Building and Environment 114 (2017) 118–128

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Within canopy temperature differences and cooling ability of *Tilia cordata* trees grown in urban conditions

Mohammad A. Rahman [a, *], Astrid Moser [b], Thomas Rötzer [b], Stephan Pauleit [a]

[a] *Strategic Landscape Planning and Management, School of Life Sciences, Weihenstephan, Technische Universität München, Emil-Ramann-Str. 6, 85354 Freising, Germany*

[b] *Forest Growth and Yield Science, School of Life Sciences, Weihenstephan, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany*

A R T I C L E I N F O

Article history:
Received 21 September 2016
Received in revised form
27 November 2016
Accepted 12 December 2016
Available online 14 December 2016

Keywords:
Urban trees
Thermal environment regulation
Heat storage
Latent heat flux
Canopy temperature

A B S T R A C T

Urban trees regulate their thermal environment mostly through the canopies. With multilayered complex canopies trees prevent solar radiation (reaching the ground) thus reduce the heat storage underneath. More importantly the intercepted energy rather increases the latent heat flux, hence reduces the air temperature during the daytime. However, there is little information on within canopy temperature of urban trees and inter-relationships between latent heat flux exchanges to identify thermal impact of vegetation. The present study continuously measured sapflow and within the canopy air temperature of *Tilia cordata* trees along with meteorological variables at two different street canyons in Munich, Germany over the summer, 2015. Within the canopy radius of 4.5 m, daytime temperature reduced up to 3.5 °C with energy loss of 75 W m^{-2} during warm and dry August when the soil moisture potential was below 1.5 MPa and vapour pressure deficit was 4 kPa, but the nighttime temperature went up to 0.5 °C. Deeper underneath the tree canopy, 1.5 m above the ground the average temperature fell by up to 0.85 °C on hot sunny days. The regression equation showed better agreement of this air temperature reduction with the sap flow of trees ($R^2 = 0.61$) rather than the differences between shaded and unshaded, paved and grass surface temperatures. Although the research is at an early stage, the results showed the potential of using canopy air temperature differences as a tool to better understand the transpiration response to within and below canopy temperature and also to be used in climate models.

1. Introduction

It is well known that urban trees can contribute to mitigating the urban heat island (UHI) since urban greening could affect temperatures through different processes [1]. Firstly tree canopies can intercept the solar radiation and prevent the underneath surface to absorb shortwave radiation consequently less convection to contribute to the heat island. Most importantly through evapotranspiration tree canopies absorb solar radiation as well as energy from surrounding environment to increase latent rather than sensible heat fluxes. Combined with oasis and clothesline effects [2] even a single tree can moderate the micro-climate [3], whereas large parks can extend the effects to the surrounding built environment [4]. Meta-analysis of Bowler, Buyung-Ali [5] have shown that air temperature within a park can be about 0.94 °C cooler than outside. Heat loss by evapotranspiration in arid environments with ample water supply can range between 24.5 and 29.5 MJ/m^2 per day whereas, in temperate climates, it can be between 0.7 and 7.4 MJ/m^2 per day [6]. The release of water vapour corresponding to these heat loss values ranges from 0.28 to 12 l/m^2 per day [7].

Thus leaf and air temperature have long been established as indicators of plant-water stress and for initiation of irrigation in agricultural crops [8]. Largely due to the higher latent heat of vaporization and specific heat, the process of evapotranspiration is particularly effective at generating high evaporative cooling [9]. However, solving the energy fluxes using leaf temperature can be very sensitive to errors since they can vary significantly over a short spatial distance due to radiation interception during the day. To eliminate leaf-to-leaf variation in terms of leaf-scale transpiration, within canopy and associate leaf and air temperature information on photosynthetic parameters and radiation regimes inside the canopy are required [9]. In case of closed canopies radiative fluxes

* Corresponding author.
E-mail address: ma.rahman@tum.de (M.A. Rahman).

http://dx.doi.org/10.1016/j.buildenv.2016.12.013
0360-1323/

are relatively homogeneous in horizontal directions, which results in average temperature distributions that are primarily one-dimensional [10].

Air temperature within the canopy will increase when there is little turbulent mixing [11]. A usual assumption is that surface net radiation of a single leaf is balanced by sensible and latent heat fluxes. Similarly, incoming and outgoing energy from a whole canopy would be balanced. Reicosky, Deaton [11] reported that 40–70% decrease in evapotranspiration can be associated with a 4–5 °C increase in the canopy air temperature. Conversely with optimum evapotranspiration tree canopies will compensate the "Oasis" effect from the surrounding environment that is not water stressed. In this way the daytime canopy heat flux is downward with strong radiational warming taking place in the outer part of the canopy layer, not inside. Taha, Akbari [12] studied the effects of evapotranspiration and shading for two warm weeks in Davis, California and measured the air temperature and wind speed along the path within a 5 m high orchard. They reported that inside the canopy day time temperature fell by 4.5–6 °C. Miyazaki [13] measured air temperature under small and larger green canopies in Osaka, Japan and reported that the cooling effect became more significant in the early morning (air temperature difference was 1.6 °C). Retrospectively, the nighttime canopy heat flux can be upward. Studies have already demonstrated that a tree canopy can retain heat at night [12,14].

Canopy micro-climate has direct influences on nearly all bio-physical processes in plants including respiration, photosynthesis, and growth [6]. Models have already been developed to predict the three-dimensional distribution of microclimate-related quantities (e.g., net radiation, surface temperature, evapotranspiration, flux partitioning) in complex canopy geometries [15,16]. Many of them considered canopy as single big leaf e.g. Sellers, Randall [17], or several layers of big leaves e.g. Dai, Dickinson [18]. Similarly, microscale modelling such as by the Vegetated Urban Canopy Model (VUCM) has been introduced by Lee and Park [19] and later coupled with the Weather Research and Forecasting (WRF) model [20] to better understand the impacts of single tree canopy within single urban canyon conditions. To simulate micro-climatic quantities at street canyon scale Lemonsu, Masson [21] also introduced a numerically efficient method by improving the Town Energy Balance (TEB) urban canopy model and including vegetation inside the canyon to more accurately simulate canyon air temperature. However, in a heterogeneous landscape such as in urban areas temperature can vary in the horizontal direction by 10 °C or more within a single tree crown [22]. Little information is available on air temperature profiles within the canopy of urban trees. Given the types of interventions involved which limit the feasibility of conducting experimental work this is not surprising [5].

Quantifying the latent heat exchange between leaves and the local environment is difficult since the later exerts control over water vapour exchange at the leaf surface and leaves also have the capacity to partially regulate their stomata [9]. Apart from the soil moisture, wind turbulence and relative humidity, in most of the canopy models radiation transfers are highly simplified neglecting important processes such as scattering, anisotropic leaf inclination effects, and anisotropic emission of radiation [23]. Vertical distribution of foliage in preferred oval shaped urban tree crowns will further complicate the accurate prediction of energy partitioning using a modelling approach. Therefore, it is important to consider the impact of any potential confounding variables which may bias the estimate of the cooling effect of a green area [5].

One possible approach could be to use energy loss per unit area (from water loss) and estimate the cooling power. Gromke, Blocken [24] used the cooling per unit area data from the empirical study carried out by Rahman, Smith [2] to estimate the volumetric cooling power P_c [W m^{-3}] per unit volume vegetation as a function of the leaf area density (LAD). This is rather a simplified approach where the transpirational cooling effect is allocated to a volume containing vegetation. At the tree scale, the leaf to air temperature difference can be used to compute the sensible heat flux H and might be combined with boundary layer resistance (gbH) and latent heat flux (E) to solve more common notation of energy flux densities (W m^{-2}).

More realistically, solving the latent heat flux of a canopy in relation to its temperature differences would be better in quantifying the cooling effects of an individual tree. Within canopy evaporative cooling is compensated for by the heat transfer from the surrounding environment after some equilibration time. Therefore, the balance between incoming and outgoing energy from a volume of vegetation can be estimated from the integrated volume of all leaves inside the canopy. The main aim of the study is to provide insights into the string of inter-relationships between latent heat flux exchanges to identify thermal impact of vegetation in the urban environment. The study used a simplified approach of air temperature differences within the canopy through basic physiology of a common urban tree *Tilia cordata* planted in contrasting urban micro-climatic conditions. Specifically the study aimed 1. To investigate the relationship of: a) meteorological variables b) tree transpiration with air temperature differences within and underneath tree canopy 2. To quantify the direct cooling effect of *T. cordata* trees under stressed urban conditions in terms of diurnal scale.

