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Temporal variations in microclimate cooling induced by urban trees in Mainz, Germany

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ABSTRACT

Global warming is likely to increase the frequency and magnitude of heat waves. As the urban geometry and material amplifies warming, city dwellers will face an intensification of heat-induced health problems and mortality. Although increased vegetation cover is frequently used in urban planning to mitigate excessive heat, temporal variations, as well as the influence of synoptic weather conditions and surrounding urban geometry on the vegetation cooling effect, are still unclear. In this study, we monitored the transpiration-induced cooling from trees over two summers in five urban settings characterized by varying levels of greenness and urban geometry in the city of Mainz (Germany). Differences in air temperature and humidity patterns were compared with estimates of tree transpiration derived from high-resolution stem size and sap flow measurements. Results from the five urban sites indicate significant cooling due to transpiration, but with large variability depending on time of day and weather conditions. The cooling effect is strongest during periods of high transpiration demand, and in the stable nocturnal boundary layer when air mixing is limited. The strongest transpiration cooling was found in an enclosed courtyard structure. These findings reveal that a few trees can substantially mitigate urban excess heat, but that the urban geometry, time of the day, and prevailing weather conditions considerably modulate this effect.

1. Introduction

Heat-related health problems and mortality are expected to rise, as global warming is projected to cause more frequent and stronger heat waves (IPCC, 2014). City dwellers in particular are at risk because of the urban heat island (UHI) effect, i.e. the intensified warming caused by altered land surface properties. These modifications include an increased thermal admittance of construction materials, the restricted radiative and advective cooling due to the urban geometry, and the lowered evapotranspiration-induced cooling due to sealed surfaces and limited vegetation coverage (e.g. Arnfield, 2003; Oke, 1987). The UHI effect is strongest at night, causing a lack of adequate nocturnal relief from heat stress for the urban inhabitants which has been linked to, for example, increased urban mortality during heat waves (Clarke, 1972; Conti et al., 2005). Appropriate urban planning is thus required to mitigate the warming effects in cities. One key approach used is to increase the abundance of vegetation (Bowler et al., 2011; Norton et al., 2015; Taha, 1997) which lowers temperatures and improves the human thermal comfort, particularly during heat waves (Harlan et al., 2006).

The cooling effect of vegetation includes shading and evapotranspiration (e.g. Bowler et al., 2011). Shading from urban trees reduces heating of surfaces and depends on the three dimensional shape and the degree of vegetation permeability to solar radiation (Konarska et al., 2014). While shading can considerably increase human comfort, its effect on air temperature (TA) appears limited (Oliveira et al., 2011). More efficient for TA is the cooling by transpiration, whereby the water that transpires during the process of photosynthesis transfers sensible heat into latent (Grimmond and Oke, 1991; Taha, 1997). Slightly lower air temperatures have been found over grassy urban surfaces than above concrete (e.g. Mueller and Day, 2005). Lower air temperatures above green roofs has also been found but effect is small and very variable (e.g. Wong et al., 2003) A review by Qiu et al. (2013) showed that transpiration, especially from taller vegetation in parks can reduce urban temperatures between 0.5 and 4 °C, with time and magnitude for maximum influence depending on park type, size, and climate. Hamada and Ohta (2010) also noted an important transpiration induced cooling from urban parks in summer, but stated that further studies are needed to clarify the physiological effects influencing the transpiration of urban vegetation. Street

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trees were found to have very strong transpiration compared to urban trees in other settings in a study by Pataki et al. (2011), but the transpiration-induced cooling from isolated trees in streets and other urban settings remain largely unknown. The rate of transpiration generally increases with atmospheric evaporative demand (often expressed as the vapour pressure deficit, VPD, Eamus et al., 2013) and depends on water availability. The influence of VPD also depend on the wood anatomy where diffuse porous taxa showed a near linear increase in transpiration with VPD (Bush et al., 2008). By using high-resolution measurements of stem size changes, King et al. (2013) showed that both meteorological conditions and soil water availability impact the diurnal cycle of tree-water relations. However, these relations are only valid as long as enough water is available in the soils (Brodribb and Holbrook, 2004; Gao et al., 2002; Gindaba et al., 2004; Ma et al., 2004; Zweifel et al., 2001).

Although numerous studies of urban climate have shown that cooler places within the city are closely connected to an increased vegetation cover (Alavipanah et al., 2015; Fan et al., 2015; Harlan et al., 2006; Lindén, 2011; Middel et al., 2012; Norton et al., 2015), the diurnal variations as well as influence of changing weather conditions on the transpiration-induced cooling are still unclear. For example, cooling was strongest in the afternoon in irrigated parks and parks in humid climates (Jonsson, 2004; Potchter et al., 2006; Spronken-Smith and Oke, 1998). However, a review by (Bowler et al., 2011) showed that cooling from urban green spaces is in general slightly stronger at nighttime and nocturnal effects also dominated in non-irrigated parks in e.g. Ouagadougou, Sacramento, and Vancouver (Lindén, 2011; Spronken-Smith and Oke, 1998).

Here we evaluate the effectiveness of transpiration-induced cooling from trees by comparing urban climate among sites with contrasting greenness and urban geometry. In particular, we aim to (1) quantify differences in seasonal and diurnal patterns of temperature and humidity among urban sites, (2) link these differences to tree transpiration as derived from continuous measurements of sap flow (SF) and stem size variations, and (3) examine the influence of atmospheric evaporative demand and extreme drought stress on the transpiration-induced cooling processes.

2. Methods

2.1. Study sites

The study has been performed in the city of Mainz in Germany (50.0°N, 8.3°E, elevation 100 m.a.s.l, Fig. 1). Mainz is an inland city with approximately 200 000 inhabitants, located in a landscape of gently rolling hills on the western side of the Rhine River. The climate is temperate and humid with an annual average TA of 10.7 °C and precipitation of 620 mm. The summers are warm and humid (June to August: 19.2 °C and 175 mm, from 1981 to 2010, www.dwd.de). The city architecture has a compact midrise structure (Stewart and Oke, 2012) with smaller parks, grassy areas, and streets with scattered trees. Soil conditions for the urban sites are varying and heavily disturbed since most structures were built on top of the rubble from the second world war.

Five sites varying in vegetation cover and building structure were selected: one suburban park of sparsely built structure according to the local climate zone (LCZ) categorization (Stewart and Oke, 2012) as well as four urban sites with different levels of greenness (with and without trees) and architectural geometry (LCZ 2 and 5) were selected (Table 1). The sub-urban forested park (hereafter Park) was chosen as a site representative of high level of greenness. The two vegetated urban sites with some mature trees but with different geometry (a closed Courtyard and an open Garden) represent the urban structure of Mainz. These were both coupled with adjacent open and sparsely vegetated urban elements (a Street and a Square, Fig. 1). Information about area average sky view factor for each site was not possible to obtain in this study, and the sites are instead described in view of vegetation cover within 30 m of the center of the area, with surrounding building structure and activity described in text (Table 1). Land cover within a similar distance was found to be most important for microclimate differences by Konarska et al. (2016a,b). For the Park, Courtyard and Garden sites, *Platanus* × *acerifolia* was chosen for measurement of stem radius change and Sap Flow where available, with addition of two *Tilia platyphyllos* in the Park, and one *Acer platanoides* in the Garden (where only two *Platanus* × *acerifolia* were available). The trees in Mainz start foliating in the beginning of April and appeared fully foliated in the beginning of June when measurements of sap flow and stem radius were initiated. The canopies of *Platanus* × *acerifolia* were very dense with large leaves (around 300 cm^2) in the urban sites, especially in the courtyard where pruning had taken place in 2011, and less dense in the park where trees were allowed to grow freely. Canopies of *Tilia platyphyllos* were also dense, while *Acer platanoides* was less dense. 2013 and 2014 started out similar, but in 2013 the leaves started going partly brown in the beginning of August, likely due to the warmer and drier conditions this summer. Leaf area density was not measured in this study but has previously been found to vary between 0.3 and 0.5 for unpruned *Platanus* × *acerifolia* (Hipps et al., 2014). *Platanus* × *acerifolia* has in a previous study shown a near linear increase in transpiration with VPD (Bush et al., 2008).

