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The Bigger, the Better? The Influence of Urban Green Space Design on Cooling Effects for Residential Areas

Madhumitha Jaganmohan,* Sonja Knapp, Carsten M. Buchmann, and Nina Schwarz

Abstract

It is well known that the cooling effect of an urban green space extends into its surroundings, cooling the immediate environment and mitigating urban heat problems. However, the effects of size, shape, and type of an urban green space on cooling remain uncertain. The objectives of our study were to quantify and compare the strength of the cooling effects of urban parks and forests, to determine how far the cooling effects extend into the surrounding residential environment, and to better understand how temperature gradients are driven by physical characteristics of the green space and the surroundings. Mobile air temperature measurements were performed in 62 urban parks and forests in the city of Leipzig, Germany, in the summer of 2013. Three indicators of cooling were calculated: the change in temperature (ΔT) at the park-width distance, the maximum ΔT, and the cooling distance. The relationships of these variables to the physical characteristics of the green spaces and their surroundings were examined in multiple regression models. Analyzing all three indicators revealed that cooling effects were greater in urban forests than in parks. Cooling increased with increasing size but in a different manner for forests and parks, whereas the influence of shape was the same for forests and parks. Generally, the characteristics of the green spaces were more important than the characteristics of the residential surroundings. These findings have the potential to assist in better planning and designing of urban green spaces to increase their cooling effects.

Core Ideas

- The cooling effect of urban forests is higher than that of urban parks.
- The differences in temperature and cooling distance measure different aspects of the cooling effects.
- The influence of size on the cooling effects is stronger than the influence of the shape.

The urban population in 2014 was 54% of the total global population (United Nation, 2014), and the global trend of such rapid urbanization has made cities a complex network for ecosystem services. Cities have heterogeneous environments, providing a wide range of ecosystem services (Bolund and Hunhammar, 1999). Urban green spaces that are prevalent in cities are biodiversity hotspots (Hermy and Cornelis, 2000). These hotspots provide areas for carbon storage (Ren et al., 2011; Strohbach and Haase, 2012) and help with air pollution reduction and micro-climate regulation (Yin et al., 2011; Vailshery et al., 2013), which improve quality of life and enhance human well-being.

Urban regions are very distinct from surrounding rural regions, with more built-up areas and fewer open spaces. For instance, urban built-up structures exacerbate heat waves due to the urban heat island (UHI) effect (Oke, 1982) and induce heat stress (Harlan et al., 2006) in urban residents. Studies (Li and Bou-zeid, 2013; Li et al., 2015) also indicate the synergies between heat wave (excessively hot periods during which the air temperature increases significantly) and UHI can lead to higher health risks to urban residents, especially those who do not have means to cool their residences, who are often the elderly and the poor (Grimmond, 2007). A UHI can develop through a difference between the urban temperature and the temperature in the rural surroundings. Simulated results for a change in the nocturnal heat island in response to atmospheric CO_2 for a global climate model showed an increase of 30% in some locations with high population growth and a global area averaged nocturnal heat island reduction of 6% (McCarthy et al., 2010). Global climate simulations for urban surfaces (Oleson et al., 2011) showed that the present day annual mean air temperatures are higher than the rural areas by up to 4°C. Results from climate change scenarios (Oleson, 2012) showed that urban and rural areas respond differently to climate change, with urban areas having more warm nights.

Water bodies and vegetated areas, such as forests, parks, and gardens, provide fresh, cool air for urban populations (Tratalos et al., 2007). Vegetation helps to moderate the microclimate and cools the environment mainly through evapotranspiration,

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*Corresponding author (madhumitha.jaganmohan@ufz.de).

M. Jaganmohan, C.M. Buchmann, and N. Schwarz, UFZ- Helmholtz Centre for Environmental Research, Dep. of Computational Landscape Ecology, Permoserstrasse 15, 04318 Leipzig, Germany; S. Knapp, UFZ-Helmholtz Centre for Environmental Research, Dep. of Community Ecology, Theodor-Lieser-Str. 4, 06120 Halle (Saale), Germany. Assigned to Associate Editor Carlo Calfapietra.

Abbreviations: AIC, Akaike information criterion; MSI, mean shape index; PWD, park-width distance; UHI, urban heat island.

shading, a low thermal storage capacity, and re-radiation of less heat compared with nonvegetated structures (Spronken-Smith and Oke, 1998). Local climate regulation is a valuable ecosystem service provided by green spaces for urban residents because it reduces the UHI effect and therefore is important for maintaining quality of life and adapting to climate change (Gill et al., 2007; Bowler et al., 2010). The cooling effect of green spaces, which is easily perceived by urban residents, is a regulating ecosystem service (TEEB, 2010) that can help mitigate heat stress (Lafortezza et al., 2009).

Local climate regulation is mostly quantified using air temperatures or land surface temperatures. Air temperatures and land surface temperatures in urban areas show some similarities in terms of their relationship to land cover/use (Schwarz et al., 2012) but are different with respect to lawns (Yilmaz et al., 2008) and exhibit different diurnal patterns (Roth et al., 1989) and are perceived differently by the urban population. To assess the cooling effect of green spaces as immediately perceived by the population, our study uses air temperature measurements. For the air temperature measurements, direct assessments using mobile (Arnfield, 2003; Chang et al., 2007) and fixed (Yu and Hien, 2006; Hamada and Ohta, 2010) temperature probes have been commonly used in the literature. Mobile measurements have been performed either by walking (Lu et al., 2012) or by using an automobile (Saito et al., 1991; Upmanis et al., 1998) to collect temperature readings at various intervals along a defined transect during the day or night. Saaroni et al., 2000 found air temperature variations of 3 to 5°C between the city center and the surrounding areas in Tel Aviv. Studies that looked at the seasonal temperature gradients have primarily used fixed sensors placed inside a green space and in reference stations in built-up areas (Hamada and Ohta, 2010).

The cooling effects of urban green spaces are often calculated as the difference in the temperature of the reference station versus the green space. This thermal contrast has multiple names in the literature; for example, it has been referred to as a "park cool island" (Spronken-Smith and Oke, 1998), the "park cooling intensity" (Lu et al., 2012; Feyisa et al., 2014), the "cool-island effect" (Hamada and Ohta, 2010), and the "local cool/heat island intensity" (Chang et al., 2007). Often, the reference point is chosen at a meteorological site (Cohen et al., 2012), the city center or central business district (Lee et al., 2009), or at the park-width distance (PWD) from the boundary of the green space (Chang et al., 2007). The PWD is defined as a distance that is the square root of the area of the green space. This is because studies have shown that the cooling effect of the green space is extended beyond the boundary, and its impact is extended to roughly one PWD (Jauregui, 1991; Spronken-Smith, 1994). Another indicator used to quantify the cooling effect is the cooling distance (Chen et al., 2012; Feyisa et al., 2014), which uses a polynomial fitted to the temperature data points and is mainly a measure of the maximum distance of the detected cooling effect. One study also obtained average temperatures at different locations using temperature probes fixed at various equidistant locations throughout the green and built-up areas (Yu and Hien, 2006).