2. Methods

2.1. Study area

The study was carried out in Munich (48°8′N, 11°35′E, at 520 m asl), one of the largest and still growing cities in Germany with a high population density (4500/km^2) (Bayerische Landesamt für Statistik, 2015). Munich has long been reported as a city with substantial effects of UHI on growing conditions or degree days [25]. Due to close proximity to the Alps, the climate of Munich is affected by its sheltered position and characterized by a warm temperate climate. The annual mean temperature is 9.1 °C with a temperature range from −4 °C (January) to 24 °C (July) and with an annual precipitation of 959 mm, mostly occurring during summer with a maximum of 125 mm in July [26]. There are only a few tall buildings higher than 100 m in Munich; however, with frequent presence of deep street canyons (aspect ratio ~ 2). Although a number of green open areas can be found [27] the city shows a strong UHI effect with monthly mean UHI intensity up to 6 °C and the effects of UHI have been increasing [28].

2.2. Site selection

Following a dedicated field campaign within the centre of Munich, two small squares with contrasting street canyon characteristics within the eastern core of the city were selected. The current study was an integral part of a longer study to investigate the micrometeorological variations and their effect on the growth and cooling effect of urban trees [29]. One square, Bordeaux Platz is an open green square and the Pariser Platz is a circular paved square with similar aspect ratio ≈0.5. The neighbourhood is characterized by 3–4 storey perimeter blocks distributed in a regular configuration (Fig. 1). The street canyons were contrasting in terms of micro-meteorology, surface cover but within close proximity and within the city centre where UHI effect is most pronounced. At Bordeaux Platz the trees were planted within grass lawns between two wide streets running from North to South and

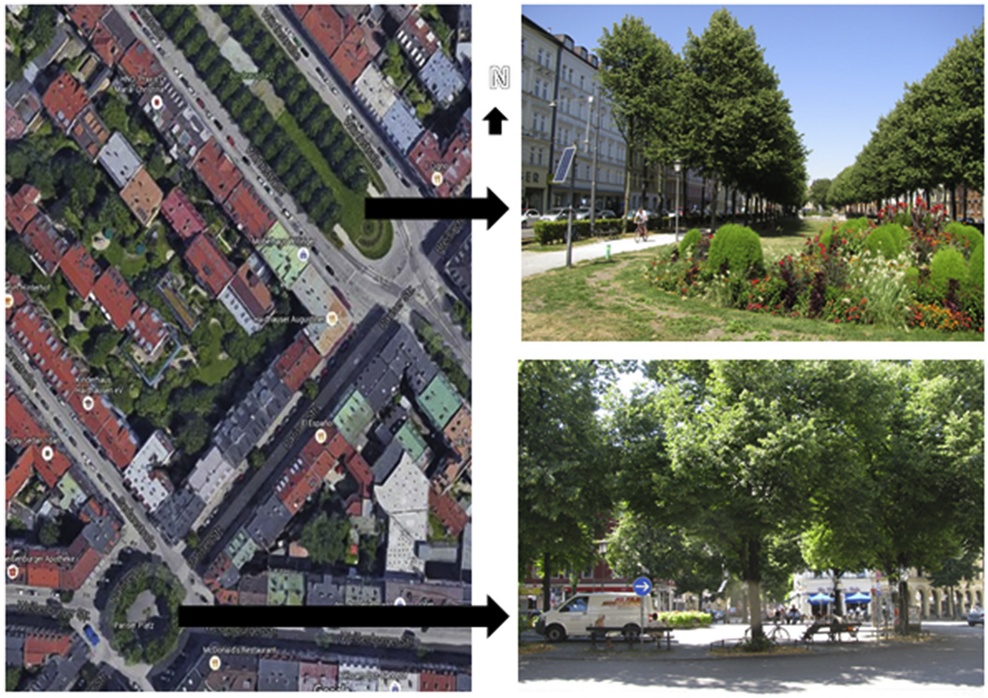

Fig. 1. A plan view of the studied sites (left) (source: Google earth) with sampled trees (right): top) Bordeaux Platz down) Pariser Platz.

from South to North; on the other hand, the Pariser Platz, a circular paved square, 10 trees were planted within the paved surfaces in small tree opening pits.

2.3. Tree selection and morphological measurements

T. cordata trees were selected since it is considered as one of the dominant urban street tree species in Munich mostly popular due to its dense pyramidal or oval crown [30]. Although trees at both the squares were affected by shading from nearby buildings, the effect was more pronounced at Pariser Platz especially during the afternoon. At Bordeaux Platz three *Tilia cordata* trees were selected from the first row of trees within the avenue with 50% of the rooting surface underneath the grass verges while the other half is covered by the unpaved pedestrian walkway. At the Pariser Platz also three *T. cordata* trees were selected planted in small pits (4–4.5 m^2).

Diameter at breast height (DBH) was measured with a diameter measurement tape at a height of 1.3 m. Tree height was calculated using a Vertex Forestor. Crown radii were measured in eight inter cardinal directions along the ground surface with a measuring tape from the centre of the trunk to the tip of the most remote downward-projecting shoot and used to calculate crown projection area (CPA). Leaf area index (LAI) was derived from hemispherical photographs captured during the fully leafed phase (August) using a Nikon CoolpixP5100 camera with fisheye lens and analysed with the program WinSCANOPY (Régent Instruments Inc.) following Moser, Roetzer [31]. Each tree was cored to the heart wood at two opposing directions (N-S) to estimate tree age.

Terrestrial laser scanning (Riegl LMS-Z420i TLS system) were used for crown surface area and volume estimation following Bayer, Seifert [32]. In order to estimate the crown surface area crown skeletonization of measured TLS point clouds were done using software developed for this purpose. Additional TLS point clouds in a distance of 10 cm or less from each other were created within branches and volume were estimated using algorithm described by Bayer, Seifert [32].

2.4. Meteorological data collection

Air temperature, air pressure, relative air humidity, precipitation, wind speed and direction were measured by installing two Vaisala Weather Transmitters WXT520 (EcoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) at the two sites. At both sites the station was mounted on top of a 3.3 m street lamp post 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 (Fig. 2a). At Bordeaux Platz on the same cross arm, a CMP3 pyranometer and a PQS1 Photosynthetically Active Radiation (PAR) sensor (Kipp & Zonen, Delft, The Netherlands) were installed to measure the global radiation and PAR respectively. All the data were recorded continuously at a 15-min resolution from August 6th to October 13th, 2015 on enviLog remote data logger (EcoTech Umwelt- Meβsysteme GmbH, Bonn, Germany) attached to one of our sampled trees (Fig. 2b).

2.5. Surface and canopy temperature

Surface temperature was calculated based on the 8 readings (N, NE, E, SE, S, SW, W and NW) in the shaded area (1 m away from the main stem) and minimum 5 m away from the main canopy shade on the fully exposed sunny surface outside the canopy projected area of 3 trees at each site using Laser gun (PTD 1, Bosch GmbH, Germany). Air temperature underneath the tree canopy (T_u) was also calculated at the same spots but at a height of 1.5 m from the ground on three warm sunny days of the summer 2015 (July 21, August 08 and 13, 2015).