2.2. Monitored parameters

Spatial and temporal variations in climate and tree transpiration were assessed at a temporal resolution of 30 min during different periods between June 2013 and February 2015 (Table 1). The measurements were performed over the full period at the Park site, but the coupled urban elements were monitored during only one summer, i.e. the Courtyard-Street in 2013 and the Garden-Square in 2014. However, the climate sensors have been kept running during the whole period in the Courtyard-Street sites and for one year in the Garden—Square sites to support comparisons of seasonal patterns.

The climate was monitored at all sites by measuring **TA** and relative humidity (HR) using HOBO U23-001 Pro v2 data loggers placed in RS1 solar radiation shields (Onset, Bourne, MA, USA), at a height of approximately 3 m to avoid vandalism. This type of sensor and shielding was found to be the most reliable in comparison to other types of shielding (Da Cunha, 2015). One sensor per site was used. As commonly found in urban areas, standard guidelines for placement of meteorological instruments was not possible to follow due to the complexity of the selected study sites, but recommendations in the WMO guidelines for urban climate studies (Oke, 2008) were carefully followed when selecting sensor placement to minimize any potential bias. Due to urban activity and traffic, posts for sensor installation could not be installed. Existing posts were of different size and material, and placed at varying distance from the walls and the HOBO-sensors were instead placed on tree stems or branches on the north side of the tree, where a free airflow around the sensor could be ensured (no leaves or dense branch structure nearby). This placement reduces the risk of temperature bias from nearby heated walls and other anthropogenic materials, and as the microclimate influence of trees is the focus of the study, any potential influence caused by differences in canopy geometry of the sensor trees was determined to be small and seen as part of the aim.

Prior to installation, a comparison among the sensors located in a well ventilated rooftop for 22 days (with TA ranging from −4 °C to 18 °C and HR from 30 to 100%) showed agreement with an average difference in TA $< \pm 0.08$ K ($<2\%$ exceeding ± 0.2 K), and in HR$<0.2\%$ ($<2\%$ exceeding 1%). These measurements were then used to derive

Table 1
Description of the sites, and of the trees and climate parameters monitored. Vegetation cover within a radius of 50 m around the site center. LCZ according to Stewart and Oke, 2012.

Site	Area description Local Climate Zone (LCZ)	Vegetation cover	Parameters measured	Tree species	Number of trees	Approximate tree height (m)	Tree stem diameter (cm)	Period used in analysis (dd.mm.yyyy)
Park	Grass covered ground with scattered bushes and trees. Paved walking paths. No roads. Open borders. (LCZ 9)	89%	Stem radius change	*Tilia platyphyllos*	2	17–18	56–57	07.06.2013–31.08.2014[a]
			Stem radius change	*Platanus* × *acerifolia*	2	23–24	60–66	07.06.2013–31.08.2014[a]
			Stem radius change	*Platanus* × *acerifolia*	2	20–22	58–62	01.06.2014–31.08.2014
			TA/Humidity	–	–	–	–	07.06.2013–12.05.2015
Courtyard	Five large trees in court yard, fully surrounded by buildings 3–4 stories. Ground covered by gravel or stone tile. (LCZ 2)	25%	Stem radius change	*Platanus* × *acerifolia*	4	12- 17	40–68	07.06.2013–31.08.2013
			Sap flow density	*Platanus* × *acerifolia*	1	12	40	07.06.2013–31.08.2013
			TA/Humidity	–	–	–	–	07.06.2013–12.05.2015[b]
Garden	Some bushes and six large trees. Partly open borders. Sparsely trafficked roads nearby. Sloping permeable ground, partly paved. (LCZ 2/5)	42%	Stem radius change	*Platanus* × *acerifolia*	2	19–22	71–72	01.06.2014–31.08.2014
			Stem radius change	*Acer platanoides*	1	15	52	01.06.2014–31.08.2014
			Sap flow density	*Platanus* × *acerifolia*	1	22	72	01.06.2014–31.08.2014[b]
			TA/Humidity	–	–	–	–	01.06.2014–12.05.2015
Street	Small trees along wide street canyon with heavy traffic. buildings 3–5 stories on both sides. Paved ground. (LCZ 2)	21%	TA/Humidity	–	–	–	–	07.06.2013–12.05.2015[b]
Square	Open, heavily trafficked crossing with few scattered trees. Partially surrounded by buildings 3–6 stories. Paved gently sloping ground. (LCZ 2)	4%	TA/Humidity	–	–	–	–	01.06.2014–12.05.2015

[a] Data analysed only for the two summer periods; June, July and August 2013 and 2014.

[b] Shorter data gap due to technical problems.