Many studies have shown that green spaces can mitigate the UHI effect considerably; a maximum nocturnal air temperature difference of 5.9°C was observed over a distance of approximately 1.5 km in Gothenburg, Sweden (Upmanis et al., 1998). In Seoul, there was a cooling effect of 2°C/100 m between a green space and the central business district area (Lee et al., 2009). In Israel, 11 different wooded sites were examined in summer, and the cooling effects of the wooded areas, which were attributed to shading at noon, averaged 2.5°C within a distance of 100 m (Shashua-bar and Hoffman, 2000). A large park in Mexico was found to be 2 to 3°C cooler than its surroundings, and the cooling effect extended to approximately 2 km, which equates to approximately one PWD (Jauregui, 1991). The presence of a water body in an urban park in Tel Aviv (Saaroni and Ziv, 2003) was found to show a cooling effect up to 40 m downwind of the pond during daytime hours under dry and humid hot weather conditions within the urban park.

However, regardless of the number of studies, most studies on the cooling effects of urban green spaces only considered a single green space (Jauregui, 1991; Lee et al., 2009; Chow et al., 2011; Skoulika et al., 2014), and a limited number of studies considered the characteristics of the surrounding areas (Hamada and Ohta, 2010; Bowler et al., 2010; Chen et al., 2012; Feyisa et al., 2014).

The cooling effects of urban green spaces were found to be related to certain characteristics of a green space, such as the vegetation cover and the vegetation structure (trees, shrubs, grass) (Spronken-Smith and Oke, 1998; Chang et al., 2007; Shashua-Bar et al., 2009). Additionally, the effects of the individual tree species can differ, as indicated by a study on surface temperatures below the crowns of different tree species in the city of Basel, Switzerland. Lower crown temperatures were associated with trees with smaller leaves (Leuzinger et al., 2010). Grass was found to have a negative impact on the cool island intensity (Cao et al., 2010), and in the Mediterranean climate lawns were warmer during the daytime than tree parks but were cooler during the night (Cohen et al., 2012). Deciduous trees have a better cooling effect, and this effect is more pronounced in summer than in winter (Hamada and Ohta, 2010; Cohen et al., 2012). However, studies on the cooling effects of urban green spaces have historically considered only the amount of different land uses or land covers as well as vegetation cover but have not accounted for their spatial configuration in the urban landscape. Additionally, little research has been conducted to compare the different types of green spaces with different indicators for the cooling effects or to include the characteristics of both urban green spaces and their surroundings in explaining it. Thus, in this paper we aim to quantify and explain the influence that size and form (shape) of urban green spaces has on the cooling effects of green spaces. Furthermore, we take into consideration the type of green space (urban parks and urban forests), the tree and shrub coverage, and the presence of water bodies as well as characteristics of the residential areas surrounding the green spaces. Our analysis finally examines the performances of and relationships between the different indicators of the cooling effect. We used air temperature measurements to quantify the cooling effects as they are perceived by the residents living in the vicinity of different types of green spaces. Our hypotheses are as follows: (i) The indicators used to quantify the cooling effects are not strongly related to each other; (ii) urban green spaces have a cooling effect on the surrounding residential areas; (iii) both the characteristics of the green space and the characteristics of its surroundings influence the cooling effect; (iv) the cooling effect depends on the type of green space, with forests having a larger cooling effect than parks; and (v) the cooling effect increases with an increasing area and complexity of the shape of a green space.

Study Area

Leipzig (51°20′ N, 12°22′ E) is a city in the federal state of Saxony, Germany, with an administrative area of 297.4 km² and approximately 532,000 inhabitants. Leipzig lies at the confluence of the rivers White Elster, Pleisse, and Parthe, with its characteristic riparian forest running south through the city. The city landscape is mostly flat and is approximately 118 m above sea level. Leipzig has many forests and parks within the administrative region, but the area surrounding the city is largely unforested. Other prominent landscape elements in the city are agricultural sites, allotment gardens, and wetlands. The case study region has a temperate climate with a mean annual air temperature of 9.3°C, an absolute high air temperature of 35.4°C, and a low temperature of −15.3°C. The mean annual precipitation was approximately 670 mm for the year 2013. The number of days observed in 2013 with maximum air temperature ≥30°C (hot days) was 11, and the number of days with maximum air temperature ≥25°C (summer days) was 41 d. (Stadt Leipzig, 2014).

Materials and Methods

Land Cover Data and Selection of Green Spaces

Green spaces here are defined as delineated urban open spaces that are generally accessible to the public with the presence of vegetation and are selected from the map of habitat and land-use types of Leipzig from the year 2005. These maps are derived from aerial photographs showing land use at the time of recording. In Germany, such photographs are made regularly, and the habitat categories and land-use types derived from these photographs are commonly applied. We chose the categories "forest" and "park" as the types of green spaces to be used in our study. Leipzig is a very green city with many green spaces scattered around (29.1 km² of forests and 1.5 km² of parks in total). Therefore, we carefully selected our study sites as a stratified random sampling to obtain an unbiased distribution of green spaces with respect to the size of the green spaces, the complexity of their shape (quantified as the mean shape index [MSI]; i.e., the perimeter divided by the square root of the area), and the distance to the city center. The MSI of each individual green space, which indicates regularity, was calculated using Spatial Analyst of ArcGIS (version 10.1). It equals 1 for circular or square patches and increases with irregularity. In total, 37 parks and 25 forests were selected (Fig. 1). Because the land use differs from the city center to the outskirts, the distance to the city center was chosen as a stratum to have the sample sites evenly distributed geographically. Because the focus of this study is on the cooling effects of green spaces in residential areas, only those green spaces with more than 30% residential area in a 300-m buffer were selected. The types of residential areas covered in our study are categorized as "open mid-rise" and "compact mid-rise" for the semi-detached housing type and the dense housing type, respectively, according to the building types for the local climate zones (Stewart and Oke, 2012). The size, shape, distance to the city center, and distance between the boundary of the green space and the subsequent locations for the temperature measurements were calculated from the map of the habitat and land-use types. The amount of tree/shrub cover within the green spaces and surroundings was calculated using color-infrared imagery from the years 2012 and 2013 with a