Four Newsteo LOP16 temperature datalogger (La Ciotat, France) were attached at four different positions of each tree (Fig. 3). The loggers were carefully attached to a twig/branch to be away from

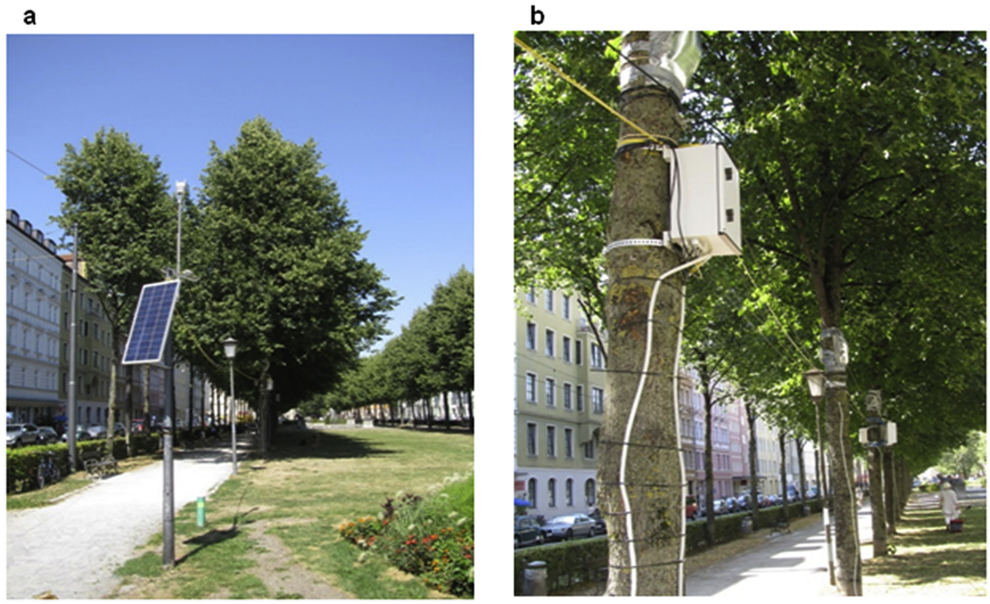

Fig. 2. Experimental plot at Bordeaux Platz a) Meteorological station b) Sampled trees with sap flow and soil moisture potential sensors installed.

direct sunlight and under the shade all time. Each of the loggers was approximately 4.5 m away from each other. One at the centre, one at the top and two at two sides (Eastern and Western). Air temperature within the canopy (T_{Air}) was recorded within the internal memory of the loggers every five minutes and was downloaded using radio signal every week.

2.6. Soil moisture potential and temperature measurements

Soil matric potential and temperature at both the sites were measured using Tensiomark 1 (4244/1, range pF0-pF7) (EcoTech Umwelt-Meßsysteme GmbH, Bonn, Germany) installed vertically through soil profile to the depth of 30 cm as described in Rahman, Moser [29]. A total of 13 sensors were installed for 6 trees at two sites approximately 3.5 m away from the main stem at Bordeaux Platz and at the furthest opening points at Pariser Platz (Fig. 3). All the sensors were also carefully installed in a place which was mostly shaded to minimize the effect of direct solar radiation.

2.7. Sap flow measurements

Tree transpiration was estimated from sap flux density (Js), measured continuously using thermal dissipation probes (TDPs) (Ecomatik, Dachau, Germany) introduced by Granier [33]. Pairs of

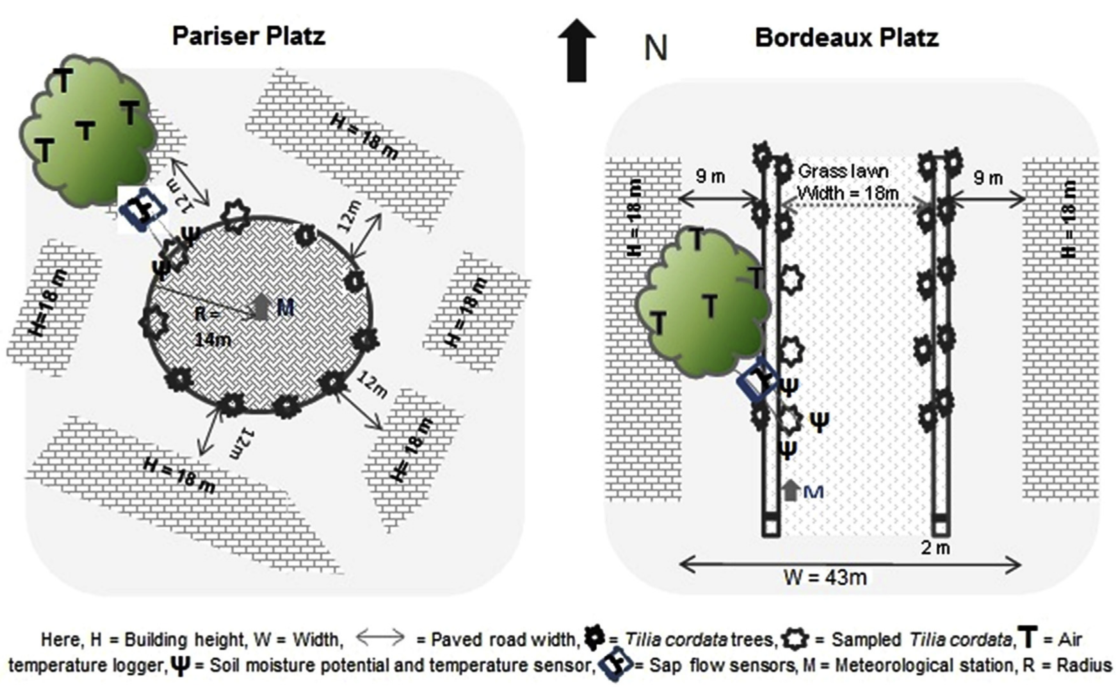

Fig. 3. A Schematic diagram of the street canyons with the sampled trees and the sensors installed.

20-mm-long probes were inserted in the stem sapwood on the north side of the trunk at 4–4.5 m stem height from the ground to deter theft or vandalism (Fig. 3). Even after that, there were vandalism at Pariser Platz and some of the continuous measurement data were lost. In order to consider the radial variations in the sapwood area [34] two pairs of longer needles were also installed at a xylem depth of 20–40 and 40–60 mm with identical heating and sensing devices having the same diameter as those drilled for the outermost (0–20 mm depth) sensors.

All probes were covered with reflective foil and transparent plastic to minimize the influence of solar irradiance and air temperature. The temperature difference (ΔT) between upper and lower sensor probes was recorded every 30 s with a CR800 data logger (Campbell Scientific, U.K.) equipped with Campbell Logger Multiplexer, AM16/32B. Five-minute means were calculated from the 30-s readings and stored by the data logger. Temperature differences were converted to sap flux densities (Js; ml cm^{-2} min^{-1}) based on Granier's empirical calibration equation (eq. (1)) [33]:

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

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

At both the sites a trend of hump shaped sap flux density (an increase towards the middle part of the sapwood depth, followed by a sharp decrease) were observed. The same tree core samples used for age estimation were also used to visually determine the sapwood depth and sap wood area (SA). The average sapwood depth for trees at Bordeaux Platz was 8.1 cm and 7.9 cm for trees at Pariser Platz. The total sap flow (SF) (ml $tree^{-1}$ min^{-1}) for trees at the Bordeaux Platz (eq. (2)) and the Pariser Platz (eq. (3)) were estimated as follows (details Rahman, Moser [29]):

$$SF = Js * SA/4 + Js * 1.27{*}SA/4 + Js * 0.52{*}SA/4 + Js * 0.25{*}SA/4 \tag{2}$$

$$SF = Js * SA/4 + Js * 1.15{*}SA/4 + Js * 0.82{*}SA/4 + Js * 0.65{*}SA/4 \tag{3}$$

SF were converted to daily values (i.e. multiplied by 60×24) and multiplied by the latent heat of vaporization L_V which is 2.45 kJ g^{-1} to calculate the energy loss per tree according to Eq. (4):

$$\text{Energy loss per tree} = SF \times L_V \times 60 \times 24 \tag{4}$$

This way, SF is the daily average cooling in W $tree^{-1}$ and energy loss per unit canopy area was calculated following Peters, McFadden [35].

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 Sample t-tests and for difference in sap flux density at different depths one-way analysis of variance (ANOVA) with Tukey's HSD test to identify the differences between the measured depths 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 association between canopy temperature differences and bio-meteorological variables and finally, multiple linear model was developed based on the highest r^2 values of individual independent variable.

3. Results

3.1. Tree morphological characteristics

Trees at the Bordeaux Platz were younger with significantly smaller DBH, crown projection area (CPA), crown surface area, crown volume than at the Pariser Platz although the total height, LAI and crown radius were not significantly different (Table 1). The average height of the branch-free trunk was about 5m at the Bordeaux Platz and 4 m at the Pariser Platz.