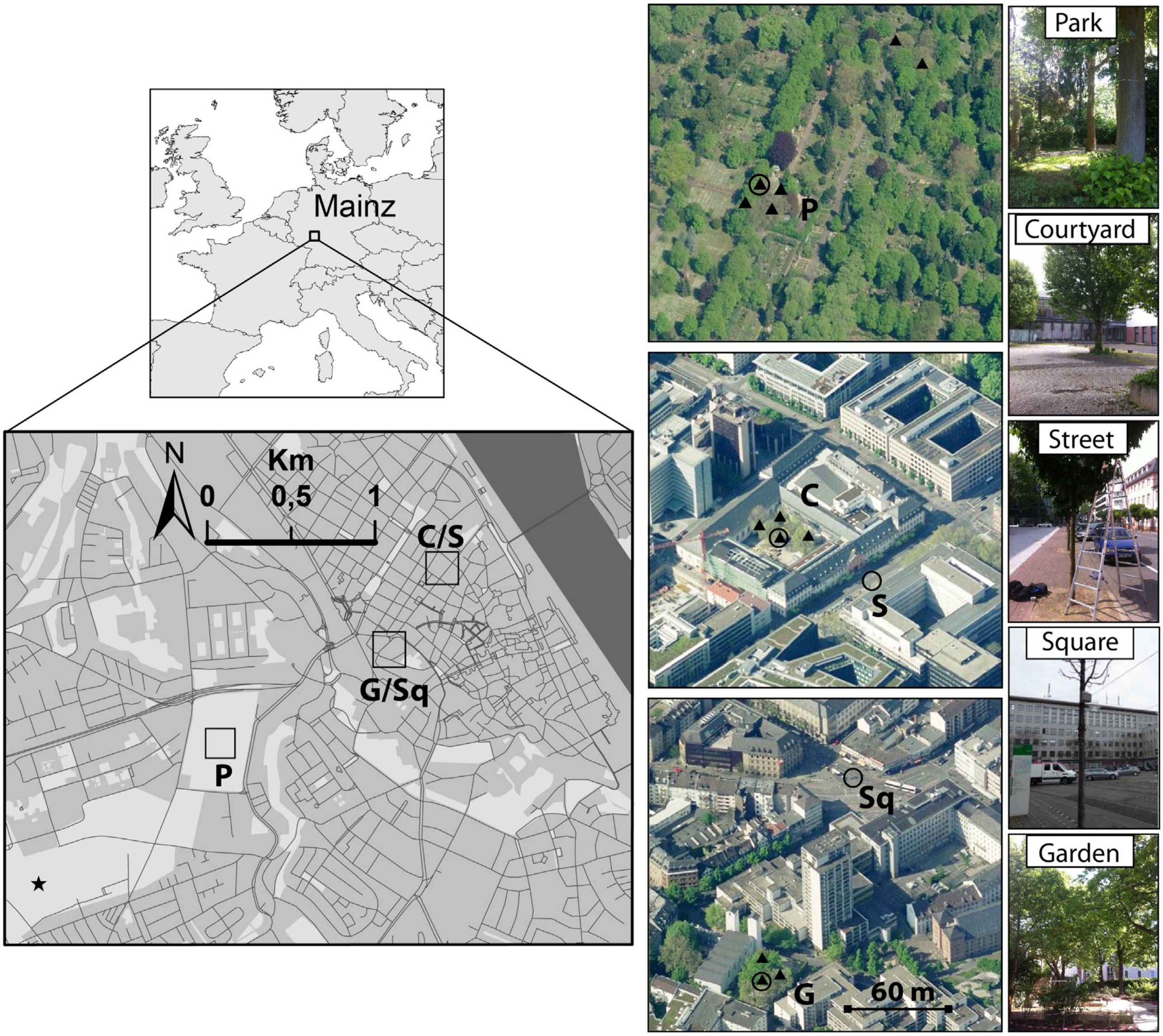

Fig. 1. The city Mainz and locations of monitored sites in the Park (P), Courtyard (C), Street (S), Garden (G), and Square (Sq). Air temperature and humidity measurements marked with circles, monitored trees marked with triangles, and synoptic met station location marked with star. Birds-eye images are from Bing maps (www.bing.com/maps).

specific humidity (**HS**) and vapour pressure deficit (**VPD**), using Eqs. (1)-(3) (e.g. Monteith and Unsworth, 2007):

$$SVP = 610.7 \times 10^{\left(\frac{7.5TA}{237.3+TA}\right)} \tag{1}$$

$$HS = \left(2.16679 \times \frac{HR * SVP}{100\,(TA + 273.3)}\right)\rho^{-1} \tag{2}$$

$$VPD = \left(1 - \frac{HR}{100}\right) \times SVP \tag{3}$$

where SVP = saturation vapour pressure (kPa), TA = air temperature (°C), HS = Specific Humidity (g/kg), HR = relative Humidity (%), ρ = density of air (kg/m^3), and VPD = Vapor pressure deficit (kPa).

The site data were then complemented with local measurements of precipitation, wind and solar radiation from a nearby (<3 km from all sites) meteorological station at the institute of Atmospheric Physics of the Johannes-Gutenberg University (Fig. 1). Accumulated precipitation over the past 20 days (**PRC20**) was calculated to estimate drought conditions as suggested by Konarska et al. (2016a,b).

Tree transpiration was indirectly quantified by monitoring stem size variation and sap flux on mature trees in the Courtyard and Garden sites, and stem size variation in the Park site (Table 1). These two parameters are good estimators for high-resolution water use and physiological stress. In particular, maximum daily stem shrinkage (**MDS**) has proved to be a good estimator for daily stem water balance (King et al., 2013). Sap flux density (**SF**) is used to quantify the amount of sap flowing up the stem, which is directly associated to the amount of transpired water (Granier, 1987; Granier et al., 1996). Measurements of stem size variability were obtained using point dendrometers (**DL-R**, Ecomatik, Munich, Germany) installed on 6 trees in the Park (2 *Tilia platyphyllus* and 4 *Platanus x acerofolia*), 4 trees in the Courtyard (4 *Platanus x acerofolia*), and 3 trees in the Garden (2 *Platanus x acerofolia* and 1 *Acer platanoides*). The **DL-R** dendrometer is installed on the tree stem using screws extending in to the heartwood to secure a highly sensitive sensor monitoring the daily fluctuations in stem radius. Sap flux density data were obtained using a Granier thermal dissipation probe (**SF-L**, Ecomatik, Munich, Germany), which make use of temperature difference between four thermocouple needles (one heated needle

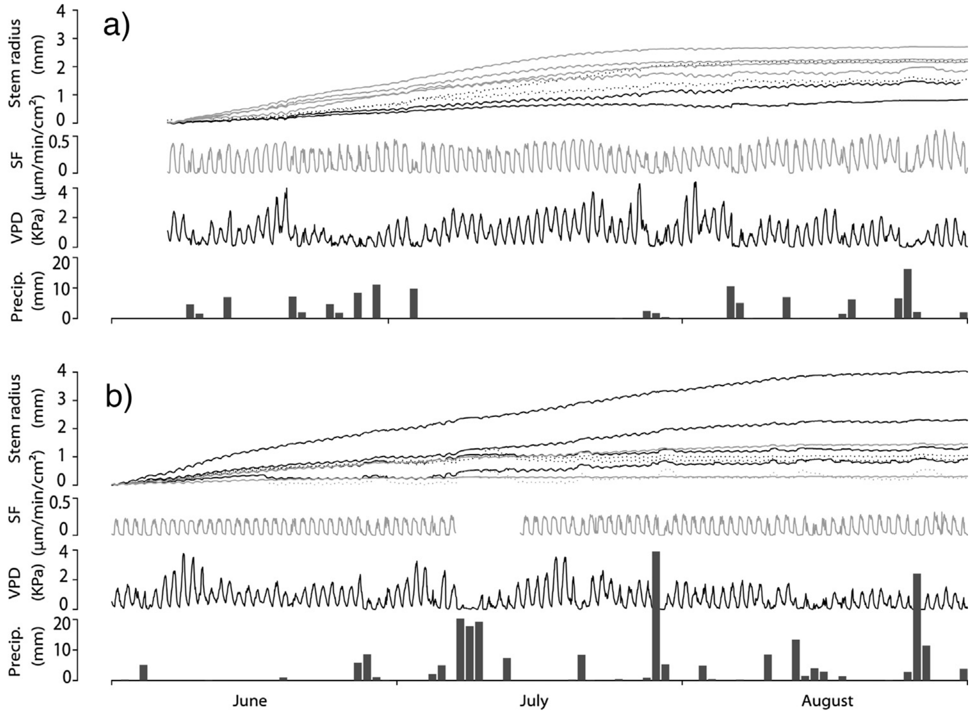

Fig. 2. Absolute stem radius change, sap flux density (SF), vapour pressure deficit (VPD) and precipitation from June to October during (a) the growing seasons 2013 and (**b**) 2014. Grey lines indicates measurements from the Courtyard (2013) and the Garden (2014), black lines are relative to the trees and sensors in the Park. Solid lines show Platanus × acerifolia, dotted lines Tilia platyphyllus, Park; and Acer Platanoides, Garden. VPD is based on measurements of temperature and humidity in the Park, and precipitation data are from the meteo-station of the University of Mainz located less than 3 km away from the sites.

and three needles above to measure sap ambient temperature, see (Granier, 1987) inserted three cm in the sapwood. Sensors were installed on the north side of the tree stems on one *Platanus x Acerofolia* in each of the Courtyard and Garden sites. The sapwood depth of *Platanus x Acerofolia* exceeds this depth (Pataki et al., 2011), and the sap flow through the stem varies on different sides depending on canopy sun exposure. Our data is therefore only used to examine the diurnal variations in sap flow and not as a measure of total amount of transpired water.