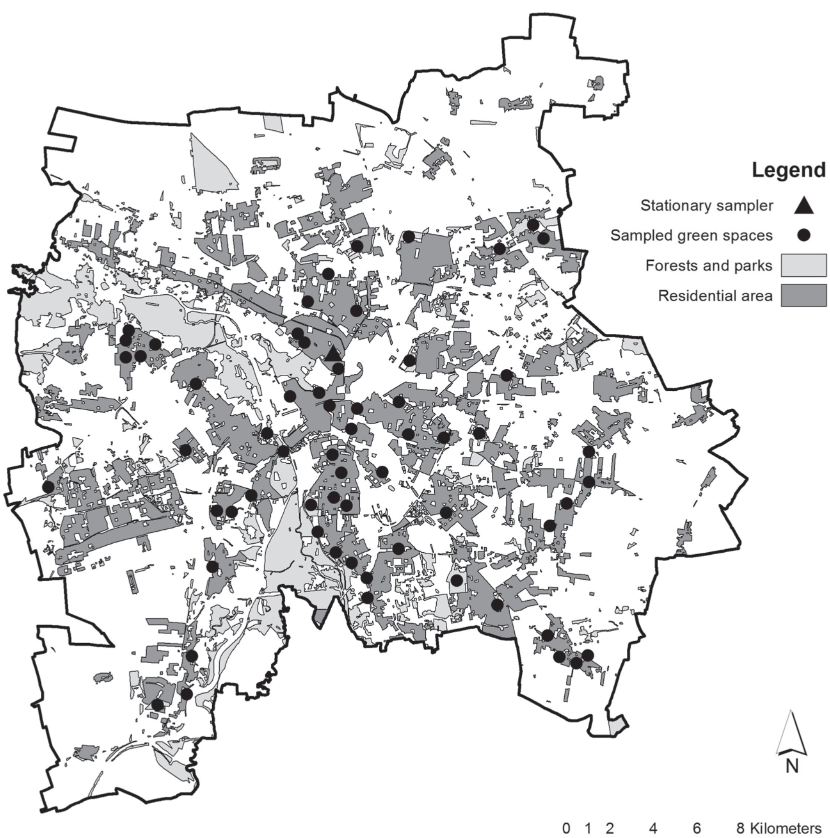

Fig. 1. Map of the habitat and land-use types in the city of Leipzig, Germany, showing the location of green spaces and of the stationary sampler used in this study.

60-cm resolution. Color-infrared imagery provides information on the location of every individual tree and shrub in the city, which is a level of precision that could not be gained from the map of the habitat and land-use types.

Air Temperature Sampling

The mobile temperature measurements were taken in the months of June to August 2013 on clear sunny days. The air temperature and humidity were measured using a Q-Trak 8552 monitor (TSI Inc.) with an accuracy of ±0.6K for air temperature and ±3.0% for relative humidity. The sensor was placed in a cylindrical tube and covered with silver foil to protect it from direct sunlight. Battery-operated ventilators at the bottom of the cylinder provided air circulation. The sensors, along with a data logger, were placed on a backpack at the height of 1 m from the ground (Schwarz et al., 2012). The transect routes and measurement times were recorded using a GPS device (Garmin GPSmap 60CSx). Wind measurements were performed using a Kestral 4000 Pocket Weather Tracker, which was also held at approximately 1 m from the ground.

Each green space was visited once during the sampling period. All of the temperature measurements were taken at an interval of 10 s. A transect of approximately 500 m (Lu et al., 2012) was chosen randomly, running from the boundary of a green space into the adjacent residential area along a street. The measurements along the entire transect took less than 20 min. The mean transect lengths were 547 and 505 m for the parks and forests, respectively. All of the measurements were performed between 9:00 AM and 5:00 PM.

One stationery sampler (Fig. 1) equipped with a temperature and humidity sensor and a data logger (OPUS10 TIC, Lufft) (accuracy ±0.3K and ±2.5% relative humidity) was mounted at a height of 1.5 m in a ventilated shelter that protected against solar radiation and precipitation (Schwarz et al., 2012). The mobile air temperature measurements were corrected to compensate for warming/cooling during the traverse by using the stationary temperature measurements collected at the time of the mobile measurements. The correction was done by subtracting the difference in air temperatures of the stationery measurement from the mobile measurement at that specific time.

Data Analysis

We identified various indicators of the cooling effects of specific green spaces. From the measurements mentioned before, a total of three indicators were derived and used in the analysis as dependent variables. The three indicators were (i) $\Delta T[PWD]$ (K), calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the PWD along the transect, with PWD being the square root of the area of the green space (Jauregui, 1991); (ii) $\Delta T[FIT]$ (K), which is the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route (this was calculated from the transect by a fitted polynomial function; see below); and (iii) cooling distance (m), which is the distance at which the maximum cooling is experienced from the boundary of the green space when fitted with a polynomial function (see below).

From the temperature measurements for each green space, the temperature difference (ΔT) was calculated by subtracting the temperature measurement taken at the boundary of a green space from each subsequent temperature measurement along the whole transect. The temperature trends found in the green spaces were of three main types: linear (Fig. 2A), flat (Fig. 2B), and increasing only up to a certain distance before flattening or decreasing again (Fig. 2C, D).

The temperature increase from the boundary to a maximum value ($\Delta T[FIT]$) and the cooling distance were fitted only for the third trend (i.e., $\Delta T[FIT]$) and the distance where ΔT reaches a maximum (i.e., the cooling distance) before flattening or decreasing again (Fig. 2C, D). The following procedure

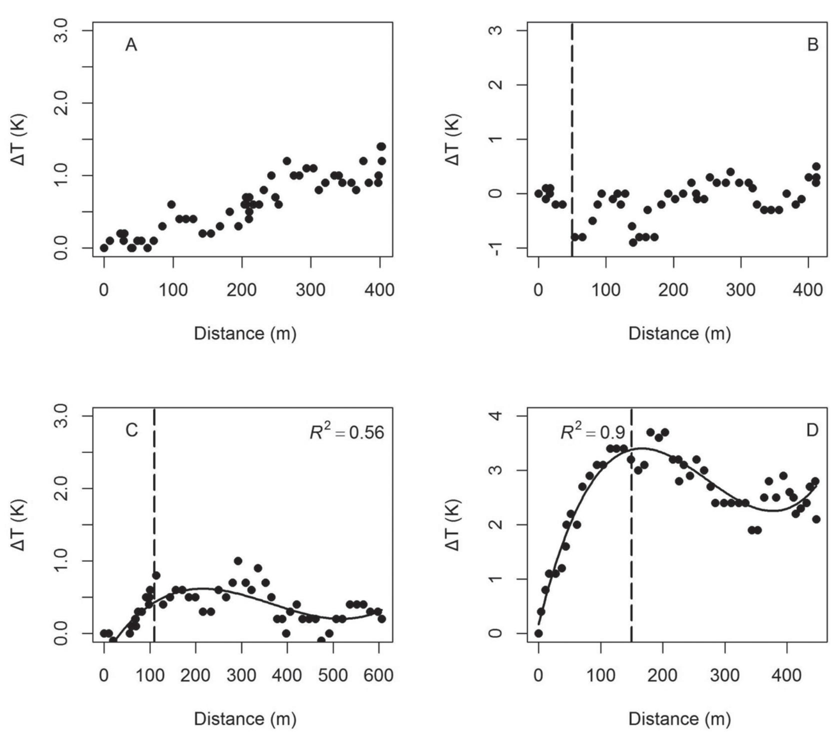

Fig. 2. The temperature difference (ΔT) for four green spaces, distinctively showing the high heterogeneity of the temperature gradients found for green spaces in Leipzig (the curve is a polynomial fit and its R^2 value; the dashed line is the park-width distance [PWD]). For (A) (linear) and (B) (flat), a polynomial was not fitted. For (A), the transect did not reach up to the PWD.

was performed. From the positive ΔT(K) values, a third-order polynomial was fitted to each transect dataset (Eq. [1]); the coefficients of the model were used to obtain values for the ΔT[FIT] (Eq. [2]) and the cooling distance (Eq. [3]) following the procedure proposed by Chen et al. (2012).

$$\Delta T\ (\text{distance}) = a^*\text{distance}^3 + b^*\text{distance}^2 + c^*\text{distance} \quad [1]$$

$$\Delta T[FIT] = \frac{2b^3 + 2b^2\sqrt{b^2-3ac} - 6ac\sqrt{b^2-3ac} - 9abc}{27a^2} \quad [2]$$

$$\text{Cooling distance} = \frac{-b-\sqrt{b^2-3ac}}{3a} \quad [3]$$

where a, b, and c are the fitting coefficients of the fitted polynomial.

