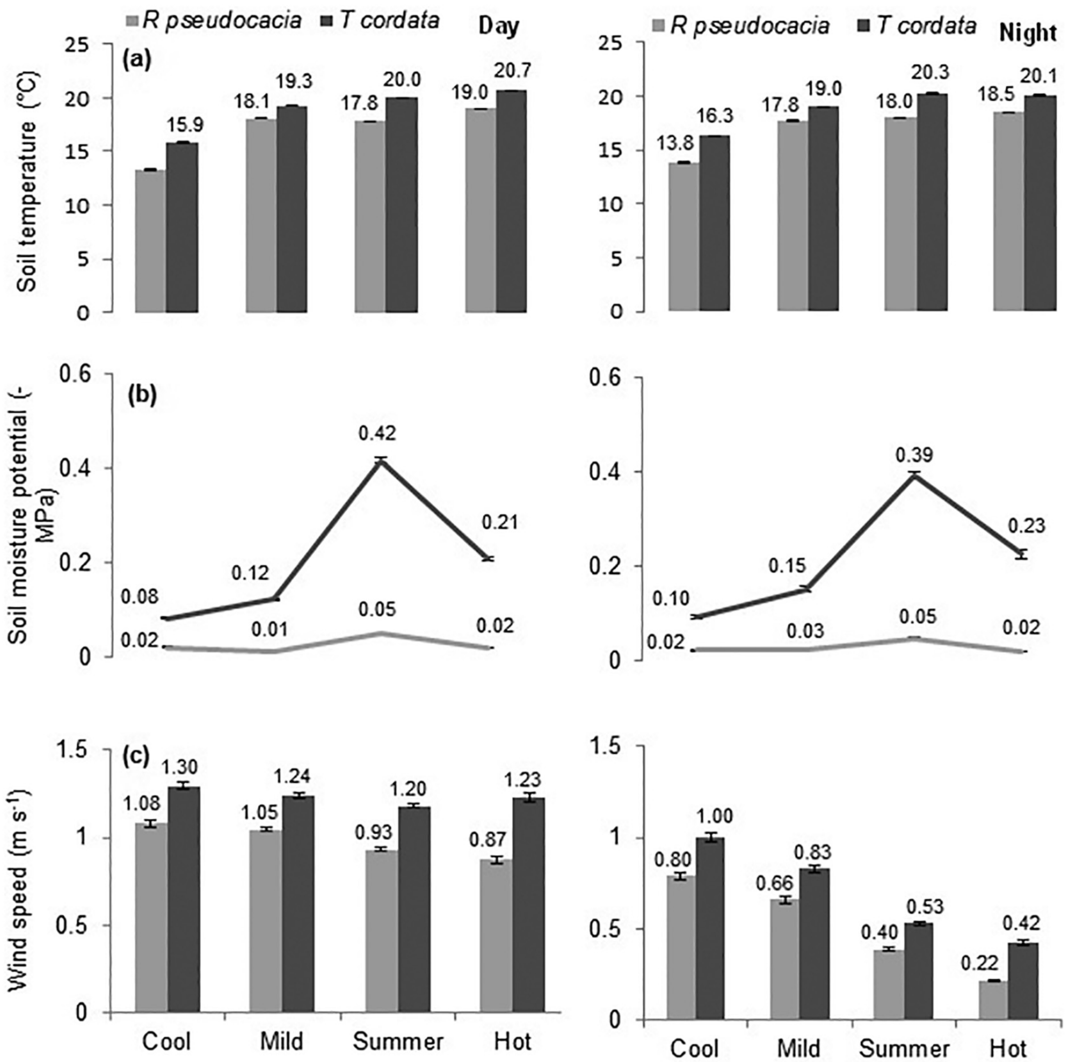

Fig. 5. Average a) soil temperature and b) soil moisture potential c) wind speed at the two sites with *R. pseudoacacia* and *T. cordata* trees during four types of summer spells over the experimental period (±SE of mean days).