2.3. Site comparisons

To examine differences in climate patterns among sites, and associate these with potential cooling effects of the trees, measurements were compared among site-couples of differing degrees of greenness and location within the city. The couplings include comparison between one densely vegetated park and two urban sites; Park–Courtyard (**P–C**), and Park–Garden (**P–G**). To examine the microclimate differences connected to transpiration, the two urban sites were also compared with nearby sites of different character (less vegetation, different building structure) in the site couples Courtyard–Street (**C–S**), and Garden–Square (**G–Sq**). Comparisons were performed considering different seasons (summer, autumn, winter, and spring), time of the day (10:00–16:00 for daytime, and 19:00–04:00 for nighttime, times apply to all day/night analyses), and demand for atmospheric evaporation. The latter has been derived from three classes of daily average VPD (measured in the Park) defined as low (VPD_L, first 20th percentile, VPD <0.54 kPa), moderate (VPD_M, 0.54 <VPD <1.315 kPa) and high (VPD_H, 80th percentile, VPD >1.315 kPa). VPD_H was further divided into 2 classes based on soil water availability considering PRC20 data (VPD_{Hwet} >6 mm and VPD_{Hdry} <6 mm).

As a target for between-site climatic differences we considered TA and HS, while daily MDS and SF were used as estimates of tree transpiration. Stem radius and sap flux density data were standardized for each tree related to the 95th percentile of their individual diurnal curves before an average curve for each site was calculated to obtain relative terms for comparison.

3. Results

3.1. Stem size variation and sap flux density responses to weather conditions

In comparison to the 1981–2010 average, the 2013 summer (from June to August) was 1 °C warmer (average 20.2 °C) and 73 mm drier (precipitation sum 102 mm) than the average, while the successive season was colder (18.9 °C), wetter (222 mm), and with relatively well distributed precipitation over the summer (Fig. 2). The parameters monitored on the tree stem were indicating that tree water balance was mainly responding to the daily weather conditions. The trees show considerable differences in cumulative stem size and a relative large range of MDS, likely a result of the difference in size and canopy density as well as soil conditions. However, the responses to changing VPD and water availability are coherent among the trees of each site. In particular, all trees showed abrupt increases in stem size in relation to precipitation events, and slightly decreasing stem size and sap flux density when there was a higher demand for transpiration under reduced condition of water availability, as for example at the beginning of August 2013.

Influence of evaporative demand and drought on SF and MDS was examined in Fig. 3. MDS increase with evaporative demand, while SF initially increase with VPD, then level out. The influence of precipitation on SF is less clear, but in the drier year 2013, the highest SF levels are measured subsequent to moderate precipitation events, and lower SF levels are recorded in very dry or very wet conditions. MDS measured in 2013 indicates that the strongest stem shrinkage occurs in dry conditions, while no connection between MDS and PRC20 was detected in 2014. The highest SF was found in the later part of the season. This pattern was found in both summers

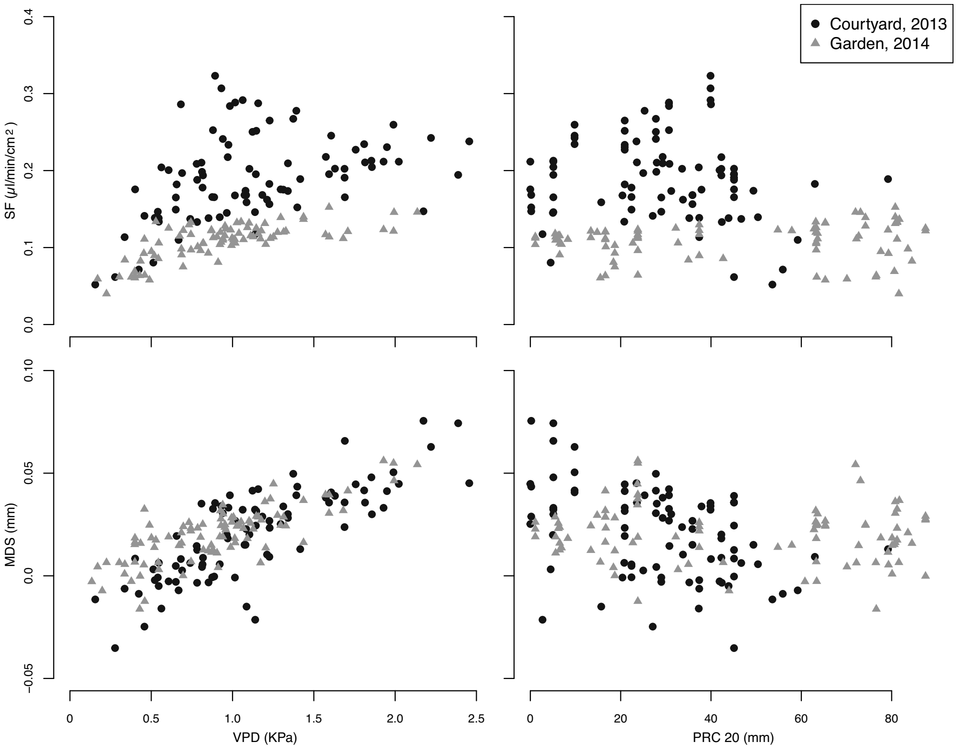

Fig. 3. Scatter plots showing the relationship between average daily sap flux density (SF, top) and maximum daily stem shrinkage (MDS, bottom) versus vapour pressure deficit (VPD, left) and precipitation (right) accumulated over the past 20 days (PRC20, right). Black circles are the measurements of SF/MDS/VPD from the Courtyard in 2013, grey triangles are from the Garden in 2014. Precipitation is measured at the meteorological station.

but stronger in 2013. The influence of VPD and PRC on MDS was very similar when examined for each individual tree (not shown in graph) confirming that averages for each site are representative.

The influence of evaporative demand and drought on the diurnal pattern of stem radius change and SF is shown in Fig. 4. Stem radius reaches a maximum around sunrise, then starts shrinking when evaporative demand causes the transpiration rate to exceed refilling rate. This continues until late afternoon, when the evaporative demand decrease and the tree stem start to expand again. The amplitude of this diurnal pattern increased with evaporative demand. Response to drought caused an increase in daily amplitude in the Park but decrease in the Courtyard. SF increases rapidly after sunrise at around 05:00, then stays high throughout the day and slowly decreases in the late afternoon. In these average curves, the level of SF equals approximately half of the daily maximum at sunset. SF equals a quarter of the daily maximum at midnight and reaches a minimum before sunrise. The average nocturnal SF in 2013/2014 were 28/17% of the daytime levels. The night to day ratio is highest for the category VPD_{Hdry} (33%) indicating that nocturnal transpiration is increased during dry conditions. A reduction of stem size is also visible during the daytime when transpiration exceeds refilling from the roots. This negative stem water balance continues until the transpiration loss is reduced in the late afternoon and stem radius increases again. The amplitude of the diurnal pattern in both stem radius change and SF increase with increasing VPD. The only exception was the SF during dry conditions (VPD_{Hdry}) when the daily maximum was reduced.

