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Research Paper

Role of street trees in mitigating effects of heat and drought at highly sealed urban sites

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HIGHLIGHTS

- Species differ significantly in their ability to reduce thermal load.
- LAD and E_{max} were most appropriate to explain reductions in air temperature.
- One unit increase in LAD reduces surface temperature by 4.63 K.
- *Tilia* and *Corylus* exhibit the highest rates of E_{max} and LAD.
- Both species are the best options to reduce air and surface temperatures.

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ABSTRACT

Vegetation and trees in particular play a key role in mitigating thermal load in urban areas. The goals of this study were to analyse species-specific microclimatic effects and to identify the role of leaf-area-density, transpiration, and stomatal conductance for cooling effects at urban sites. Air temperature, relative humidity and surface temperature were used to study the effects of six tree species with similar age structure in a residential area with comparable site conditions. Transpiration, stomatal conductance and leaf-area density were measured during the summer months in 2013. Air temperatures and relative humidity were monitored for four trees per street in hourly intervals, and surface temperatures were recorded in the afternoon for three hot days on the shaded and unshaded asphalt surfaces beneath the trees.

Species differ significantly in their ability to reduce air and surface temperatures, as well as to increase relative humidity. Trees showing both a high leaf-area density and a high rate of transpiration are more effective in cooling the air temperatures. Differences in the surface temperatures of the tree shaded areas are more pronounced compared to the air temperatures. Thus, the surface temperatures of the full sun exposed areas are up to 15.2 K warmer than that in the tree shaded areas. The results provide information to decrease thermal load in urban areas for future tree planting by choosing species with high cooling potential. The highest cooling potential was measured for *Corylus colurna* and *Tilia cordata* '*Greenspire*' and the lowest for *Ulmus* × *hollandica* 'Lobel'.

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1. Introduction

In industrialised countries, the most of the population lives in urban areas. However, the urbanisation dynamics can be observed on a global scale, and the urban population will be more than twice the proportion of rural population by the year 2050 (United Nations, 2008). The built-up areas and urban infrastructure are typically constructed with impervious materials, such as concrete, asphalt, and bricks, which have commonly darker surfaces that modify the

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surface energy balance (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Oke, 1982; Souch & Souch, 1993). These material characteristics, the input of anthropogenic heat, the design of infrastructure and buildings and the lack of vegetation are the primary factors contributing to the 'urban heat island effect' (UHI effect) that induces high temperature, low humidity and changing wind and radiation conditions (Kuttler, 2008; Oke, 1982; Oke, Crowther, McNaughton, Monoteith, & Gardiner, 1989; Taha, 1997). However, modifications of climatic parameters depend on a multitude of large-scale factors, such as the geographical location and local-scale factors, including the size of the city, the density and roughness of urban structures and the thermo-physical properties of materials (Oke, 1982). In addition, the extent of heating and temperature fluctuation is strongly correlated to the type of surface material (Christen, Meier, & Scherer, 2011). Generally, higher temperatures caused by the UHI negatively affect human health and well-being, particularly in periods of heat during the summer months in the southern and middle latitudes (Kovats & Hajat, 2008; Stafoggia et al., 2008; Tomlinson, Chapman, Thornes, & Baker, 2011). An increased occurrence of heat stroke and mortality can be observed in the 2003 heat wave all over western and southern Europe but also in less severe events, such as the 1995 heat wave in Great Britain and 1994 heat wave in the Netherlands (Kovats & Hajat, 2008; Stafoggia et al., 2008). The predicted climate change will increase the intensity and frequency of heat waves and thus amplify the biophysical load (Kuttler, 2011). Detecting specific thermal stress risk on a spatial scale is of urgent need to lower thermal stress especially of vulnerable populations (Krüger et al., 2013). Municipalities, city planners and managers are therefore asked to find and develop innovative strategies for adaptation to climate change and to mitigate the negative effects of UHI. Apart from technical solutions such as modifications of infrastructure, insulation of buildings or the installation of irrigation systems, the integration and expansion of urban green is one effective way to boost the resilience to climate change (Gill, Handley, Ennos, & Pauleit, 2007). Tree canopies absorb and reflect solar radiation received by impervious urban materials, thereby lowering air and surface temperatures. Although tree shade only reduces air temperatures by 1–2 °C on warm and sunny days, perceived temperatures are significantly lower in the shade (Armson, Stringer, & Ennos, 2012). Globe temperature is more suitable to determine perceived heat than air temperature (Armson et al., 2012). Globe temperature, which is measured with a globe thermometer that integrates convection and radiation, is a helpful measure to evaluate human thermal comfort (Thorsson, Lindberg, Eliasson, & Holmer, 2007). The globe temperature, and thus perceived temperature, can be reduced by 5–7 °C by tree shade (Armson et al., 2012). Thus, human well-being and thermal comfort can be improved significantly by trees (Armson et al., 2012; Meier, Scherer, & Richters, 2010; Roy, Byrne, & Pickering, 2012; Shashua-Bar & Hoffman, 2000). Elderly people and children with a high susceptibility to health risks related to thermal stress may in particular profit from the implementation of urban green. Reductions in surface temperatures are still more pronounced, and tree shading can diminish surface temperatures by 12 °C on concrete (Armson et al., 2012). Compared to vegetated areas such as lawns or green spaces covered with trees, higher average daily surface temperatures ranging from 6 K for road surfaces to 14 K for metal roofs can been observed already in the beginning of the vegetation period (Christen et al., 2011). Because collection and convection of thermal energy are noticeably diminished in shaded areas, it is elementary to measure surface temperatures to quantify the role of trees in urban areas (Armson et al., 2012). Evapotranspiration, describing the sum of transpiration and evaporation, is an additional process approving the cooling effects resulting in a temperature decrease (Taha, 1997). Because leaf fall enables solar irradiance on surfaces during winter time and further warming of buildings can be promoted (Berry, Livesley, & Aye, 2013), we concentrate on deciduous tree species growing on streets in residential areas. Conifers are more threatened by the use of de-icing salt during winter time (Goodrich & Jacobi, 2012) and frequently exhibit sensitive reactions to air pollution (Rigling & Cherubini, 1999); for these reasons, deciduous trees are more common on street tree sites. Several studies have proved the mitigation effects of urban trees on air temperatures, humidity or surface temperatures (Georgi & Zafiriadis, 2006; Golden, Carlson, Kaloush, & Phelan, 2007; Leuzinger, Vogt, & Körner, 2010; Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010; Streiling & Matzarakis, 2003), but most regardless of trees species attributes such as growth and physical characteristics. Armson et al. (2012) indicated the importance of extending future research on the different tree species with diverging attributes, e.g., size and age. In this context the plantation of trees well adapted at the specific environmental conditions and a significant potential for reducing temperatures should be preferred.

