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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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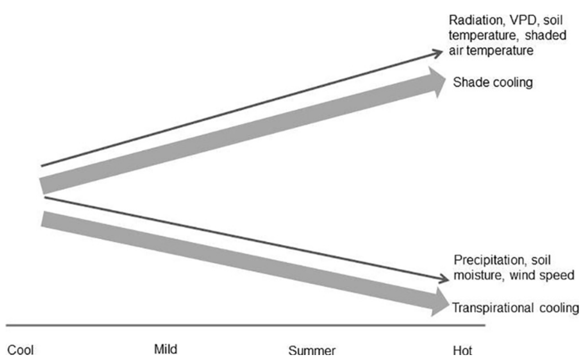
HIGHLIGHTS

- 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