3.2. Air temperature reductions underneath the tree canopy

Irrespective of the surface cover, air temperature (at 1.5 m height) was lower underneath the tree shade compared to the sunny exposed site. The average differences in terms of surface temperature and air temperature underneath the tree shade (ΔT_u) was lower at the Bordeaux Platz (11.73 °C and 0.71 °C) compared to the Pariser Platz (15.21 °C and 0.77 °C). There was a trend that higher surface temperature differences leads to higher air temperature reductions (Fig. 4). However, the regression equation showed that the air temperature reductions can be explained up to 44% by the surface temperature differences.

3.3. Influence of meteorological variables in terms of canopy temperature reductions

2015 was significantly drier than the average [26] and the soil moisture potential during August 2015 reached over 1.5 MPa (Fig. 5) [over the threshold of most of the plant's capability to take water from the soil [36]]. There was a significant relationship (<0.01) between soil moisture potentials and canopy temperature differences; however, the r^2 values were quite low (<0.01).

Hot and dry 2015 also showed high vapour pressure deficit (VPD) (Fig. 5) (peaked to 4 kPa throughout August 2015). The wind speed (WS) was comparatively lower with higher VPD. However, there was a significant relationship between WS and VPD (Table 2) with canopy temperature reductions.

Air temperature was in good agreement with global radiation (GR). Air temperature frequently reached around 35 °C in August 2015 and bright sunny days during August, September and October 2015 (Fig. 5) showed significant relationship between GR and air temperature. Both of these variables also showed a significant relationship with canopy temperature reductions (Table 2).

Table 1
Average morphological characteristics of trees and degree of openness within the crown projection areas (CPA) of two sites.

Sites	Age (years)	CPA (m^2 ± SE)	Degree of grass area within CPA (% ± SE)	Crown radius (m ± SE)	Crown Surface area (m^2 ± SE)	Crown volume (m^3 ± SE)	DBH (cm ± SE)	Height (m ± SE)	LAI (±SE)
Borde-aux Platz	40 ± 20	62.2 ± 0.40	57.66 ± 2.93	4.46 ± 0.03	670 ± 24	290 ± 26	28.7 ± 0.76	14.9 ± 0.29	2.3 ± 0.28
Pariser Platz	92 ± 13	79.8 ± 3.21	5.21 ± 0.45	5.04 ± 0.10	1216 ± 75	458 ± 70	44.27 ± 1.53	16.37 ± 0.26	2.42 ± 0.24

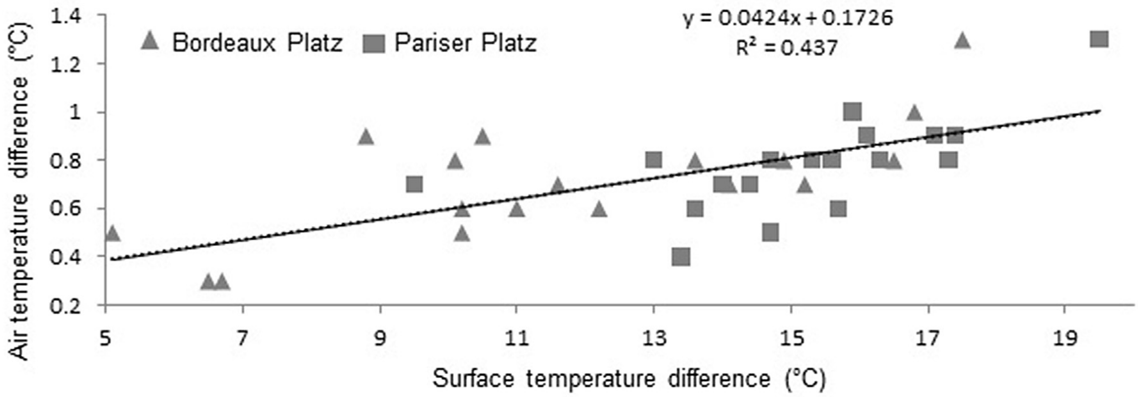

Fig. 4. Reductions in air temperature (ΔT_u) in relation to surface temperature differences underneath tree shade compared to the outside (sunny side) on three warm sunny days (July 21, August 08 and 13, 2015).

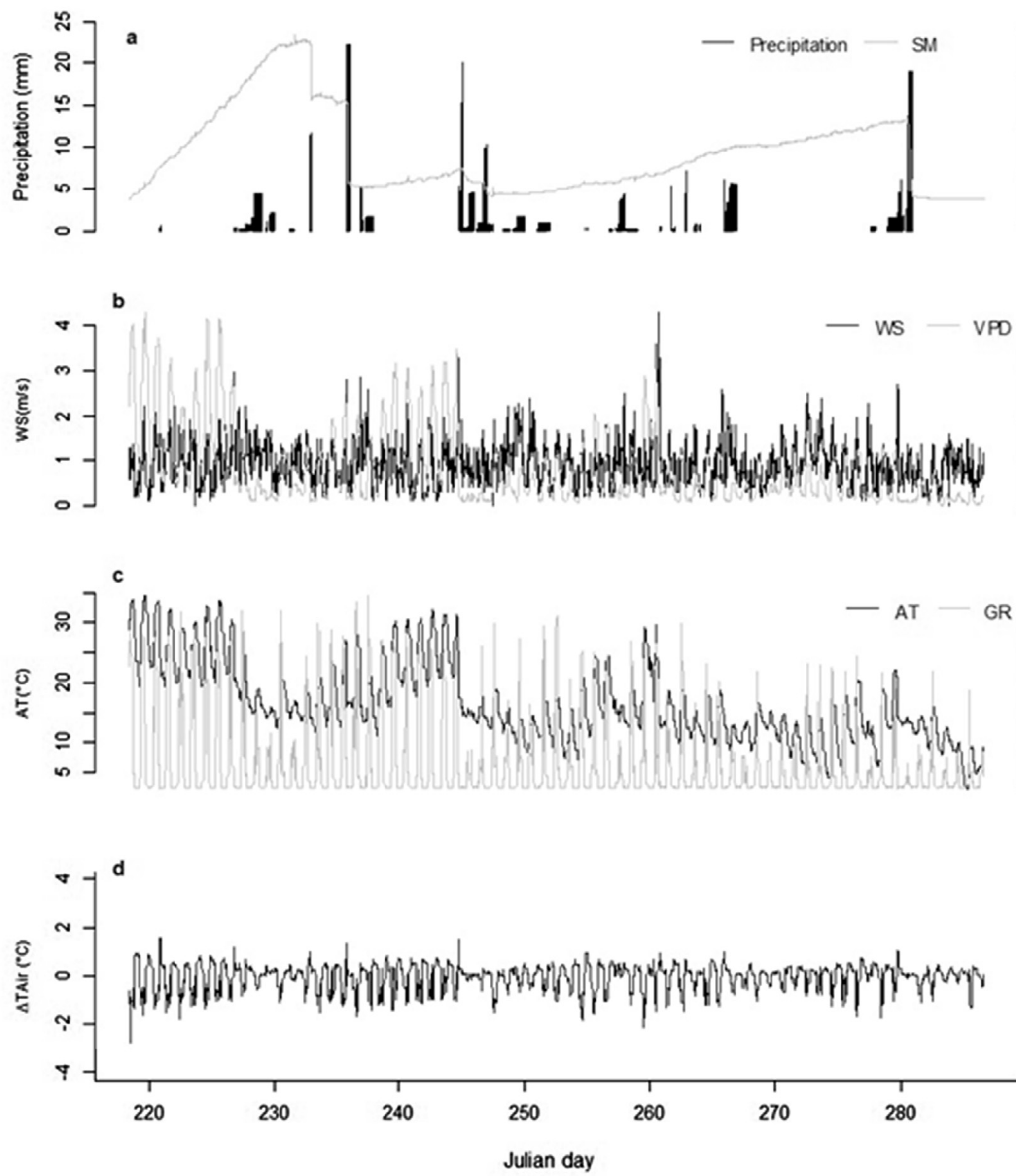

Fig. 5. Relationship between meteorological variables and within canopy temperature differences in terms of daily courses: a) precipitation and soil moisture potentials b) wind speed (WS) and vapour pressure deficit (VPD) c) air temperature (AT) and global radiation (GR) d) canopy temperature differences ΔT_{Air} (Centre − rest 3 positions).

Table 2
Linear regression models based on the relationship between within canopy temperature difference ΔT_{Air}°C (centre − rest 3 positions) and meteorological variables measured outside the canopy; wind speed (WS); air temperature (AT); vapour pressure deficit (VPD); global radiation (GR); and total sapflow (SF).