3.2. *Spatial climate differences*

Comparisons between the sites revealed reduced temperatures in the more vegetated areas (Fig. 5). Differences were generally largest at night when the Park was 1.0/0.8 K colder than the vegetated urban areas (Courtyard/Garden, median, full period), which in turn were colder than their nearby and sparsely vegetated counterparts (Street and Square) by 0.2 and 0.5 K, respectively. These differences varied among seasons, with largest magnitudes in spring and summer when a maximum nocturnal urban heat island of 3.9/3.2 K was measured between the Park and the Street/Square sites.

A comparison of the urban sites showed some deviations from the general pattern. For example, warmer daytime temperatures were found in the closed-in Courtyard compared to the open and less vegetated adjacent Street in spring ($\Delta TA_{C\text{-}S}$, difference of 0.3 K) mainly included days before trees were foliated. The differences diminished and eventually turned opposite during the summer and autumn when trees were fully foliated. Deviating patterns were also found between the vegetated Garden and the adjacent open Square partially surrounded by buildings ($\Delta TA_{G\text{-}Sq}$), where daytime differences always exceeded nighttime differences.

While humidity was generally higher in the more vegetated sites, both the Courtyard and the Garden sites showed similar, and in autumn even higher, nighttime humidity levels compared to the Park. The courtyard was more humid compared to the Street at night in the foliated summer and autumn period, but slightly less humid in winter and spring, and the Garden was surprisingly less humid than the Square at all times and seasons, except for summer daytimes.

3.3. *Linking climate differences with transpiration*

We found stronger cooling of the more vegetated sites during periods of increased transpiration. However, this relationship varied between daytime and nighttime and with respect to the surrounding architectural structures (Fig. 6). The association between ΔTA and ΔHS generally revealed colder conditions to be associated with higher humidity, although the relationship varied among sites. The strongest relationship was found in the differences between

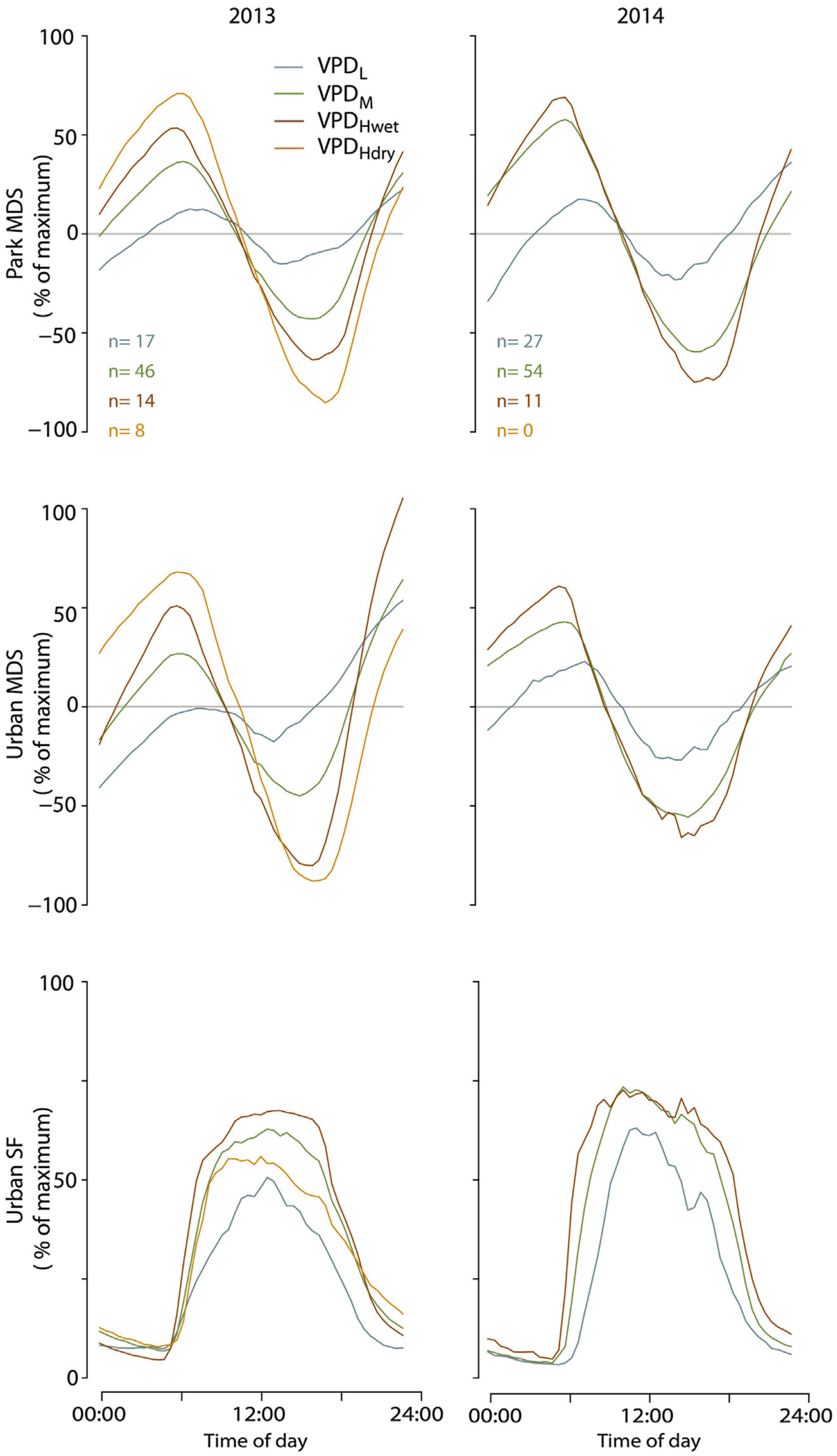

Fig. 4. Standardized maximum daily stem shrinkage (MDS) and sap flux density (SF) during the summer season in the Park (2013 left, and 2014 right), Courtyard (2013, left), and Garden (2014 right) sites. Lines show the mean values for the VPD categorized days including VPD$_L$ <0.68 kPa (20th percentile), VPD$_M$ (0.68–1.4 kPa), and VPD$_H$ >1.4 kPa (80th percentile). VPD days are further separated in to low (VPD$_{Hwet,}$ PRC20 > 6 mm) and high (VPD$_{Hdry,}$ PRC20 < 6 mm) drought stress. N indicates the number of days included in each category. All times shown are CET, i.e. sunrise occurs at approximately 05:00, sunset at 20:00, and solar noon at 12:30.

the enclosed Courtyard and adjacent Street, where a more humid Courtyard was also colder than the street. For this site comparison, variation in ΔHS could explain 73% of the variation in ΔTA. However, a weaker opposite relationship was also found, indicating that when the Courtyard during day-time was more humid than the Street, it was also warmer. This was also found for the Park – Courtyard comparison at night. For the remaining site comparisons, significant relationships were always negative. Significant negative relationships were found between ΔTA, and both MDS and SF, demonstrating that increased transpiration generally results in an increased cooling of the more vegetated site. This effect is stronger in the night than in the day. The colour coding based on day of year show slightly stronger SF in the later part of the summer (lighter dots), especially in the nighttime data. This pattern does not affect the relationship between SF and cooling.