3.4. Relationship between leaf area index and surface temperature difference and tree sap flow

While analyzing two species with significantly different LAI and sap flow a significant relationship between sapflow and LAI could be detected ($F(1, 17) = 5.35$, $p < 0.05$, $r^2 = 0.24$) (Fig. 7). LAI had a significant influence in terms of surface temperature reduction potential when the surface was asphalt ($F(1, 17) = 8.31$, $p < 0.05$) with $r^2 = 0.33$. However, no significant relationship was found when the surface under the tree canopy was grass covered (Fig. 7). These relationships can be explained in a way that a doubling of the LAI from 3 to 6 would mean an increase in sap flow from 22 to 39 ml tree^{-1} d^{-1}; an increase of surface temperature reduction (ΔST) from 18 °C to 31 °C when it is asphalt and an increase from 8 °C to only 11 °C when it is grass surfaces.

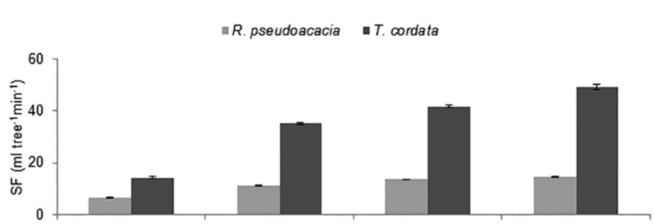

Fig. 6. Sapflow rate of *T. cordata* and *R. pseudoacacia* during four types of days over the summer, 2016.

3.5. Below-canopy air temperature compared to the open areas

Irrespective of heights of measurements, air temperature was significantly lower under the tree canopies of both the species compared to

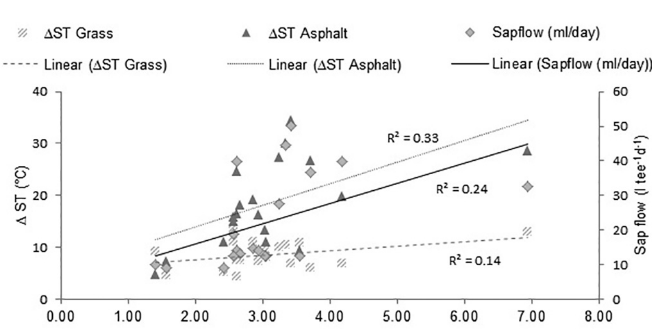

Fig. 7. Relationship between leaf area index (LAI) and surface temperature difference (ΔST), and between LAI and sap flow for the period June to August 2016.

the reference points. Regarding the magnitude and pattern it was different between the species. A one way ANOVA showed a significant difference between reference and air temperature at 4.5, 3 and 1.5 m height (F (3, 43,408) = 99.25, p < 0.000 for *T. cordata* and F (3, 42,548) = 82.85, p < 0.000 for *R. pseudoacacia*). Further post hoc analysis showed that air temperature at 4.5 m was cooler than at 3 m and 1.5 m under the canopies of *T. cordata* but not under *R. pseudoacacia.* There were no significant differences between 3 m and 1.5 for both the species.

On an average the highest air temperature reduction compared to the outside was at 4.5 m; however, the magnitude varies both along the types of days and species. The highest difference was during cool days (1.8 °C for *T. cordata* and 1.5 °C for *R. pseudoacacia*) and gradually declined to 1.3 °C for *T. cordata* but only to 0.5 °C for *R. pseudoacacia* during hot days (Fig. 8). For both species the cooling effect gradually decreased at the height of 3 m. Compared to the reference points the air temperature under the canopies of *T. cordata* was around 1.5 °C cooler during the cool days to around 1 °C during hot days. Under the canopies of *R. pseudoacacia* air temperature was cooler around 1 °C during the cool days to around 0.5 °C during hot days. However, at the bottom (1.5 m) air temperature was significantly cooler under the canopies of *R. pseudoacacia* than *T. cordata* during mild and summer days.

3.6. Vertical air temperature differences under the canopies of T. cordata and R. pseudoacacia

With three times higher transpiration rates, within canopy air temperatures of *T. cordata* trees were significantly lower than the reference point (mean = 1.1 °C) compared to the *R. pseudoacacia* (mean = 0.78 °C) (t = 4.2, df = 467, p < 0.001) (Fig. 9a) during those eight warm and clear days of measurements. However, the cooling effect declined significantly along the increase in vertical distance towards the ground. At 1.5 m air temperature under the canopies of *R. pseudoacacia* was significantly lower than at the reference point (mean = 1.5 °C) compared to *T. cordata* (mean = 0.9 °C) (t = −6.03, df = 501, p < 0.001) (Fig. 9b).