To obtain the values specific to a particular sample site, selected small green spaces (n = 21) were fitted for the polynomial function only up to twice the PWD to prevent the influence of a temperature decrease due to other vegetated areas in the surroundings. For the green spaces that exhibited a negative or flat trend, the values of ΔT[FIT] and the cooling distance were set to zero (n = 11). The green spaces that showed a linear temperature trend (n = 3) were ignored for the calculation of the cooling effect for ΔT[FIT] and the cooling distance. The green spaces that were so large that PWD was not reached within the 500-m transect (n = 2) were ignored for the cooling effect of ΔT[PWD].

To examine the influence of the characteristics of green spaces and their residential surroundings on the observed cooling effect, multiple regressions were used. The ΔT[FIT], cooling distance, and the ΔT[PWD] were used as dependent variables, and the type of green space (forest or park), the area, and the MSI were used as independent variables. Furthermore, the following variables were taken into consideration to account for other characteristics of the green space and the surroundings: the percentage of tree/shrub cover, the area of water bodies, the distance to the city center, the sampling month, the average wind speed of the transect, the percentage of tree/shrub cover in a 25-m buffer around the transect, and the type of housing (dense or semi-detached). An overview of all independent variables used in the model is provided in Table 1. Instead of the actual air temperature measurements, all of the analyses of the microclimate data used the temperature differences, which were corrected using the temperatures measured at the stationary sampler to compensate for warming/cooling throughout the transect. A statistical analysis was performed using the R language environment for the statistical computing version 3.1.2 (R Core Team, 2014).

Results

On average, for the ΔT[FIT], a cooling effect of 0.8K (range, 0.0–3.3K) was observed for forests, and a cooling effect of 0.5K (range, 0.0–3.2K) was observed for parks. A maximum cooling distance of 469 m for forests and 391 m for parks was estimated. The ΔT[PWD] for forests was averaged at 0.3K (range −0.7 to 1.9K) and for parks it was averaged at 0.1K (range, −0.7 to 3.2K).

Hypothesis 1: Relationship of Indicators to Quantify the Cooling Effect

Hypothesis 1 states that the indicators used to quantify the cooling effects are not strongly related to each other. Spearman correlations between the different indicators for quantifying the cooling effect indicate significant positive correlations (rs = 0.8; $p < 0.001$ for both the ΔT[PWD] and the ΔT[FIT] as well as for the ΔT[FIT] and cooling distance). An increase in the ΔT[FIT] is related to increases in the ΔT[PWD] (Fig. 3A) and the cooling distance (Fig. 3B), but the differences for forests and parks, as indicated with the separate fitted lines, are

Table 1. Independent variables that are used in the model with their minimum, maximum, and median values.

	Forests			Parks		
	Min.	Median	Max.	Min.	Median	Max.
Area, ha	0.4	2.2	35.6	0.2	0.8	3.4
Shape (mean shape index)	1.1	1.4	2.5	1.1	1.2	1.9
Percentage of tree/shrub cover	56.0	96.5	99.6	39.1	74.0	99.8
Total area of waterbody, ha	0.08	0	1.2	0.07	0	0.8
Distance to city center, m	1876	5589	9885	359	3928	9778
Percentage of tree/shrub cover in 25-m buffer	12.31	39.11	52.76	11.04	28.62	53.00
Average wind speed of transect, m s^{-1}	0.2	0.82	2.26	0.06	0.8	1.54

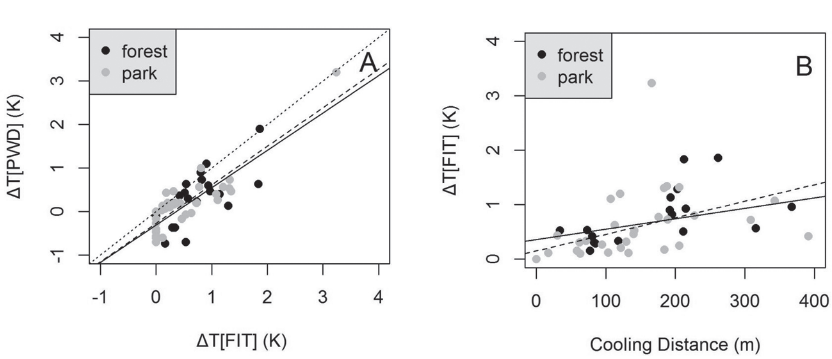

Fig. 3. The relationships between the various indicators for quantifying the cooling effect. (A) The bisecting line (dotted line) demonstrates perfect agreement of the two different measures of the temperature difference. The lines represent the slopes for the forests (bold line) and the parks (dashed line). ΔT[FIT] is the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route. ΔT[PWD] is calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance (PWD) along the transect, with PWD being the square root of the area of the green space.

not strong. However, there is a remarkable degree of scatter, indicating that the two variables cannot simply be replaced by each other. Therefore, the scatter plots imply that the three different indicators do not exactly measure the same aspects of the cooling effect, and a broad variety in the relationship between the indicators and the effects is present. This holds especially true for the cooling distance versus the temperature differences (Fig. 3B). A comparison of the PWD and the cooling distance shows considerable differences (Fig. 4), especially for parks; the PWD strongly overestimates the cooling distance as fitted from the observed temperatures. Hence, hypothesis 1 was confirmed, and all three indicators will be explored further in the remainder of this study.

Hypothesis 2: Presence of the Cooling Effects of Green Spaces

Hypothesis 2 states that urban green spaces have a cooling effect that extends into the surrounding residential area. To test that hypothesis, we analyzed both the ΔT[FIT] and the ΔT[PWD]. We consider a green space to have a cooling effect if the indicator has a positive value; if the value is 0 (ΔT[FIT], ΔT[PWD]) or negative (ΔT[PWD]), the green space has a warming effect. Out of the 58 urban green spaces with complete datasets, 39 were considered to have a cooling effect for both indicators, and 8 had a cooling effect only for the ΔT[FIT] indicator; meanwhile, the ΔT[PWD] indicated a warming effect for the same green spaces. None of the green spaces showed any warming indicated by ΔT[FIT] and cooling by ΔT[PWD]. In total, 11 urban green spaces were found to have a warming effect for both indicators. Thus, a considerable portion of the urban green spaces did not provide a cooling effect that extended into the surrounding residential areas. This indicates (i) that there are differences in the cooling and warming effects between different urban green spaces and (ii) that the assessment depends on the calculation method. The different characteristics of the urban green spaces and their surroundings may be the main factors influencing their cooling effects. However, in this study we found a significant influence on the warming/cooling effect only from the size (Fig. 5, 6). The warmer green spaces were generally smaller in size and did not have any bodies of water in them. In summary, the measurements provided some support for hypothesis 2, and they indicated that a considerable portion of the urban green spaces does not have a cooling effect that extends into the surroundings.

