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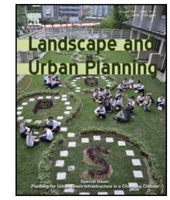

Research Paper

Effect of tree planting design and tree species on human thermal comfort in the tropics

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HIGHLIGHTS

- Single and clusters of trees are quantified on a quantitative manner.
- Thermal comfort conditions are strong influenced by solar radiation and wind.
- Must appropriate tree for the improvement of thermal comfort conditions are *Caesalpinia pluviosa*.
- Reduction of T_{mrt} can improve thermal comfort conditions about 16 °C (PET) during summer condition.

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ABSTRACT

Trees behave in different ways on microclimate due to mainly distinct features of each species and planting strategies especially in the tropics. This paper quantifies the daily and seasonal microclimate behavior of various tree species with different planting design either individual or in clusters. This specific knowledge is an important step in the development of urban design guidelines based on the shading of trees and climate adaptation in urban areas in the tropics. It focuses on human thermal comfort based on the physiologically equivalent temperature (PET) for different species. Twelve species were analyzed: *Handroanthus chrysotrichus* (Mart. ex A.DC.) Mattos, *Jacaranda mimosaefolia* D. Don., *Syzygium cumini* L., *Mangifera indica* L., *Pinus palustris* L., *Pinus coulteri* L.; *Lafoensia glyptocarpa* L., *Caesalpinia pluviosa* F., *Spathodea campanulata* P. Beauv., *Tipuana tipu* F., *Delonix indica* F. and *Senna siamea* L. The results show that shading of trees can influence significantly human thermal comfort expressed by (PET). The species *C. pluviosa* F. presents the best possibility in terms of PET because it can reduce between 12 and 16 °C for individual trees cluster can reduce between 12.5 and 14.5 °C. Appropriate vegetation used for shading public and private areas is essential to mitigate heat stress and can create better human thermal comfort especially in cities. The results can be seen as a possibility of improvement of outdoor thermal comfort conditions and as an important step in order to achieve sustainability in cities.

1. Introduction

An important characteristic of tropical cities is urban greenery that creates shading along streets and in residential areas and can assist in the development of adaptation possibilities against climate change. It also acts as a carbon sink, relative to the amount of green coverage (Abreu-Harbich, Labaki, & Matzarakis 2013a, 2013b; Emmanuel, 2005; Emmanuel, Rosenlund, & Johansson, 2007; Grimmond, 2007; Lin, Matzarakis, & Hwang, 2010). The characteristics of the various surfaces in urban spaces and their behavior with respect to incident solar radiation have serious impacts on the urban environment (Guderian, 2000). The study of vegetation in the control of incident solar radiation, and as a regulator of urban climatic changes involves qualifying and quantifying the influence of trees on human thermal comfort (Abreu-Harbich, Labaki, & Matzarakis, 2012; Matzarakis, 2013; Matzarakis & Endler, 2010; Shashua-Bar, Pearlmutter, & Erell, 2009; Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010; Streiling & Matzarakis, 2003; Yilmaz, Toy, Irmaka, & Yilmaz, 2007). Numerous studies focusing on trees and their benefits in urban environment have been published (Bernatzky, 1979; Cardelino & Chameides, 1990; Dimoudi & Nikolopoulou, 2003; Heisler, 1977; Herrington, 1977; McPherson, Nowak, & Rowantree, 1994; Meyer & Bauermel,

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1982; Montague & Kjelgren, 1998; Oke, 1989; Santamouris, 2001; Shashua-Bar & Hoffman, 2000; Shashua-Bar et al., 2010). Various methodologies confirm that vegetation can influence urban microclimate, improve human thermal comfort, and decrease the potential for health impairment of urban populations (Akbari, 2002; Akbari, Rosenfeld, Taha, & Gartland, 1996; Dimoudi & Nikolopoulou, 2003; Mayer, Salovey, & Caruso, 2008; Santamouris, 2001; Streiling & Matzarakis, 2003). Arboreal species behave in diverse ways in outdoor spaces, especially in terms of differences in shade, with previous studies quantifying these benefits (Bueno-Bartholomei & Labaki, 2003; Lin et al., 2010; Shahidan, Shariff, Jones, Salleh, & Abdullah, 2010; Shashua-Bar & Hoffman, 2000; Shashua-Bar et al., 2009, 2010).