With 30% higher LAI, shaded grass surfaces under *T. cordata* did not show higher surface (grass) cooling potential compared to *R. pseudoacacia* (Fig. 9c). Fig. 9d shows that grass latent heat flux under the canopies of *R. pseudoacacia* was significantly higher compared to *T. cordata*. This was probably linked with the lower heat gain from the sensible heat flux towards the ground under the canopies of *R. pseudoacacia* compared to *T. cordata* (Fig. 9d) since the energy from the storage release is channeled into LE due to higher water availability.

3.7. Relationship between tree transpiration and air temperature under the shade

All meteorological variables showed significant relationships with air temperature at different heights under the shade of both species. Most significantly, the total amount of sap flow (SF) was strongly correlated with the within canopy air temperature at 4.5 m (R^2 = 0.58) (Fig. 10a). Including WS, AT, VPD, GR and SF in the correlation did not improve the line of best fit. The collinearity of the meteorological variables did not help to improve the R^2 values in terms of air temperature along the vertical gradient of the tree shade. Collinearity indicated that they are the major driver of the tree sapflow rate as shown in earlier research such as Rahman et al. (2017a). Further down from the canopy towards the ground the transpiration effect got diffused as shown by the reduction of the correlation strength (R^2 = 0.46 and 0.37 at 3 and 1.5 m from the ground) (Fig. 10b and c). Air temperature at 1.5 m height showed significant correlation (R^2 = 0.63) (Fig. 10d) with the grass surface temperature which is again an artefact of other micro-climatic and edaphic variables.

4. Discussion

The current study demonstrates the importance of quantifying below-canopy microclimate depending on different functional aspects and weather conditions. Moreover, it is suggested that the knowledge of eco-physiological characteristics of tree species in urban settings can strengthen management and mitigation plans for future warmer cities. Our study showed that along with radiative warming even though tree transpiration increases, less water using species such as *R. pseudoacacia* planted on grass surfaces can provide higher air cooling at 1.5 m height from the ground. Grass surfaces modulated by lower crown density allow latent heat flux from the ground to reduce the air temperature near the ground at human thermal comfort level. Increase in ambient air temperature is usually associated with higher radiation, lower wind speed and humidity. *T. cordata* is an anisohydric species and transpired almost three times more than *R. pseudoacacia* trees and exploited water in the soil much faster. The drier soil underneath the