Hypotheses 3, 4, and 5: Explaining the Cooling Effects

To explore hypotheses 3, 4, and 5, multiple linear regressions were fitted to explain the cooling effects with different independent variables. The initial models included all of the independent variables, but they were reduced to a minimal adequate version according to the Akaike's information criterion (AIC) (Mac Nally, 2000). The AIC is used to compare models: the lower the AIC, the better the fit of the model. The automated model simplification is done using "step" function in R. A comparative summary of the minimum adequate models after a stepwise reduction is given in Table 2. The R^2 values are highest for the cooling distance (0.51) and lower for the temperature differences (ΔT[FIT] = 0.35 and ΔT[PWD] = 0.05). Because the R^2 values of the ΔT[PWD] model were found to be very low, the results of this model are not discussed below.

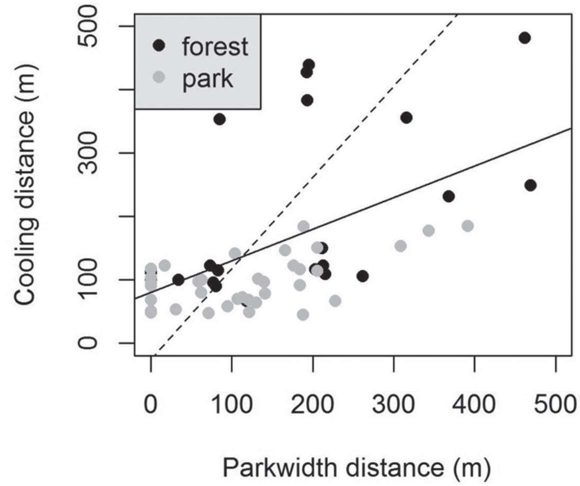

Fig. 4. Comparison between the park-width distance and the cooling distance. The lines represent the slopes for the forests (bold line) and the parks (dashed line).

Hypothesis 3: Effects of Surroundings and Green Space Characteristics

Hypothesis 3 states that the characteristics of the green space and its surroundings influence the cooling effects. The residential surroundings of urban green spaces are characterized by their distance to the city center, the type of housing, and the percent tree/shrub coverage within a 25-m buffer around the measurement transects. Table 2 indicates that the characteristics of the surroundings are of medium importance for the cooling effects. The distance to the city center was not included in the minimal adequate models. The type of housing was only included for the cooling distance. Compared with dense housing, semi-detached housing implies a cooling distance that is approximately 50 m shorter. Tree/shrub cover in the 25-m buffer was found to be important for both the cooling distance and the ΔT[FIT] model, whereby the increased tree/shrub coverage on streets indicates a larger cooling effect. Furthermore, the measurement-specific variable "sampling month" was not included in any of the final models. Regarding wind speed in the ΔT[FIT] model, a higher wind speed implied a lower temperature difference between the green spaces and the surroundings. Thus, hypothesis 3 is only partly valid for the characteristics of the surroundings; the characteristics of the green spaces themselves were included in the final models. Other green space characteristics, namely the percent tree/shrub coverage within the green space and the size of the body of water, slightly decreased the cooling distance. The effects of the type, size, and shape of the green space are presented in more detail in the following hypotheses.

Hypothesis 4: Parks versus Forests

Hypothesis 4 states that the cooling effect depends on the type of green space, with forests having a larger cooling effect than parks. For all three indicators, the cooling effect was higher in the forests than in the parks (Fig. 7). This finding was also confirmed using the multiple regression model (Table 2), where the slope given for the cooling effect of the parks was smaller than

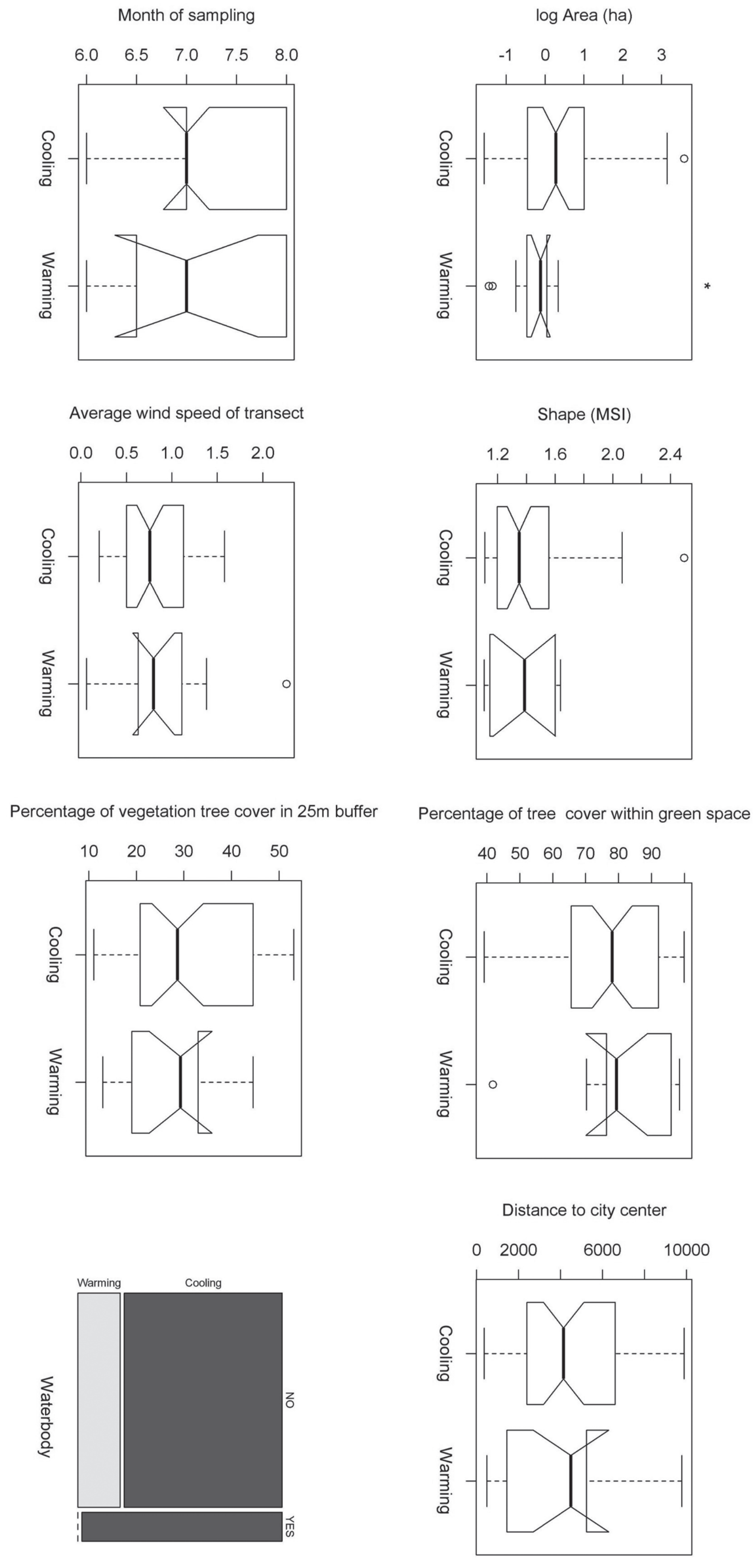

Fig. 5. Box plots and mosaic plot showing a comparison of the cooling and warming green space using the ΔT[FIT] indicator (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) with respect to various independent variables. The asterisk above a box plot indicates a statistically significant difference between cooling and warming green spaces. The notch marks the 95% confidence interval for the medians. MSI, mean shape index.