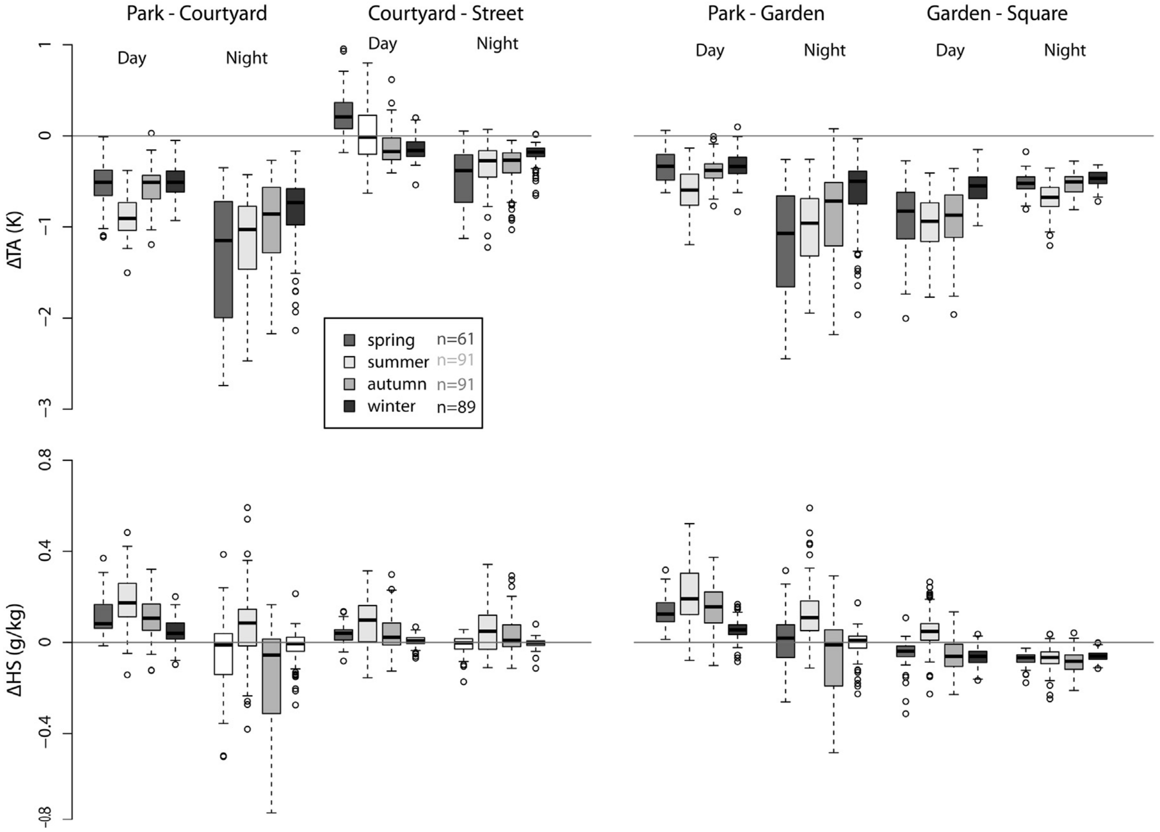

Fig. 5. Boxplots of seasonal differences in air temperature (TA, top) and specific humidity (HS, bottom) between urban sites in Mainz. Boxes show 25–75 percentile, lines indicate the median, whiskers extend to approximately 5–95 percentile, and circles show outliers. Unfilled boxes are shown when sites are not significantly different. Results for spring, summer, autumn and winter are shown.

The categorization of summer days with respect to evaporative demand—an important driver for tree transpiration – emphasizes the link between sites ΔTA and VPD (Fig. 7). The ΔTA between the Park and the urban sites generally increased with increasing VPD reaching a maximum at night. The only exception was the courtyard that is not significantly different during daytime from the less vegetated street. The drier category (VPD_{Hdry}) indicated an increased cooling in the courtyard relative to both Park and Street, compared to the wet days (VPD_{Hwet}). The general weather conditions during VPD_{Hdry} were on average slightly less windy (1.8 m/s vs 2.0 m/s for VPD_{Hwet}) and had higher average VPD (2.2 kPa vs 1.9 kPa for VPD_{Hwet}). The vegetated sites were also more humid, with the exception for nocturnal Garden—Square comparison, where the vegetated garden was less humid compared to the very sparsely vegetated square.

4. Discussion

In this study we show that transpiration-induced cooling from urban trees is important for the development of microclimatic differences in a mid-size (200.000 inhabitant) city like Mainz. The cooling effects show seasonal and diurnal variations, as well as sensitivity to the surrounding urban geometry and weather conditions. In the following sections we will discuss the magnitude and temporal variability of this cooling effect, and address the significance of urban geometry, weather, and water availability.

4.1. Link between microclimate cooling and transpiration

An urban heat island effect was found in the center of Mainz throughout the two examined years, with magnitudes similar to that reported from other cities in Germany, e.g. Krefeld (Blankenstein and Kuttler, 2004) and Trier (Junk et al., 2003). Although the urban heat island effect was largest in spring, the urban vegetated sites were cooler and more humid relative to the adjacent sparsely vegetated urban sites during the summer. A stronger cooling was also linked to a higher ambient humidity of the vegetated sites relative to their coupled sparsely vegetated sites, indicating evapotranspiration cooling as the cause for the temperature differences, as also found by Hamada and Ohta (2010). Furthermore, our findings indicate that the influence of tree transpiration, as deduced from SF and MDS, is also significantly linked to a stronger cooling. As direct measurements of transpiration, for example through measurements of leaf gas exchange, are labour intense and expensive, estimation of transpiration from SF has been used in several studies (e.g. Daley and Phillips 2006; Dawson et al., 2007; Granier et al., 1996) and the significant relationships to temperature differences found here indicate that measurements of SF can also be used for assessing the transpiration-induced cooling.

There are, however, several variations in this pattern that need to be addressed. Transpiration induced cooling is most pronounced during the nighttime when transpiration is generally considered to be insignificant as stomata are thought to be close (Berninger et al., 1996; Cowan and Farquhar, 1977; Hari et al., 1986). However, a stronger nocturnal cooling in vegetated sites has also been found in other studies (Bowler et al., 2011; Holmer et al., 2013; Lindén, 2011; Qiu et al., 2013; Spronken-Smith and Oke, 1998). In addition, it has been demonstrated that the stomata of many tree species remain partially open at night (Alvarado-Barrientos et al., 2015; Barbour et al., 2005; Bucci et al., 2004; Cavender-Bares and Bazzaz, 2000; Dawson et al., 2007; Grulke et al., 2004; Matyssek et al., 1995; Scholz et al., 2007; Snyder et al., 2003). Nocturnal SF