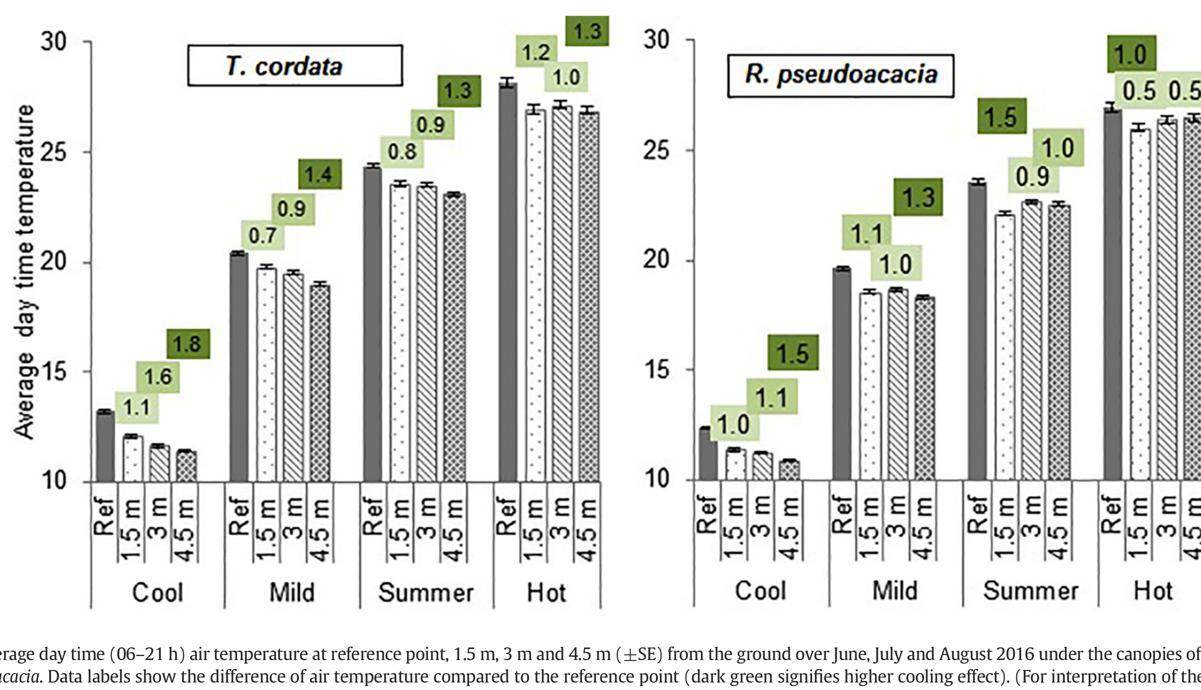

Fig. 8. Average day time (06–21 h) air temperature at reference point, 1.5 m, 3 m and 4.5 m (±SE) from the ground over June, July and August 2016 under the canopies of *T. cordata* and *R. pseudoacacia.* Data labels show the difference of air temperature compared to the reference point (dark green signifies higher cooling effect). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

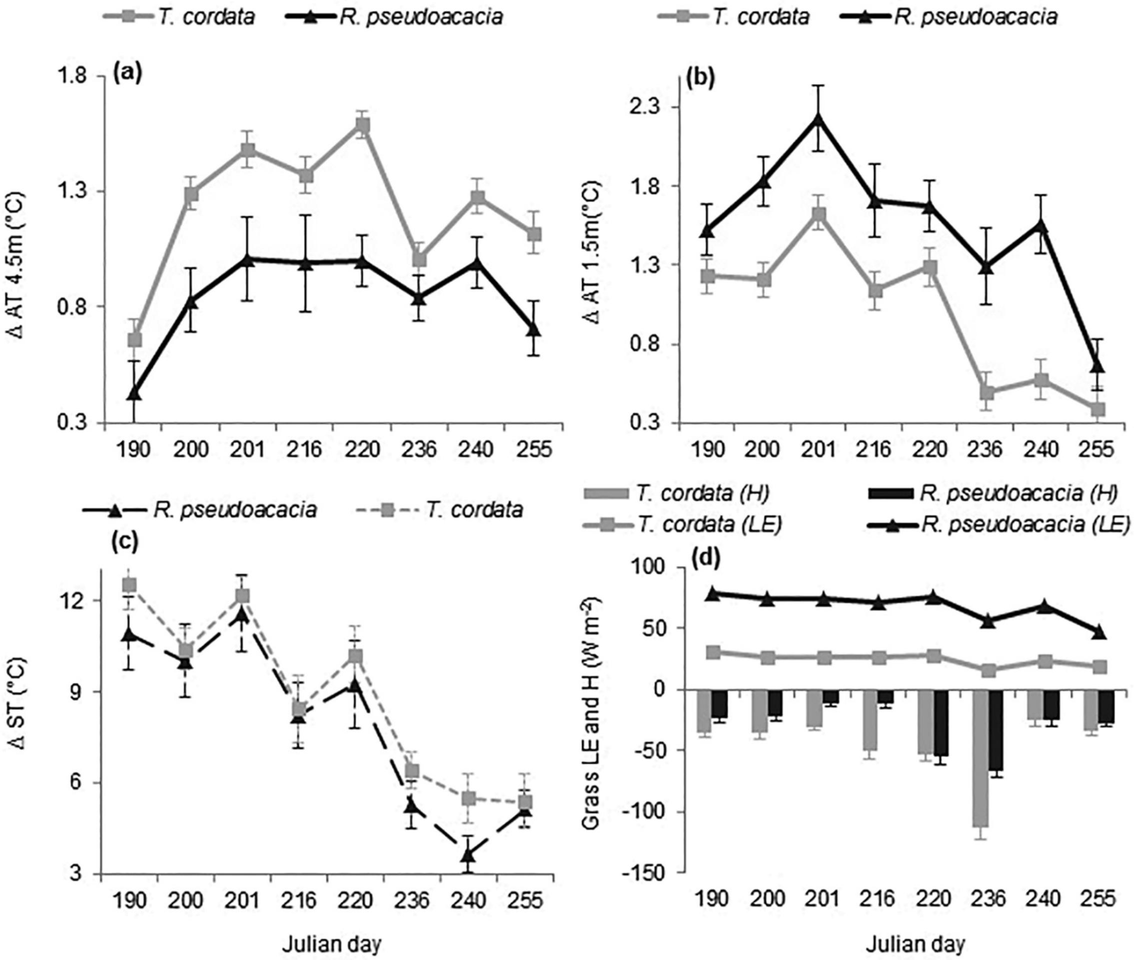

Fig. 9. Average a) air temperature difference between reference point and within crown (4.5 m) b) air temperature difference between reference point and shaded (1.5 m) c) surface temperature difference between sunny and shaded grass surface d) heat fluxes (both sensible (H) and latent heat (LE) of shaded grass surfaces (±SE) over the eight clear and warm days during hot and summer days (10–18 h).