Dependent variable (x)	Regression Equation	r^2 (adj.)	p-value
Wind speed	ΔT_{Air}°C = 0.26−0.35 WS	0.09	<0.001
Air temperature (°C)	ΔT_{Air}°C = 0.39−0.03 AT	0.12	<0.001
Vapour pressure deficit (kPa)	ΔT_{Air}°C = 0.16−0.26 VPD	0.18	<0.001
Global radiation (w m^{-2})	ΔT_{Air}°C = 0.26−0.002 GR	0.53	<0.001
Sap flow (ml 15$min^{-1}tree^{-1}$)	ΔT_{Air}°C = 0.27−0.0008 SF	0.61	<0.001

3.4. Sap flow and canopy temperature differences

A significant relationship between canopy temperature reductions was observed with the sap flow of the trees (Table 2). Overall total sap flow per tree was significantly higher from trees at Pariser Platz (643 ml 15 $min^{-1}tree^{-1}$) ($t = -24.53$, $df = 6948.7$, p-value < 0.001) compared to trees at Bordeaux Platz (358 ml 15 $min^{-1}tree^{-1}$). This was followed by higher canopy temperature reductions ($t = 16.309$, $df = 12939$, p-value < 0.001) for trees at Pariser Platz compared to trees at Bordeaux Platz (Fig. 6).

3.5. Linear models of canopy temperature differences

All the meteorological variables showed significant relationships with canopy air temperature differences. However, reduced wind speed within street canyon conditions could explain some of the variations of the air temperature within the tree canopy. Neither the air temperature nor the VPD outside the canopy could explain better. However, global radiation alone can explain more than half of the differences in canopy air temperatures (Table 2). Most significantly, the total amount of sap flow could explain 61% of the variability in terms of canopy air temperature differences.

However, including WS, AT, VPD, GR and SF in the linear model to explain the canopy temperature reduction did not improve a lot the model. The collinearity of the meteorological variables did not help to improve the r^2 values in terms of within canopy air temperature gradient. Rather the latent heat exchanges showed the greatest influence in reducing the air temperature at the centre of the canopy compared to the outer surface.

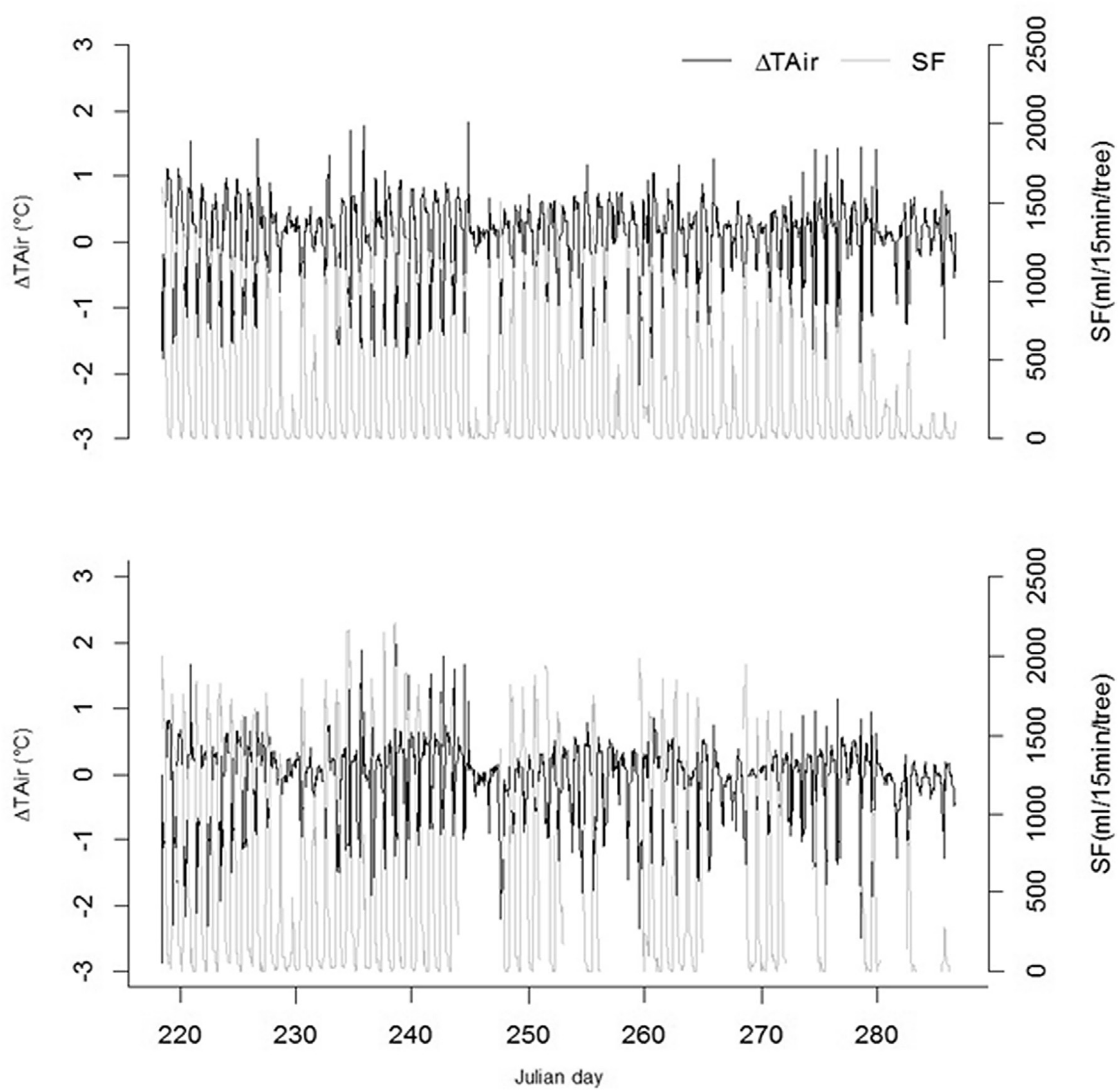

Fig. 6. Daily course of canopy temperature reductions ΔT_{Air} (centre - rest 3 positions) and the total sap flow: top-Bordeaux Platz; bottom-Pariser Platz over the measured period (August 06 to October 13, 2015, missing values of Sap flow in Pariser Platz is due to vandalism).

3.6. Diurnal pattern of evapotranspirational cooling

Average canopy air temperature reductions (ΔT_{Air}) reached around 0.8 °C during mid-day in August (Fig. 7). A similar pattern was also found for the energy loss around mid-day with up to 50 W m^{-2} during August. With gradual decrease of energy loss per unit area the temperature reductions potential also declined. At night the heat retention was also higher during August. Along with the reduction in energy loss during night the air temperature towards the centre of the canopy also converged with the temperatures measured in the outer crown towards September and October. Diurnally average air temperature reduction was higher during early afternoon and late afternoon (Fig. 8).

The peak air temperature reductions (ΔT_{Air}) reached up to 3.5 °C during early afternoon on August as well as the peak energy loss of around 75 W m^{-2}.

4. Discussion

The present study showed that there is a general trend of an increasing cooling effect with decreasing distance from the centre of the tree shade. Air temperature near the ground will be affected by convected heat in sunny areas in contrast to the air underneath the tree which will have less turbulent heat exchange due to tree shading, and the roof effect of the crown. However, with the high advection, the air gets readily mixed and almost 56% of the variation actually cannot be explained by the convection alone, this is mainly due to the latent heat exchange from the canopy above. The downward heat flux was further indicated by a strong coupling with the sap flow of the trees. Other bio-meteorological variables also showed significant implications. However, they could not improve the model due to the collinearity with the sap flow of trees. Peak cooling effect of trees (ΔT_{Air}) was about 3.5 °C with peak energy loss of around 75 W m^{-2}. With higher crown dimensions and consequently more sap flow, trees at Pariser Platz showed higher canopy temperature differences compared to the trees at Bordeaux Platz.