The results for the tree species of pine oak, sugar maple, and walnut growing at urban street sites in Indiana, USA, confirm the cooling effects from 0.7 to 1.3 °C with maxima in the early afternoon and higher relative humidities up to 30% in the tree canopies (Souch & Souch, 1993). However, no significant linear relationships between the crown and climatic parameters nor differences among the species were found. This observation might be due to the similarities in growth characteristics of the chosen species, i.e., the spectrum of LAI (leaf-area index) ranged only from 3.73 to 4.35. The findings of Hardin and Jensen (2007) indicated that 62% of the variation in surface temperatures, as measured using thermal satellite imagery, was related to LAI. This finding means that every unit in LAI reduces surface temperature by 1.2 °C (Hardin & Jensen, 2007).

To be able to assess the effects of street trees on micro-climate, we focus on the measurements of relative humidity and air temperature in tree canopies as well as the road surface temperature of shaded and unshaded areas. Air temperature and relative humidity were considered during three summer months from June to August. During this time-horizon, different periods have to be observed because cooling effects can differ considerably in periods of cool and hot weather conditions as well as in day- and night-time (Armson et al., 2012; Bowler et al., 2010; Souch & Souch, 1993; Taha, Akbari, & Rosenfeld, 1991). Furthermore, the effects of urban trees on climatic parameters show a seasonal variation (Sung, 2013). LAD (leaf-area-density), transpiration and stomatal conductance were measured, allowing predictions of the cooling effects depending on these parameters, and further to evaluate the species-specific characteristics.

This study has therefore two main objectives: (i) the identification of species-specific microclimatic benefits and (ii) the investigation of relationships between microclimatic effects and the three parameters LAD, transpiration, and stomatal conductance. Based on the results of these two goals, a classification of six species should be achieved regarding their potential on cooling effects.

2. Materials and methods

2.1. Study site and species

The study was carried out in the city of Dresden, Germany. Dresden has a humid continental climate considered by the Köppen classification as Dfb with a mean annual temperature of approximately 9.2 °C and an annual precipitation below 700 mm for the period of 1961 to 1991 (Bernhofer, Matschullat, & Bobeth, 2009). In the year 2013, the climatic conditions differed considerably from the long-term means and are characterised by several extremes. Colder-than-average temperatures in March and above-average

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