T. cordata trees increased the sensible heat flux. Simultaneously the heat flux is mixed with the air which warms the air temperature from the ground to the canopy gradually and withdraws the air cooling from the top. Significantly lower soil moisture potential and soil temperature under the canopies of *R. pseudoacacia* can explain the lower air temperature at 1.5 m height despite lower tree canopy transpiration and comparatively higher canopy temperature. Research such as Gill et al. (2013) has shown that evapotranspiration from grass surfaces falls linearly with soil water potential below the field capacity (0.05 MPa). In our study soil moisture under the shade of *R. pseudoacacia* never dropped below field capacity whereas under the shade of *T. cordata* it reached below 0.4 MPa during summer days (Fig. 5). This might, however, not be the case if the trees were planted on built surfaces. Tree species with comparatively lower LAI such as *R. pseudoacacia* would have allowed much more radiation through their canopy (Rahman et al., unpublished results) and significantly higher sensible heat exchange to warm up the air from the ground to the canopy with no strong transpiration cooling to diffuse the heat flux. Consequently, during hot days even on grass surfaces deep shading effects from species such as *T. cordata* showed higher air cooling at heights of 1.5 m, 3 m or 4.5 m above the ground.

4.1. Weather differentiation in terms of meteorological and edaphic variables

By classifying the actual weather conditions during the observation period, the cooling effects of trees under different weather conditions can be established (Wang et al., 2015) since they can affect the cooling potential of trees (Wang et al., 2014). Daily solar radiation input was the overarching factor of weather differentiation, with hot days having around 17 MJ m^{-2}, summer and mild days between 12 and 14 MJ m^{-2}, while cool days with below 6 MJ m^{-2} signified cloudy days. Therefore, the total amount of rainfall was significantly higher during mild and cool days than during summer or hot days (Fig. 4). Moreover, wind speed gradually declined as the days got warmer. VPD was higher during the summer or on hot days which were more prominent during night time than during day time contributing to the higher night time UHI (Oke, 1989). Reduced wind velocity can induce optimum air cooling effect from the tree canopies during day time (Dimoudi and Nikolopoulou, 2003) whereas in the absence of tree transpiration at night it can increase the heat convection (Hedquist and Brazel, 2014; Shahidan et al., 2012). Several authors showed that the moderating effect of tree canopies on air temperature is most pronounced on warm, sunny days (Holst et al., 2004; Renaud and Rebetez, 2009; von Arx et al., 2012).

The general weather situation showed significant influence on edaphic variables under the tree canopy in a complex way that is putatively depended on soil water status (von Arx et al., 2012). In our study canopy density and soil moisture was partly coupled; *T. cordata* with higher LAI (>3.5) transpired more water than *R. pseudoacacia* (LAI ~ 2.5) and depleted soil moisture faster (Fig. 5) as shown by previous studies (Aussenac, 2000; Scharenbroch and Bockheim, 2007; von Arx et al., 2013). Consequently the soil temperature was significantly higher under the canopies of *T. cordata* than of *R. pseudoacacia*. Moreover, the soil temperature followed the pattern of warming up both during day and night as the days get warmer and drier. However, with increasing