the slope for the forests in both the ΔT[FIT] and cooling distance models. This shows that forests provide greater cooling effects with higher mean ΔT[FIT] values and larger cooling distances than parks. Thus, hypothesis 4 was confirmed: forests have a larger cooling effect than parks.

Hypothesis 5: Size and Shape of Green Spaces

Hypothesis 5 states that the cooling effect increases with the increasing area and complexity (shape) of the green spaces. The interaction between the size and shape shows a positive effect on the ΔT[FIT] and a negative effect on the cooling distance regardless of whether a green space is a forest or a park. However, this interaction alone does not tell us whether the area and shape of a green space has a positive or negative effect on the ΔT[FIT] or the cooling distance. To test this and to refine visual interpretation (Fig. 8), we considered simple slopes (e.g., Bauer and Curran, 2005). These showed that the increasing complexity of a green space has a negative effect on the ΔT[FIT] for green spaces smaller than 5.6 ha, but it has a positive effect on the ΔT[FIT] for green spaces larger than 5.6 ha (e.g., the minimal adequate model; Table 2 shows that the simple slope for the MSI in the ΔT[FIT] model equals $-0.28 + 0.05 \times$ area, which is >0 for areas >5.6 and <0 for areas <5.6). This suggests that a complex green space provides a smaller cooling effect when it is small but not for larger green spaces. The opposite relationship is shown for cooling distance, with a positive effect from the complexity for green spaces smaller than 6.27 ha and a negative effect for green spaces larger than 6.27 ha (e.g., the minimal adequate model; Table 2 shows that the simple slope for the MSI in the cooling distance model equals $45.13 - 7.2 \times$ area, which is >0 for area <6.27 and <0 for area >6.27). Thus, we cannot accept that increases in both area and shape increase the cooling effect, as suggested by hypothesis 5; rather, we found a more complex pattern of relationships.

Discussion

Quantifying the Cooling Effects

The most frequently used indicator of the cooling effect is the thermal contrast between urban and green spaces ($\Delta T_{u\text{-}p}$). In our study, we focused on the temperature gradient and used the following different measures: the temperature difference at PWD and the green space boundary, a calculated fitted maximum temperature difference, and cooling distance calculated from the mobile air temperature measurements. The derivation of the cooling distance has been attempted in very few studies (Chen et al., 2012; Feyisa et al., 2014) even though it is an important indicator of the cooling effect. As seen from our results regarding hypothesis 1, the ΔT[PWD] and the ΔT[FIT] varied among green spaces. Furthermore, we found that the cooling distance (i.e., the distance from the boundary of the green space with the maximum temperature difference) is not identical to the PWD, which is a strong indication that focusing only on the ΔT[PWD] misses important information on the actual cooling effect of an urban green space. Additionally, our regression analysis revealed that the ΔT[PWD] cannot be explained with the characteristics of the green space and its surroundings, which was also found by Chang et al. (2007) for the characteristics of the green space alone.

With the fitted indicators, we see that some of the green spaces with larger cooling distances had low ΔT[FIT] and vice versa (Fig. 3B). This demonstrates that there is a considerable amount of variation in the relationship between the cooling distance and the temperature differences, indicating the necessity for evaluating both aspects for the proper quantification of the cooling effects. This is attributed to the heterogeneity and complexity of urban environments, which results in the varied temperature profiles shown in Fig. 2. We attempted to tackle this urban complexity by including in this study the various factors that could influence the cooling effects.