Nonetheless, with no significant difference in terms of LAI of trees grown at Pariser Platz compared to those grown at Bordeaux Platz, the air temperature reductions underneath the canopy were not significantly different. The paved surfaces at the Pariser Platz absorbed more shortwave radiation compared to the grass lawns at the Bordeaux Platz and showed higher surface temperature differences. Though surface and air temperature show some similar spatial and temporal patterns, this correlation is not exact [37]. Air temperature across the boundary layer will be nearly identical due to the efficient mixing of the air, whereas surface temperatures vary more [38].

Air temperature reductions underneath the tree shade (ΔT_u) of up to 0.85 °C in the present study seems conservative compared to the values of the study of Souch and Souch [14] or Golden, Carlson [39]. Souch and Souch [14] reported midday air temperatures reductions between 0.7 and 1.3 °C while comparing individual trees of three different species over concrete and grass in Bloomington, Indiana. Golden [39] reported even more of up to 3.5 °C during midday within a parking lot in Phoenix, USA. On the other hand, Coutts, White [40] reported average day time cooling between 0.2 and 0.9 °C with a maximum of 1.5 °C underneath the street trees on a wide street canyon conditions in Melbourne, Australia. However, while reporting this, it is also important to consider the influence of

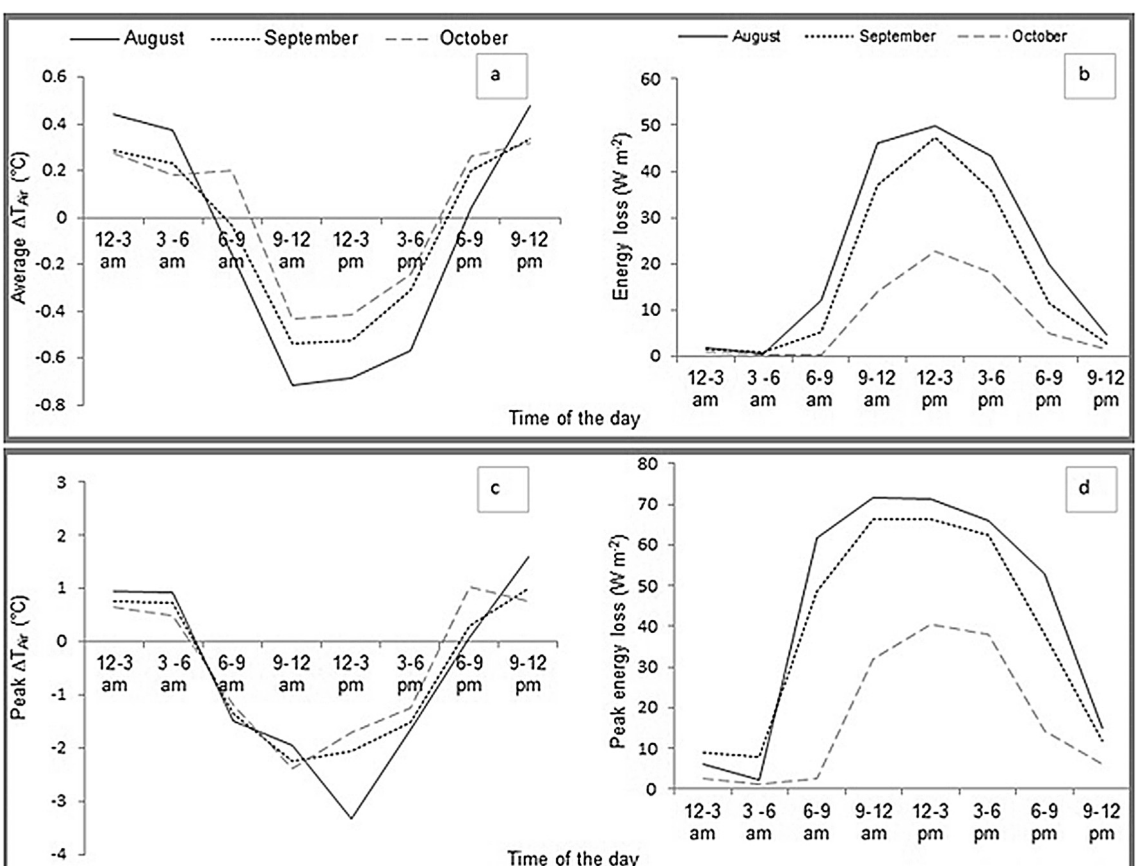

Fig. 7. Average and peak temperature reductions (ΔT_{Air}) and energy loss per unit area over the three measured months at different time of the day averaged over two plots a) average temperature reductions b) average energy loss per unit area c) peak temperature reductions d) peak energy loss per unit area.

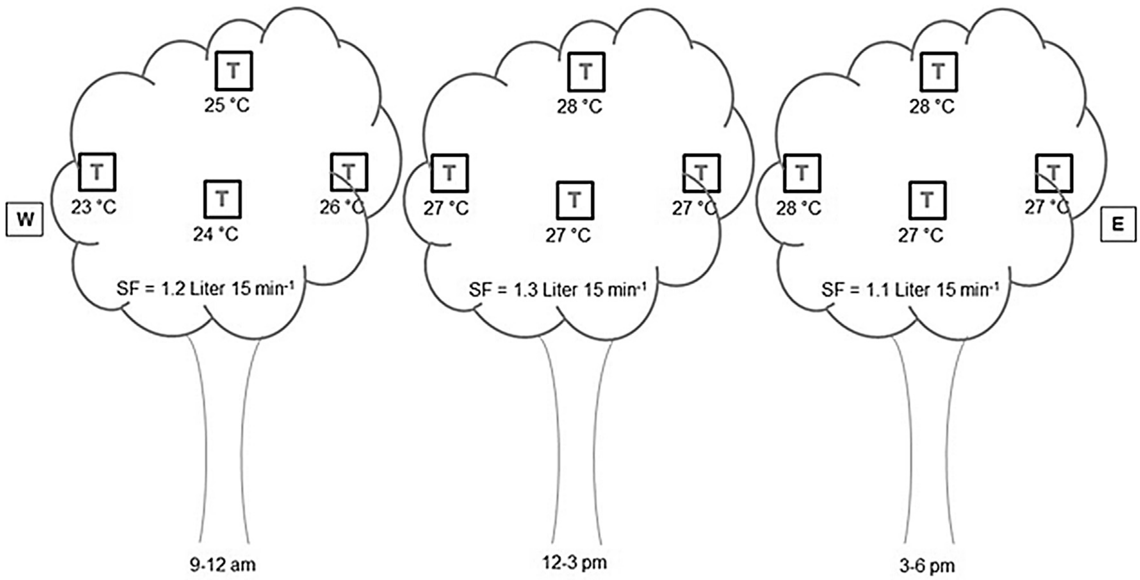

Fig. 8. Schematic diagram of average air temperature at both sites during August 2015 at four different positions along with the total sap flow over the day. Here, T represents the air temperature and the position of the logger, W and E stands for the direction west and east.

tree clusters, if there is any, compared to the individual trees. A tree interacting with prevailing weather is subjected to continual fluxes of heat and water vapour. Due to the albedo of deciduous trees [0.11–0.17, [41]], they reflect less compared to the other built surfaces, and this extra energy is also used for evapotranspiration. Whereas the surface underneath has less chance of conduction which ultimately also influence the air temperature underneath tree canopy. However, they cannot explain the turbulent mixing of air and resultant heat and moisture transport properly without downward latent heat fluxes from the canopy.

Within urban fabric, sensible heat is often used to indicate the total energy ignoring the latent heat flux likewise in CTTC model developed by Swaid and Hoffman [42]. Later Shashua-Bar and Hoffman [43] added vegetation effect on it to modify the model as Green CTTC. The model estimate the convective heat exchange factor to predict the air temperature underneath urban greenspaces since the usual assumption is that air temperature decline towards the vertical gradient of tree canopy due to the shading [44]. However, considering the wind speed of 3 m/s, global radiation of 800 W/m^2 (Fig. 5) and sap flow of 7 l/hr (Fig. 6) during August 13, 2015 for instance, it is not possible to understand the decline in air temperature underneath the tree shade with only longwave radiation and convection. Previous researchers such as Chang, Li [45] have already shown that the percentage of tree and shrub cover explained differences in temperature between parks and their surroundings and this was not simply due to a tree shading effect, as measurements were taken in unshaded regions of the parks. Although, with soil drought the energy used in evapotranspiration would be dissipated in the form of sensible heat and increase the plant and canopy air temperatures with minimum advection [11]. Understanding the role of microclimate across scales in canopies with complex, heterogeneous architectures is challenging, as it is difficult to represent the relevant range of scales [23]. The present study showed higher radiation and momentum absorption at the outer surface of the tree canopies (Fig. 7). Moreover, the street canyon conditions of Pariser Platz showed comparatively lower wind speed and VPD meaning less boundary layer conductance when compared with Bordeaux Platz. Therefore, even without wind driven transpiration, higher VPD and air temperature can influence higher evapotranspiration hence latent heat fluxes given optimum soil moisture condition. This is in support of the "Oasis" effect of individual urban trees in street canyon conditions [2]. Thus individual urban trees are better in terms of urban cooling compared to a cluster of trees in terms of per unit crown projected area.