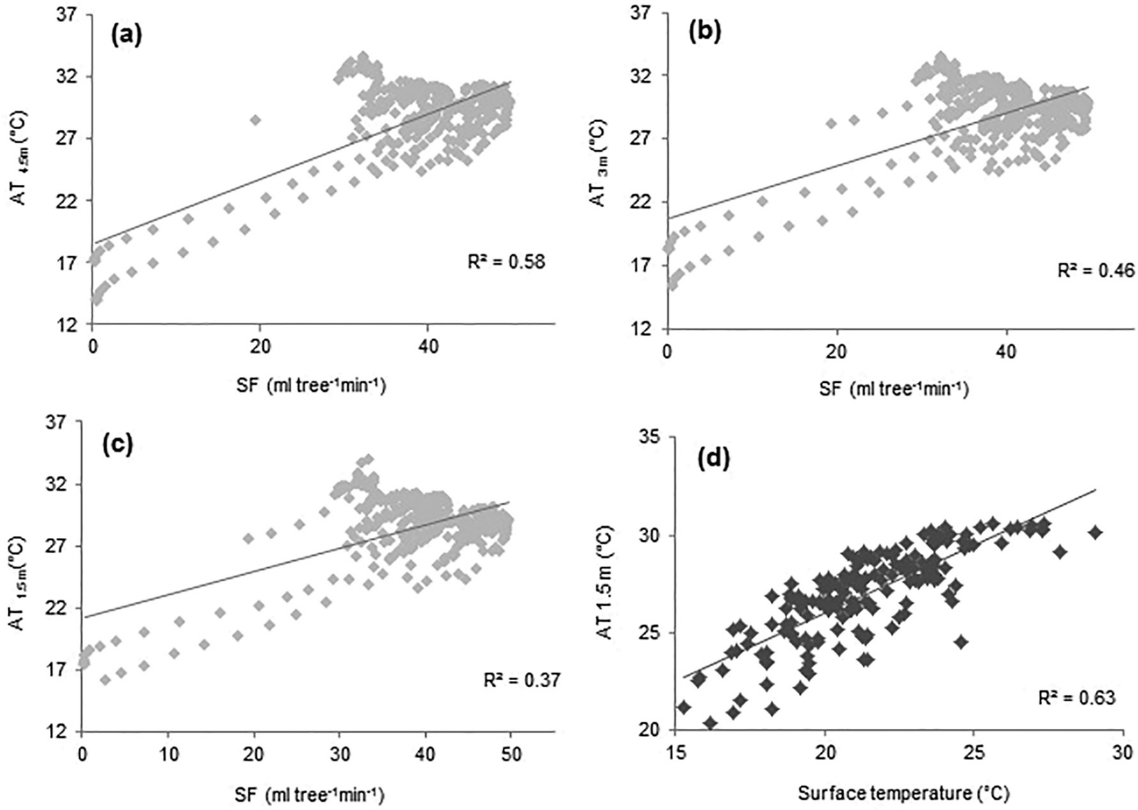

Fig. 10. Scatter plot of measured air temperature at a) 4.5 m b) 3 m c) 1.5 m from the ground and sap flow; d) air temperature at 1.5 m and grass surface temperature. Each point represents the average value from and under the shade of *T. cordata* and *R. pseudoacacia* trees when surface temperature was measured during eight warm and sunny days.

LAI and decreasing soil moisture content, we also observed some unforeseen interactions between these weather events and soil moisture potential under the canopies of both the species. Following short drought spells the soil moisture potential was not higher during hot days but rather decreased compared to summer days (Fig. 5). One reason might be the low number of sampling days (only 10 hot days compared to 42 summer, 33 mild and 19 cool days). Another explanation can be related to the complex water dynamics of functionally different trees species grown in urban conditions with significantly higher input of solar radiations.

4.2. Interactive influence of LAI and tree transpiration and surface temperature

A significant relationship between LAI, tree transpiration and surface cooling potential (Fig. 7) is in line with previous studies (Armson et al., 2013; Rahman et al., 2015). Although *R. pseudoacacia* were younger than *T. cordata* trees (Table 1), still they showed higher DBH, height and canopy spread. However, *R. pseudoacacia* trees had lower LAI and most significantly lower sap wood area which is in line with species characteristics. Higher water using efficiencies of *R. pseudoacacia* (Jiao et al., 2016) might contribute to the better growth rate at the expense of stomatal regulation and consequently reduced transpiration. A notable difference in terms of surface cooling potential was found for asphalt and grass surfaces (Fig. 7). For instance, Armson et al. (2012) showed tree shade reduced surface temperatures by up to 19 °C, compared to a 24 °C reduction in maximum surface temperature related to grass cover. An additional impact of soil on surface temperature resulting from evaporative cooling or latent heat flux is eminent (von Arx et al., 2013). That is why Baldocchi et al. (2000) argued that tree canopies with reduced canopy density require accurate representations of mass and energy exchange at the soil surface, where substantial energy exchange occurs.