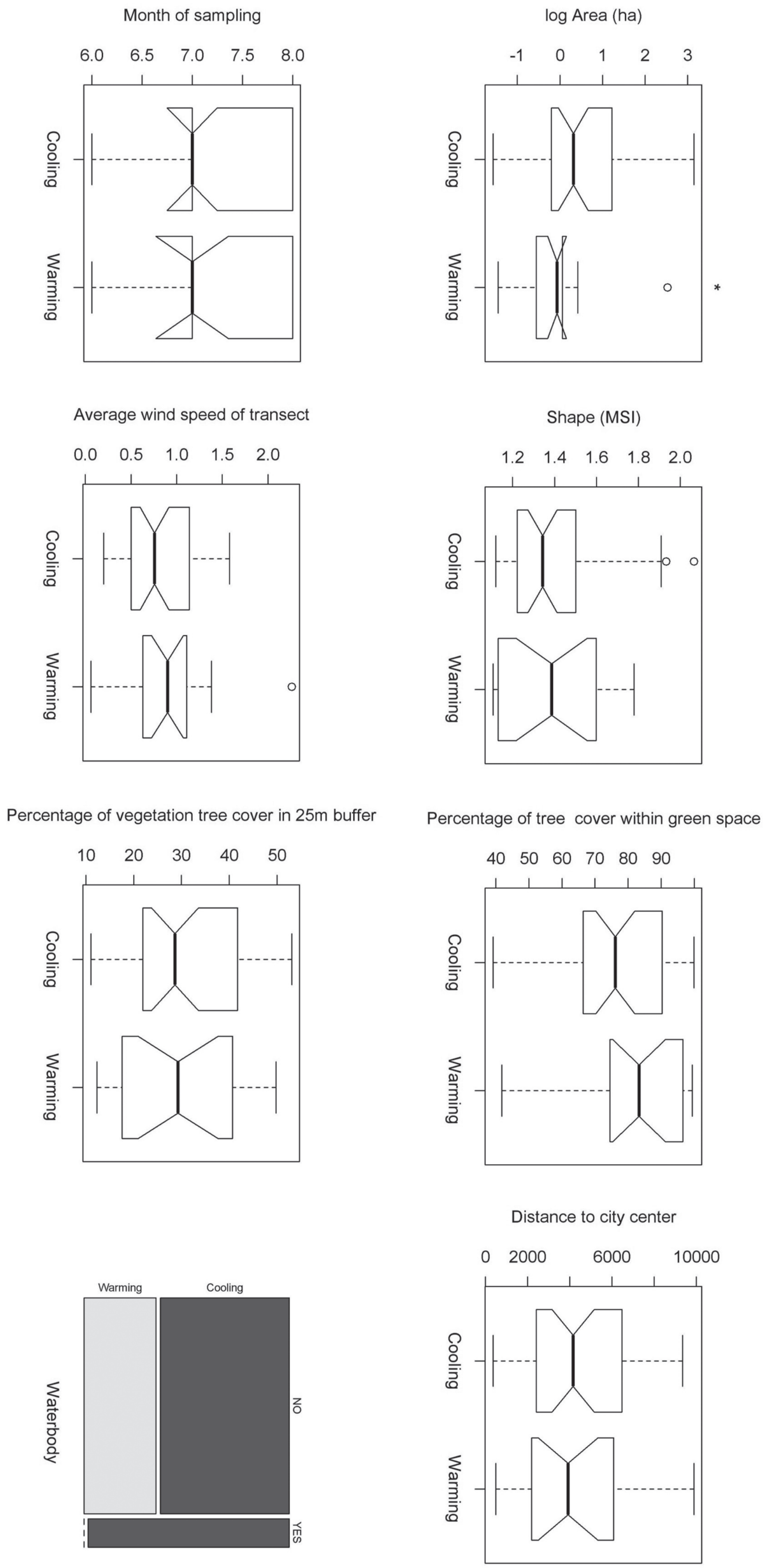

Fig. 6. Box plots and mosaic plot showing a comparison of the cooling and warming green spaces using the ΔT[PWD] indicator (calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance [PWD] along the transect, with PWD being the square root of the area of the green space) with respect to various independent variables. The asterisk above a box plot indicates a statistically significant difference between cooling and warming green spaces. The notch marks the 95% confidence interval for the medians. MSI, mean shape index.

Influence of Urban Green Space Design

Our results show that urban green spaces are cooler than their surroundings in most cases and thus they provide a cooling effect. However, our study confirms the finding of other studies (Potchter et al., 2006; Chang et al., 2007) that not all green spaces provide cooling effects (see results regarding hypothesis 2). Our regression analysis revealed the following aspects that are considered important for urban green space design: (i) forests provide a higher cooling effect than parks (hypothesis 4) and (ii) the influence of area on the cooling effect is complex (hypothesis 5). Further, the effect of area on cooling is dependent on the type of green space (e.g., for parks, an increase in the cooling effect as area increases is stronger than for forests [Fig. 7]). In addition, the area variable interacts with the shape variable regarding the cooling effect. The increasing complexity of smaller green spaces has a negative effect on the ΔT[FIT] but a positive effect for green spaces >5.6 ha. The relationship of area and shape is opposite for the cooling distance, with a slightly different threshold of 6.3 ha, meaning that the increasing complexity for small green spaces has a positive effect on the cooling distance and vice versa. A trade-off exists when designing

Table 2. A multiple linear regression (final models) showing the relationship between the ΔT[FIT], the cooling distance, and the ΔT[PWD] and the variables characterizing the green spaces, their residential surroundings, and the measurement specifics in the city of Leipzig, Germany.

	Model ΔT[FIT]†	Model cooling distance	Model ΔT[PWD]‡
R^2	0.35	0.51	0.05
Adj. R^2	0.26	0.42	0.04
Intercept	1.04	313.35**	0.14
Urban green space characteristics			
Type of green space (park)	−0.40	−159.30***	–§
Area	−0.07	17.96*	0.03¶
Shape (mean shape index)	−0.28	45.13	–
Interaction			
Type of green space (park):area	0.20¶	72.48***	–
Type of green space (park):shape	–	–	–
Area:shape	0.05*	−7.2¶	–
Type of green space (park):area:shape	–	–	–
Percentage of tree/shrub cover within green space	–	−2.90**	–
Area of waterbody	–	−131.15*	–
Surrounding characteristics			
Distance to city center	–	–	–
Type of housing (semi-detached)	–	−51.74	–
Percentage of tree/shrub cover in 25-m buffer	0.01	1.92	–
Other variables			
Month of sampling	–	–	–
Average wind speed of transect	−0.31	–	–

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Maximum temperature difference between the green space boundary and the surrounding area measured within the transect route.

‡ Calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance (PWD) along the transect, with PWD being the square root of the area of the green space.

§ – Variable not included in the final model. The model included the interaction between the type of green space × area × shape, and the coefficients indicate how different the parks are from the forests.

¶ Significant at the 0.1 probability level.

urban green spaces: one can either increase the absolute temperature difference between the green space and the residential surroundings at the cost of a smaller area of influence (i.e., a shorter cooling distance), or one can increase the distance to which a temperature reduction is noticeable at the cost of an overall decrease in the temperature difference. This trade-off for smaller green spaces is likely because an increase in the shape irregularity provides a longer interface between a green space and its surroundings. This provides more opportunities for cooler air to influence the residential surroundings; however, it also means that more cool air can be transported away from the green space, thus reducing the maximum temperature difference. Why this process is opposite for larger green spaces needs to be investigated in future studies. Similar studies have found the area of the green space to be the primary factor influencing the cooling intensity, and the effect is obvious when the area exceeds 14 ha (Lu et al., 2012); green spaces above 3 ha were more consistently cooler than their surroundings (Chang et al., 2007).

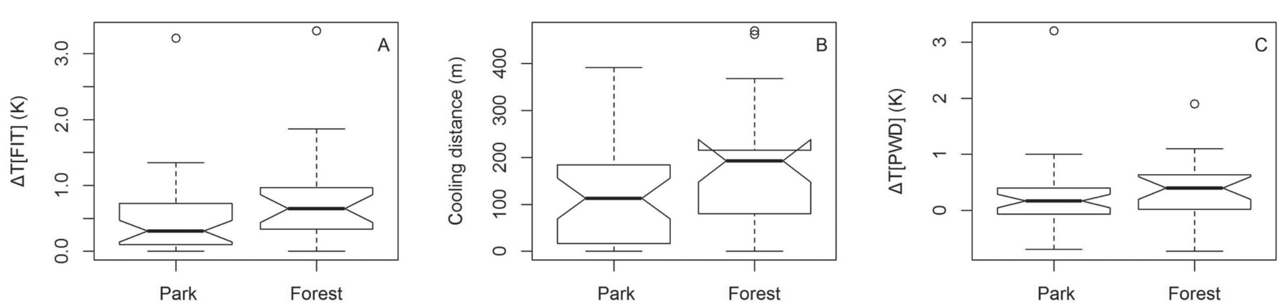

Fig. 7. Box plots showing a comparison of the parks and forests with respect to cooling distance and the temperature differences ΔT[FIT] (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) and ΔT[PWD] (calculated by subtracting the mean temperature measurement taken at the boundary of the green space from the temperature measured at the park-width distance [PWD] along the transect, with PWD being the square root of the area of the green space). The horizontal line indicates the median cooling effect for each type of vegetation; the notch marks the 95% confidence interval for the medians.