All the bio-meteorological variables showed significant relationships with the canopy temperature differences and global radiation showed even a higher r^2 value. They are the main drivers of the leaf transpiration which (between SF and GR correlation coefficient $r = 0.80$) in turn again influence the relative humidity and air temperature within the boundary layer of the canopy. Average and peak cooling effect of trees during the midday is in agreement with previous researchers [2,46,47]. These cooling effects were the consequence of energy loss from trees through transpiration which are also in agreement with previous researchers [2,46,48]. With a drought year such as 2015 where soil moisture potential was below 1.5 MPa even in August, lower amount of transpirational energy loss per unit area is not surprising. The peak energy loss of around 75 W m^{-2} in August and peak cooling of around 3.5 °C are very impressive. With ample supply of water, the energy loss may even reach to around 200 W m^{-2} [49,50], and consequently, it may be assumed that the peak cooling effect within the canopy will reach up to 7–8 °C. This might consequently help downward heat fluxes to further reduce the air temperature underneath a single tree canopy from 0.85 °C to 2–2.3 °C as such Golden [39] showed in a parking lot in Phoenix, USA. Although this work is at its early stage, new developments are under way in order to improve the method including aerial images over multiple seasons and different types of urban vegetation. Further studies have demonstrated the influence of diurnal and seasonal variations in the relationships between the parameters measured and cover features, and have recommended the use of multiple daytime and nighttime values for different seasons [51].

5. Conclusion

In order to understand the whole canopy energy balance a complex set of processes needs to be involved such as wind and transfer process as well as partitioning of absorbed energy [52]. Over the last two decades researchers have shown the lower air temperature within or below forest canopy mainly using generic models [53,54]. However, due to heterogeneity at a fine scale in urban areas, explanation of in-canopy air temperature profile needs to incorporate biological, micro-meteorological and edaphic factors [55]. But, for various logistical constraints, for instance only to calculate the net radiation around an isolated urban tree canopy [56] can be really challenging and precise empirical quantification become impracticable. We are not aware of any studies that have decoupled energy transfer process from the influence of temperature on transpiration within matured tree canopy of individual trees at outdoor settings.

The present study rather attempted to understand the interplay among different meteorological variables to investigate the transpiration response to within canopy and directly underneath canopy temperature gradients. Thus the study investigated the within crown and beneath the crown air temperature feedback together with water flux over a spatial and temporal scale rather a short-term (diurnal and/or daily) data to validate estimate. The study showed that even after the summer droughts of 2015, approximately 60 years old *T. cordata* trees can provide 0.85 °C cooling of air temperature directly underneath the tree canopy. Additionally, this correlates well with the latent heat flux of tree canopies, and with the optimum tree transpiration peak canopy temperature differences might go up to 7–8 °C, and the cooling effect directly underneath might reach up to 2–2.3 °C. These findings have direct implications to improve our ability to scale-up water exchange in order to estimate transpiration simulations models that address urban climate models. The energy balance at the canopy as a whole is the sum of incoming and outgoing fluxes of latent and sensible heat and of short wave and long wave radiation. So, coupling between the atmospheric model and the surface layer model will help us to synchronise the profiles of temperature and humidity across two models when the coupled model is run over comparatively larger time steps [57]. However, more empirical studies including more species, sites and also prevalent meteorological conditions not only outside the canopy but also within the canopy might provide better estimates.

Acknowledgements

This study was carried out while the corresponding author was in receipt of an Alexander von Humboldt Fellowship at the Technical University of Munich, Germany. The authors want to thank the department for the municipal green areas of Munich especially Mr. Michael Brunner for their support and encouragement. The authors thank Prof. Dr. Rainer Matyssek for his suggestions during the experimental design and Dr. Bernhard Förster for his help during the data analysis. The authors also want to acknowledge kind help of Mr Chao Xu, Mr Jens Dahlhausen, Ms Teresa Zölch, Mr Alexander Hellwig, Mr Martin Honold, Ms Claudia Chreptun for their help during the field work.

References

[1] T.R. Oke, The micrometeorology of the urban forest, Philos. Trans. R. Soc. Lond Ser. B-Biol Sci. 324 (1989) 335–349.
[2] M.A. Rahman, J.G. Smith, P. Stringer, A.R. Ennos, Effect of rooting conditions on the growth and cooling ability of Pyrus calleryana, Urban For. Urban Green. 10 (2011) 185–192.
[3] F.H. Kong, W.J. Yan, G. Zheng, H.W. Yin, G. Cavan, W.F. Zhan, et al., Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation, Agric For. Meteorol 217 (2016) 22–34.
[4] C. Yu, W.N. Hien, Thermal benefits of city parks, Energy Build. 38 (2006) 105–120.
[5] D.E. Bowler, L. Buyung-Ali, T.M. Knight, A.S. Pullin, Urban greening to cool towns and cities: a systematic review of the empirical evidence, Landsc. Urban Plan. 97 (2010) 147–155.
[6] H.G. Jones, Plants and Microclimate: a Quantitative Approach to Environmental Plant Physiology, third ed., 2014.
[7] M. Ballinas, V.L. Barradas, The urban tree as a tool to mitigate the urban heat island in Mexico city: a simple phenomenological model, J. Environ. Qual. 45 (2016) 157–166.
[8] D.M. Gates, Transpiration and leaf temperature, Annu. Rev. Plant Physiology 19 (1968), 211-&.
[9] G.G. Katul, R. Oren, S. Manzoni, C. Higgins, M.B. Parlange, Evapotranspiration: a process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system, Rev. Geophys. 50 (2012).
[10] J.L. Monteith, M.H. Unsworth, Principles of Environmental Physics: Plants, Animals, and the Atmosphere, fourth ed., 2013.
[11] D.C. Reicosky, D.E. Deaton, J.E. Parsons, Canopy air temperatures and evapotranspiration from irrigated and stressed soybeans, Agric. Meteorol. 21 (1980) 21–35.
[12] H. Taha, H. Akbari, A. Rosenfeld, Heat-island and oasis effects of vegetative canopies - micro-meteorological field-measurements, Theor. Appl. Climatol. 44 (1991) 123–138.
[13] H. Miyazaki, M. Moriyama, A. Yoshida, Field study on green canopy as urban cool-spot, Nat. Hum. Act. 1 (1996) 51–56.
[14] C.A. Souch, C. Souch, The effect of trees on summertime below canopy urban climates: a case study Bloomington, Indiana, J. Arboric. 19 (1993) 303–312.
[15] J. Dauzat, B. Rapidel, A. Berger, Simulation of leaf transpiration and sap flow in virtual plants: model description and application to a coffee plantation in Costa Rica, Agric For. Meteorol 109 (2001) 143–160.
[16] H. Sinoquet, X. Le Roux, B. Adam, T. Ameglio, F.A. Daudet, RATP: a model for simulating the spatial distribution of radiation absorption, transpiration and photosynthesis within canopies: application to an isolated tree crown, Plant Cell. Environ. 24 (2001) 395–406.
[17] P.J. Sellers, D.A. Randall, G.J. Collatz, J.A. Berry, C.B. Field, D.A. Dazlich, et al., A revised land surface parameterization (SiB2) for atmospheric GCMs .1. Model formulation, J. Clim. 9 (1996) 676–705.
[18] Y.J. Dai, R.E. Dickinson, Y.P. Wang, A two-big-leaf model for canopy temperature, photosynthesis, and stomatal conductance, J. Clim. 17 (2004) 2281–2299.
[19] S.H. Lee, S.U. Park, A vegetated urban canopy model for meteorological and environmental modelling, Boundary-Layer Meteorol. 126 (2008) 73–102.
[20] S.H. Lee, H. Lee, S.B. Park, J.W. Woo, D.I. Lee, J.J. Baik, Impacts of in-canyon vegetation and canyon aspect ratio on the thermal environment of street canyons: numerical investigation using a coupled WRF-VUCM model, Q. J. R. Meteorological Soc. 142 (2016) 2562–2578.
[21] A. Lemonsu, V. Masson, L. Shashua-Bar, E. Erell, D. Pearlmutter, Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas, Geosci. Model. Dev. 5 (2012) 1377–1393.
[22] M.T. Tyree, T.R. Wilmot, Errors in the calculation of evaporation and leaf conductance in steady-state porometry - the importance of accurate measurement of leaf temperature, Can J For. Res-Rev Can Rech For. 20 (1990) 1031–1035.
[23] B.N. Bailey, R. Stoll, E.R. Pardyjak, N.E. Miller, A new three-dimensional energy balance model for complex plant canopy geometries: model development and improved validation strategies, Agric For. Meteorol 218 (2016) 146–160.
[24] C. Gromke, B. Blocken, W. Janssen, B. Merema, T. van Hooff, H. Timmermans, CFD analysis of transpirational cooling by vegetation: case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands, Build. Environ. 83 (2015) 11–26.
[25] J. Schatz, C.J. Kucharik, Urban heat island effects on growing seasons and heating and cooling degree days in Madison (n/a-n/a), Wis. USA. Int. J. Climatol. 36 (15) (December 2016) 4873–4884.
[26] DWD. Deutscher Wetterdienst. 2015.
[27] S. Pauleit, F. Duhme, Assessing the environmental performance of land cover types for urban planning, Landsc. Urban Plan. 52 (2000) 1–20.
[28] R. Pongracz, J. Bartholy, Z. Dezsoe, Application of remotely sensed thermal information to urban climatology of Central European cities, Phys. Chem. Earth 35 (2010) 95–99.
[29] M.A. Rahman, A. Moser, T. Rötzer, S. Pauleit, Microclimatic differences and their influence on transpirational cooling of *Tilia cordata* in two contrasting street canyons in Munich, Germany, Agric For. Meteorol 232 (2017) 443–456.
[30] S. Pauleit, N. Jones, G. Garcia-Martin, J.L. Garcia-Valdecantos, L.M. Riviere, L. Vidal-Beaudet, et al., Tree establishment practice in towns and cities: results from a European survey, Urban For. Urban Green. 1 (2002) 83–96.
[31] A. Moser, T. Roetzer, S. Pauleit, H. Pretzsch, Structure and ecosystem services of small-leaved lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) in urban environments, Urban For. Urban Green. 14 (2015) 1110–1121.
[32] D. Bayer, S. Seifert, H. Pretzsch, Structural crown properties of Norway spruce (Picea abies L. Karst.) and European beech (Fagus sylvatica L.) in mixed versus pure stands revealed by terrestrial laser scanning, Trees-Struct Funct. 27 (2013) 1035–1047.
[33] A. Granier, Evaluation of transpiration in a douglas-fir stand by means of sap flow measurements, Tree Physiol. 3 (1987) 309–319.
[34] J. Cermak, N. Nadezhdina, Sapwood as the scaling parameter defining according to xylem water content or radial pattern of sap flow? Ann Sci For. 55 (1998) 509–521.
[35] E.B. Peters, J.P. McFadden, R.A. Montgomery, Biological and environmental controls on tree transpiration in a suburban landscape, J. Geophys. Research-