Both the species showed significantly lower surface temperature compared to air temperature to make the sensible heat flux negative (i.e. the flux is directed towards the surface) which is a common pattern of advective environments (from nearby asphalt street, buildings etc.) (Spronken-Smith et al., 2000). A significantly higher heat sources under the canopies of *T. cordata* (>110 W m^{-2}) compared to (>65 W m^{-2}) (Fig. 9d) might have supplemented radiation to enforce higher grass evapotranspiration. However, significantly lower soil moisture content (Fig. 5) might have reduced the LE exchange under the canopies of *T. cordata*. Grass surfaces in fact can heat up even more than built surfaces during day time because of the lower thermal mass (Gill et al., 2013). In the case of shaded canopy grass surface under *R. pseudoacacia* with higher soil moisture content and radiative input the sensible heat would become a source of heat and the latent heat an even larger sink.

T. cordata with anisohydric characteristics exploited much more soil moisture and, therefore, showed different vertical air temperature acclimation response than *R. pseudoacacia* trees. The acclimation response also varied depending on the hot, summer, mild or cool spells.

4.3. Vertical air temperature acclimation

The present study showed that during daytime, air temperature was always lower under the canopy than in the open area regardless of soil moisture, tree transpiration rate and LAI. With increasing transpiration of both species their average moderating effect on air temperatures within the canopy compared to the open areas dropped from 1.8 °C to 1.3 °C for *T. cordata* and from 1.5 °C to only 0.5 °C for *R. pseudoacacia* as the days got warmer. Regarding the species differences, the reason may be twofold; with higher canopy density, *T. cordata* might have higher latent heat flux (Rahman et al., 2015) along with less radiative warming inside the canopies as the days got warmer. At the same time, due to the its anisohydric nature, *T. cordata* keeps its stomata open even during short drought spells in contrast to the isohydric species *R. pseudoacacia* (Moser et al., 2016). In relation to different weather conditions direct comparisons of the values inside the canopy compared to the open areas in urban areas were not possible due to the scarcity of other empirical studies. However, previous studies such as Wang et al. (2015) while measuring the air temperature under shaded and unshaded areas showed that on relatively clear and hot days, the air temperature moderation by the trees was about two times higher than on cloudy and cool days. Firstly, in urban conditions with intense radiation during summer and hot days and with increased VPD, tree transpiration may not be able to (counter) balance the increase of sensible heat as during comparatively cloudy and less VPD conditions. Secondly, the differences between the air cooling effects from tree canopies during hot, summer, mild or cool days may be easier to discuss if we further look at the below-canopy vertical air temperature stratifications.

On average vertical reduction of the air cooling moderation was around 1 °C from canopy to the near-ground in case of *T. cordata* but *R. pseudoacacia* showed a reverse pattern with an even higher cooling effect at 1.5 m than at 4.5 m height. The magnitude – at least for *T. cordata* trees – is close to the reported value of 1 °C temperature for every 4 m vertical gradient inside a *Picea abies* L. forest (Zweifel et al., 2002). However, the vertical air temperature decline starting from tree canopy towards the ground diffused significantly especially in a complex urban system and at pedestrian level (1.5 m from the ground) making the below-canopy surfaces rather the determinant of cooling potential of trees. At night a higher positive peak of air temperature differences between 4.5 and 1.5 m (data not shown) was found which is not only because of the reduction in sap flow and less transmission of latent heat accompanied by reduced wind speed but also due to the absorbance of long wave radiation from the ground. It is evident that on cool or mild days transpirational cooling is more prominent from 4.5 m down to the 1.5 m height. However, during summer or hot days when air cooling is more in demand the major driver of the air cooling is not the transpirational cooling from the tree canopy. Rather it is the soil moisture status of the surface under the tree canopy (to contribute to the transpirational cooling from the grass surface) or the deep shading (with high LAI) which contribute to the air cooling effect.

Our results suggest that there is a threshold of latent heat flux induced air cooling either from tree canopy or below depending on the weather conditions. With extreme summer hot days especially at the advent of climate change tree canopy might not be able to negate the sensible heat from the below-canopy at least in high VPD conditions such as in urban areas. Therefore, shading from dense canopies and incorporation of grass surfaces might help to mitigate the UHI better than random planting of street trees alone. However, it is difficult to include many of the parameters of thermodynamic experiments such as continuous measurements of sensible heat flux components of the energy balance and below-canopy meteorological parameters such as wind speed in empirical studies in urban settings. Further studies with interdisciplinary interest including more species and urban settings will strengthen our conclusion.

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