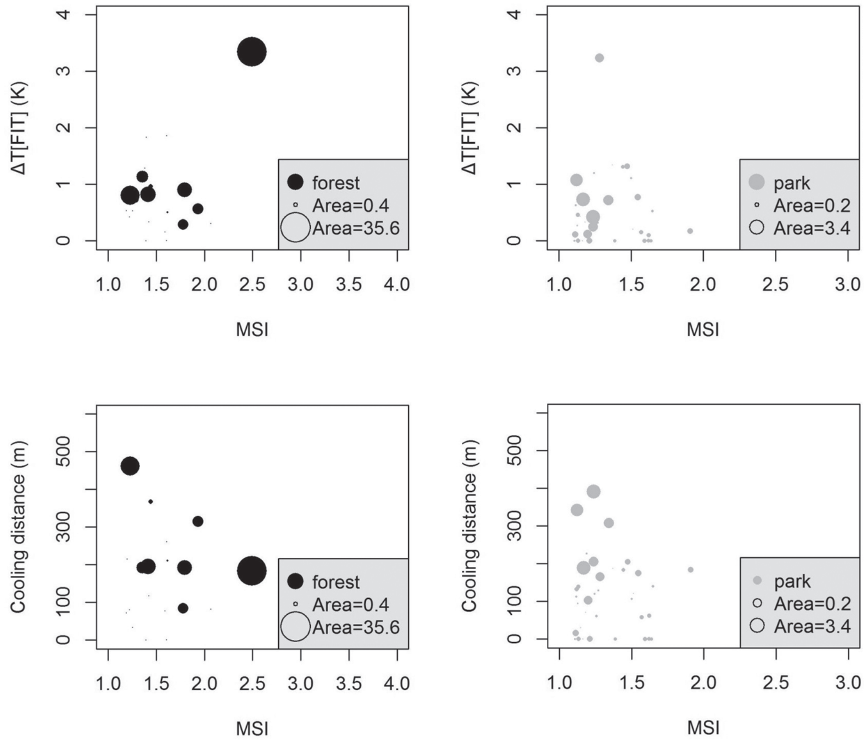

Fig. 8. Scatter plots showing the relationship of ΔT[FIT] (i.e., the maximum temperature difference between the green space boundary and the surrounding area measured within the transect route) and cooling distance with the mean shape index (MSI) of green spaces. The larger the points, the larger the area, indicating increasing size.

Third, an increase in tree/shrub coverage within a green space reduces the cooling distance, which is quite surprising. This could be due to a lower albedo of vegetation in the green space compared with the surroundings during the daytime. Also, the cooling distance decreases with the increasing area of waterbody within green spaces.

Influence of Other Variables

The distance to the city center was insignificant for explaining the cooling effects. Therefore, regardless of the location of a green space in the city, green spaces provide a cooling effect. This is interesting because the UHI of Leipzig (Schwarz et al., 2012) indicates a decrease of absolute temperatures from the city center, which apparently does not affect the cooling function of urban green spaces.

There was a decrease in the cooling distance for residential areas characterized as semi-detached housing type compared with areas characterized by densely compacted housing. In the semi-detached housing locations, the composition of the residential area varies. The houses are apart from each other and have open spaces or residential gardens around them, and these residential open spaces should have a cooling effect themselves. This implies that the distance where the maximum temperature is measured is not close to the residential open spaces but might be affected by large streets or buildings close to the green space. This result differs from that of a comparative study in California between neighborhoods with varied tree cover; that study found that temperatures were slightly higher in neighborhoods with higher tree cover (Grimmond et al., 1996).

The increase in percentage of trees/shrubs in a 25-m buffer around the transects increased the cooling distance as well as the thermal contrast between green space boundary and its surroundings. Thus, linear vegetation structures, such as trees and bushes along roads, enhance the cooling effect.

The influence of wind speed on the temperature and humidity is highlighted in studies in Mexico (Jauregui, 1991) and Turkey (Yilmaz et al., 2008). In our study, the results show that an increase in wind speed decreases the difference in the temperature of a green space boundary and its surroundings, as expected (Watkins, 2002), because higher wind speeds cause turbulence, which mixes the air and reduces temperature gradients. The sampling month did not influence any of the cooling effect indicators, suggesting that during the summer season (June to August 2013), the results were stable on clear, sunny days, regardless of any slight variations in the wind speed.

Limitations

The present study was conducted during a period of 3 mo, and the green spaces were sampled on different days and at different times of the day. The simultaneous collection of synchronized air temperature measurements would be helpful to better compare the data. This, however, is not usually feasible with respect to manpower because many green spaces were sampled in our study. A study with the diurnal, seasonal, and annual variations of the cooling effect would be more helpful in explaining the importance of the shape and size of the green spaces. However, as it is very difficult to record air temperatures on a large scale with traditional site-measurement methods that use probes; remote sensing could be used as an alternative (Schwarz et al., 2012). Furthermore, other parameters, such as the sky view factor, architectural design, and other buildings characteristics, could be included in further studies. In our study, the measurements were not performed up to their potential cooling distances for some of the large forests, and the ΔT[PWD] was not computed for this reason. Therefore, our findings for very large forests are limited for this indicator. The study included mobile routes along transects in residential areas assuming that the data collected would represent a gradient within the built-up area and would accurately illustrate any meaningful influence from the characteristics of residential surroundings on the cooling effect of the green spaces. Our study might not have accounted for all facets of the urban environment; however, our study is the first to understand the effects of green space design using various cooling indicators.

Conclusions

This study investigated the influence of the cooling effects of urban green spaces on residential areas for 62 green spaces in the city of Leipzig, Germany. An investigation of different indicators to quantify the cooling effect revealed that the temperature differences between the boundaries of the green spaces and the temperatures at the PWD do not reliably illustrate the temperature gradient in the surroundings. We suggest analyzing the temperature patterns along an entire transect from a green space into the surroundings and calculating the maximum temperature and the distance at which this is found.

Furthermore, not all urban forests and parks were found to be cooler than their surroundings. The influence of the area and shape of the park is complex, hinting at a trade-off between maximizing temperature differences and the distance at which cooling is still noticeable. Urban planners will have to clearly specify the aim of any measure that should be taken with respect to cooling. In most cases, an increase in area leads to an increase in the cooling effect. This suggests that a number of small green spaces distributed throughout a city may not individually have a great cooling effect on their surroundings, but it still remains to be clarified whether they, in sum, might have a stronger or lesser cooling effect than a few larger green spaces. This indicates that urban planning for heat mitigation might not work along the same lines as urban planning for environmental justice (with many people having access to green spaces close to their homes, as discussed by Kabisch and Haase [2014]). Forests in general were found to provide higher maximum temperature differences and cooling distances than parks. The fact that urban forests provide better cooling than urban parks should be taken into account in urban planning. Shrinking cities, for example, often contain a number of brownfields. Because Leipzig had been a shrinking city for many years after German reunification, the city administration aimed at developing urban brownfields into urban forests to improve their recreational value (Arndt and Rink, 2013). Our results suggest that this is beneficial for heat mitigation. Future research should further investigate the role of large urban green spaces and the interactions between the area and shape with respect to cooling effects. Furthermore, the effect of the composition of tree species in the urban green spaces should also be taken into consideration because this is another valuable aspect of urban planning and green space design.

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