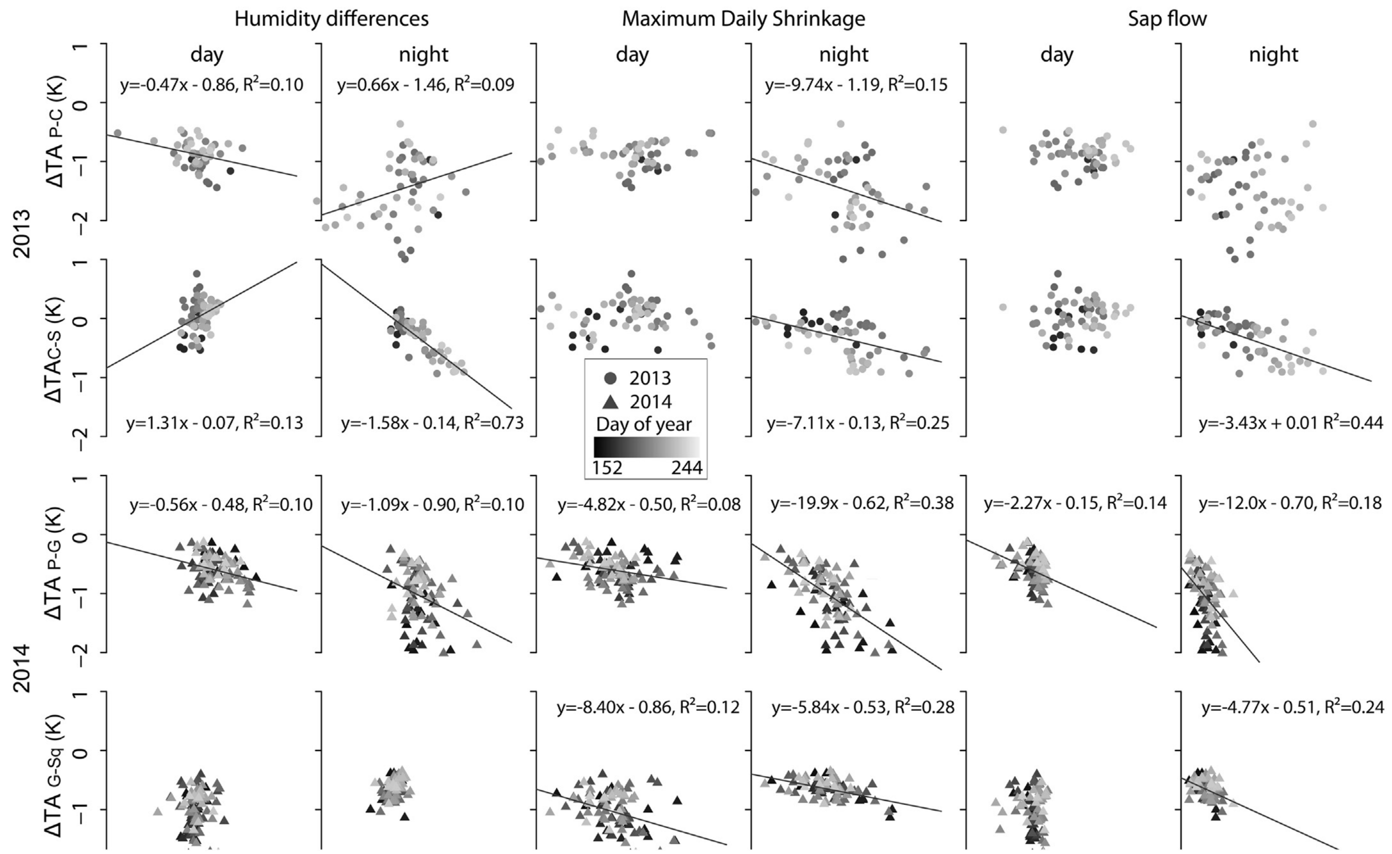

Fig. 6. Correlation matrix showing comparisons between daily site temperature differences (ΔTA) with concurring site humidity differences (ΔHS), maximum daily shrinkage (MDS) and concurring sap flux density (SF) during day and night (different columns). The MDS and SF values used here represent the urban sites (Courtyard/Garden). Data from the two summers are measured in the courtyard (2013, circles) and Garden (2014, triangles) and grey scale colour coded based on day of year. Regression lines of the corresponding linear models are included if $p < 0.01$.

and transpiration has been documented in other studies (Daley and Phillips, 2006; Dawson et al., 2007; Fisher et al., 2007; Konarska et al., 2016a,b; Marks and Lechowicz, 2007; Moore et al., 2008; Rosado et al., 2012; Scholz et al., 2007; Snyder et al., 2003; Zeppel et al., 2010) and quantified to reach 5–40% of the daytime levels (Caird et al., 2007). In single sites, night transpirations of up to 50% of day maximum has been reported (Matyssek et al., 1995). Our results are thus in line with evidence summarized in the review by Zeppel et al. (2014) indicating that wide range of ecosystems may lose substantial amounts of water at night. Although it remains unclear how much of the nocturnal SF is indeed transpired and how much is used for refilling of the stem and embolism repair (Zeppel et al., 2014), other work indicated that 50–95% of the nocturnal SF is lost through transpiration from the canopy (Alvarado-Barrientos et al., 2015; Moore et al., 2008; Zeppel et al., 2010). The indication of an increase in nocturnal transpiration in the later part of the summers could be caused by a reduced ability to prevent water loss due to aging of the leaves, as described by for example Raschke and Zeevaart (1976) and Wilson et al. (2000). Zhou et al. (2015) found that the temperature response in dark respiration was affected by the age of the leaves. However, the variation in levels of SF throughout the summer, did not affect the microclimate influence where a stronger SF was linked to a stronger cooling.

These findings support our observations that a substantial fraction of the total tree transpiration occurred during nighttime, potentially reaching up to one third of daytime levels in the city of Mainz (Fig. 4). This fraction alone does, however, not explain why transpiration-induced cooling is most pronounced at night. A similar pattern was reported by Konarska et al. (2016a,b) who show that although the latent heat flux from nocturnal transpiration cooling in Gothenburg, Sweden, was estimated to around 12% of that at midday, a cooling effect was only observed around and shortly after sunset. Stronger nighttime cooling in Gothenburg was attributed to a lower nocturnal atmospheric mixing, a phenomenon that is well known from many sites (e.g. Eliasson and Holmer, 1990). Liu and Liang (2010) showed that the boundary layer, where mixing occurs, reaches a nocturnal height of about 15% of the daytime, due a stabilizing of the nocturnal surface layer because of infrared radiative cooling, while solar heating causes convective unstable conditions in the daytime. Although the height of the boundary layer is generally increased over urban areas (Oke, 1982), dispersion of the air cooled by nocturnal transpiration would be considerably restricted at night, supporting indications that the limited nocturnal transpiration is an important cooling factor in urban climate.

4.2. Impact of urban geometry

As urban structure can prevent ventilation by obstructing winds (e.g. Oke, 1987), and thus favour microclimate differences, the most pronounced transpiration-induced cooling is recorded in the enclosed courtyard where ventilation is limited. As courtyards are common in urban environments, the substantial cooling of just a few trees as reported here appears critical to this type of environment. Taleghani et al. (2014) showed that also ground vegetation and ponds cool temperatures and increase comfort in courtyards, though their study focused on daytime effects. The more open geometry and sloping ground of the examined garden allows for dispersion of the cooled air thus preventing strong correlations with transpiration cooling. Furthermore, a downhill flow of cooled air during stable nocturnal conditions (Bigg et al., 2014), from the