Biogeosciences 115 (2010).
[36] J.M. Torres-Ruiz, A. Diaz-Espejo, A. Perez-Martin, V. Hernandez-Santana, Role of hydraulic and chemical signals in leaves, stems and roots in the stomatal behaviour of olive trees under water stress and recovery conditions, Tree Physiol. 35 (2015) 415–424.
[37] A.J. Arnfield, Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island, Int. J. Climatol. 23 (2003) 1–26.
[38] R.D. Brown, T.J. Gillespie, Microclimate Landscape Design: Creating Thermal Comfort and Energy Efficiency, John Wiley & Sons, Chichester, 1995.
[39] J.S. Golden, J. Carlson, K.E. Kaloush, P. Phelan, A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures, Sol. Energy 81 (2007) 872–883.
[40] A.M. Coutts, E.C. White, N.J. Tapper, J. Beringer, S.J. Livesley, Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments, Theor. Appl. Climatol. 124 (2016) 55–68.
[41] R.T. Pinker, O.E. Thompson, T.F. Eck, The albedo of a tropical evergreen forest, Q. J. R. Meteorological Soc. 106 (1980) 551–558.
[42] H. Swaid, M.E. Hoffman, Climatic impacts of urban design-features for high-latitude and midlatitude cities, Energy Build. 14 (1990) 325–336.
[43] L. Shashua-Bar, M.E. Hoffman, The Green CTTC model for predicting the air temperature in small urban wooded sites, Build. Environ. 37 (2002) 1279–1288.
[44] W.L. Bauerle, J.D. Bowden, G.G. Wang, M.A. Shahba, Exploring the importance of within-canopy spatial temperature variation on transpiration predictions, J. Exp. Bot. 60 (2009) 3665–3676.
[45] C.R. Chang, M.H. Li, S.D. Chang, A preliminary study on the local cool-island intensity of Taipei city parks, Landsc. Urban Plan. 80 (2007) 386–395.
[46] J. Konarska, J. Uddling, B. Holmer, M. Lutz, F. Lindberg, H. Pleijel, et al., Transpiration of urban trees and its cooling effect in a high latitude city, Int. J. Biometeorology 60 (2016) 159–172.
[47] M.A. Rahman, P. Stringer, A.R. Ennos, Effect of pit design and soil composition on performance of pyrus calleryana street trees in the establishment period, Arboric. Urban For. 39 (2013) 256–266.
[48] M.A. Rahman, D. Armson, A.R. Ennos, A comparison of the growth and cooling effectiveness of five commonly planted urban tree species, Urban Ecosyst. 18 (2015) 371–389.
[49] C.S.B. Grimmond, T.R. Oke, Evapotranspiration rates in urban areas, in: J.B. Ellis (Ed.), Impacts of Urban Growth on Surface Water and Groundwater Quality, Int Assoc Hydrological Sciences, Wallingford, 1999, pp. 235–243.
[50] C. Jacobs, J. Elbers, R. Brolsma, O. Hartogensis, E. Moors, M.T.R.-C. Marquez, et al., Assessment of evaporative water loss from Dutch cities, Build. Environ. 83 (2015) 27–38.
[51] S.W. Myint, E.A. Wentz, A.J. Brazel, D.A. Quattrochi, The impact of distinct anthropogenic and vegetation features on urban warming, Landsc. Ecol. 28 (2013) 959–978.
[52] J. Landsberg, P. Sands, Weather and Energy Balance. Physiological Ecology of Forest Production: Principles, Processes and Models vol. 4, 2011, pp. 13–48.
[53] N. Jarosz, Y. Brunet, E. Lamaud, M. Irvine, J.M. Bonnefond, D. Loustau, Carbon dioxide and energy flux partitioning between the understorey and the overstorey of a maritime pine forest during a year with reduced soil water availability, Agric For. Meteorol 148 (2008) 1508–1523.
[54] C. Emmel, E. Paul-Limoges, T.A. Black, A. Christen, Vertical distribution of radiation and energy balance partitioning within and above a lodgepole pine stand recovering from a recent insect attack, Boundary-Layer Meteorol. 149 (2013) 133–163.
[55] M.A. Rahman, D. Armson, A.R. Ennos, Effect of urbanization and climate change in the rooting zone on the growth and physiology of Pyrus calleryana, Urban For. Urban Green. 13 (2014) 325–335.
[56] K.G. McNaughton, S.R. Green, T.A. Black, B.R. Tynan, W.R.N. Edwards, Direct measurement of net-radiation and photosynthetically active radiation absorbed by a single tree, Agric For. Meteorol 62 (1992) 87–107.
[57] K. Naudts, J. Ryder, M.J. McGrath, J. Otto, Y. Chen, A. Valade, et al., A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes, Geosci. Model. Dev. 8 (2015) 2035–2065.