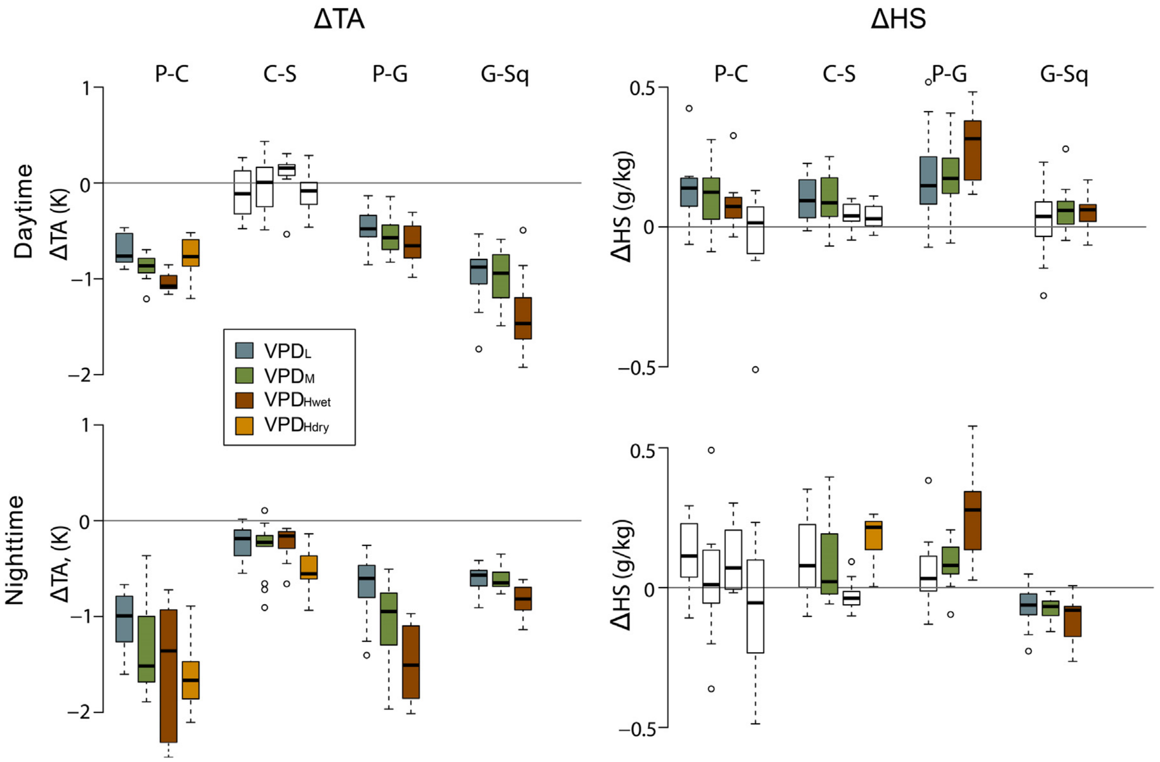

Fig. 7. Boxplots showing the variations in day (top) and night (bottom) ΔTA (left) and ΔHS (right) for the four categories of transpiration demand; low VPD (VPD_L), medium VPD (VPD_M), high VPD, wet (VPD_{Hwet}), and high VPD, dry (VPD_{Hdry}). Data from the 2013 (Park—Courtyard and Courtyard—Street comparison, n = 7/34/10/8 for the different categories) and 2014 (Park—Garden and Garden—Square comparison, n = 27/54/11/0) summers are used. Boxes show 25–75 percentile, with lines across the median. Whiskers indicate the 5–95 percentile and circles show outliers. Unfilled boxes indicate that the compared sites were not significantly different ($p < 0.01$).

garden towards the Square, could explain both the reduced nocturnal TA differences as well as the higher humidity levels in the sparsely vegetated Square.

The weaker, and partly opposite, relationship (i.e., increased humidity and temperature in the courtyard, compared to the street) during daytime, may be caused by a reversed influence where a stronger heating of the urban materials raises TA and thus increases evaporative demand and transpiration. This process might counteract the transpiration cooling and hinder the statistical validation of daytime transpiration cooling effects. Furthermore, the high daytime spring temperatures in the courtyard, mainly measured before the trees were foliated, provides good indication that without shading and transpiration from the trees, the courtyard would be considerably warmer. While heat stress is highest during daytime, when tree shading is known to considerably increase the level of comfort (Emmanuel et al., 2007; Konarska et al., 2014; Lee et al., 2013; Oliveira and Soares, 2002), the lack of adequate nocturnal relief from heat stress is linked to, for example, increased urban mortality during heat waves (Clarke, 1972; Conti et al., 2005). The nocturnal transpiration cooling reported in this study is thus of great importance for the well-being of the urban inhabitants.

4.3. *Influence of evaporative demand and drought on transpiration cooling*

As reported in other studies (e.g. Eamus et al., 2013), increased evaporative demand (VPD), i.e. warmer temperatures and reduced humidity, resulted in increased transpiration in Mainz. Our analysis shows that this dependency is reflected in the transpiration-induced cooling as well. While transpiration-induced cooling increases thermal comfort, the increased humidity caused by the transpiration could likewise decrease comfort. However, this effect was not found to be relevant for human heat stress in the similar climate of Freiburg, Germany (Lee et al., 2016).

We here showed that dry conditions as observed within our monitoring period only caused slight sap flow reductions in the courtyard during day, and an increase during night. Decoupling of midday transpiration under drought as a water saving behaviour has previously been observed in tropical (Brodribb and Holbrook, 2004; Gindaba et al., 2004; Kosugi et al., 2009) and temperate trees (Kamakura et al., 2012). However, no reduction in MDS during drought was found in our study. Furthermore, during dry conditions the transpiration-induced cooling in the courtyard appeared considerably stronger at night, but also slightly stronger during daytime, compared to when water availability was higher. If daytime transpiration was reduced for water saving purposes, cooling should not be stronger at this time. This indicates that the examined trees did not suffer from drought stress in the examined conditions, which could be due to that the main species in this study, *Platanus x acerifolia*, is known to be drought tolerant (e.g. Bowden and Bauerle, 2008) or that its root system had continuous access to water. In a study by Gillner et al. (2015) the leaf gas exchange rate of *Platanus x acerifolia* was found to be significantly higher compared to *Tilia platyphyllos* and *Acer platanoides*, especially during periods of high VPD. Although no indications of species-specific differences in MDS were found in this study, considerable differences in transpiration between species has been found (e.g. Dawson et al., 2007; Gillner et al., 2015), and the nocturnal transpiration-induced cooling of different species needs to be further examined. The shape of the individual trees used for installing temperature sensors could potentially affect the temperature patterns as differences in canopy geometry canopy has been found to influence below-canopy temperatures (Lin and Lin, 2010). However, the canopy geometry of street trees often differ from that of park and garden trees by necessity as it has to be shaped not to obstruct activity such as traffic. The potential influence of canopy geometry is therefore likely to reflect the general influence of urban trees.

It should be noted that slightly different wind and VPD conditions during the dry and wet categories might impact the cooling effects. The influence of drought on the transpiration-induced urban cooling thus needs to be studied further to improve our understanding of how trees would affect the microclimate in a warming world.

5. Conclusion

In this study we show that transpiration-induced cooling from trees is an important driver of intra-urban differences in a 200.000 inhabitant city in Germany. The cooling effect explains a considerable fraction of spatial temperature variations in summer, particularly during night and in a framed courtyard environment. As the observed nighttime transpiration is lower compared to daytime, the overall stronger nighttime cooling signal is attributed to the limited dispersion of cooled air in the stable nocturnal atmospheric conditions. We also show that transpiration-induced cooling increase with atmospheric evaporative demand. Whereas indications of changing temperature pattern during drought stress were found, the impact of sustained drought on urban trees and environments needs to be further investigated.

These findings show that even a few trees can make a significant difference in urban environments and thus represent a suitable tool to mitigate excessive urban heat when planning for a warmer future climate. However, in order to maximize heat mitigation through tree transpiration, it is important to carefully consider how variation of atmospheric evaporative demand and surrounding geometry impact the diurnal and seasonal variations of the cooling effect.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2016.09.001.

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