Urban trees can modify air temperature, increase air humidity, reduce wind speed, and modify air pollutants (Streiling & Matzarakis, 2003). It has been confirmed that the positive effects on the bioclimatic conditions of a city, the mean radiant temperature (T_{mrt}) and the human biometeorological thermal index – the physiologically equivalent temperature (PET), of single trees and clusters are distinct because of differences between areas with trees and without trees. Local air temperature can be influenced by green coverage and leaf area index (LAI), which are important arboreal characteristics (Tsutsumi, Ishii, & Katayama, 2003). Some studies confirm that specific features of species, like structure and density of the treetop, size, shape and color of leaves, tree age and growth, can influence the performance of solar radiation attenuated by canopy, air temperature and air humidity (Abreu-Harbich et al., 2012; Bueno-Bartholomei & Labaki, 2003; Correa, Ruiz, Canton, & Lesino, 2012; Gulyás, Unger, & Matzarakis, 2006; Scudo, 2002; Shashua-Bar et al., 2009). Tree canopies are able to modify to microclimatic environments because of reflection, transmission and absorption of solar radiation and control wind speed (Steven, Biscoe, Jaggard, & Paruntu, 1986). In tropical climates, the possibility of changing wind conditions and shade will modify the microclimate and improve human thermal comfort (Lin et al., 2010).

In Brazil, it was recently concluded that outdoor thermal comfort is closely related to urban tree management (Spangenberg, Shinzato, Johansson, & Duarte, 2008). Various Brazilian researchers have used PET, but these indexes need to be adapted to the local climate (Monteiro & Alucci, 2010).

Studies have shown that shade and increase wind speed can improve human thermal comfort in tropical climates (Abreu-Harbich et al., 2013a; Akbari & Rose, 2008; Akbari & Taha, 1992; Lin et al., 2010). Therefore, planting trees is a good solution for improving thermal comfort in tropical cities.

The shade cast by trees, and the amount of radiation filtered, is influenced by the form and density of the canopy. The amount of radiation intercepted depends on the density of the twigs, branches, and leaf cover. These elements influence the overall characteristics of tree shape and density (Abreu-Harbich et al., 2012; Brown & Gillespie, 1995; Scudo, 2002). Tree shade qualities are also influenced by the individuality of trunks and of leaves, which should be considered (Abreu-Harbich et al., 2012; Shashua-Bar et al., 2010).

As an example, tree species in Brazil can attenuate solar radiation from 76.3 to 92.8% in the summer months (Abreu-Harbich et al., 2012; Bueno-Bartholomei & Labaki, 2003). These results confirm that the structure of the crown, and the dimension, shape and color of leaves influence the levels of reduction in solar radiation. It is important to observe the vegetation parameters which affect solar radiation and wind in relation to their thermal control strategies, and their different green elements (Table 1). It is also important to quantify the thermal conditions of trees with field measurements, and to combine these results with the tree features to improve green design. Accordingly, planting the right trees in the cities can improve and adapt the cities to climate change.

Our aim was to quantify the daily and seasonal microclimate behavior of various tree species in different planting configurations. Such knowledge is important in the development of urban design guidelines based on the shading of trees and climate adaptation in urban areas of the tropics. We have focused on thermal comfort of humans based on the PET for different tree species. We intend to quantify these affects by providing quantitative results, which can be applied in tropical regions.

2. Methodology

2.1. Study area

Our study was conducted in Campinas (22°48′57″ S; 47°03′33″ W; 640 m elevation), in the southeast of Brazil. It is one of the larger cities in the country, with 1.1 million inhabitants and a very high population density of 1300/km^2 (Brazil, 2010). The Köppen-Geiger climate classification of the city is subtropical (Cwa; Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), with less rainfall in winter, and rainy, warm-to-hot days in summer. Mean annual air temperature is 22.3 °C and annual rainfall 1411 mm. Rain is predominant from November to March, with dry periods of 30–60 days in July and August. The summer period is from November to April, with average maximum temperatures between 28.5 and 30.5 °C and minimum temperatures between 11.3 and 13.8 °C. The warmest month is February, with an average temperature of 24.9 °C (maximum 30.0 °C and minimum 19.9 °C). The winter season is June, July and August, with maximum temperatures between 24.8 and 29.1 °C and minimum between 11.3 and 13.8 °C. The coldest month is July, with an average temperature of 18.5 °C (maximum 24.8 °C and minimum 11.3 °C). The prevalent wind direction is southeast, with a mean annual speed of 1.4 m/s. Annual sunshine duration is 2373 h, and the mean daily solar radiation is 4.9 kWh/m^2. Weather variations in Campinas are caused by regional atmospheric circulation shifts and diverse topography. There are tropical, equatorial continental, tropical Atlantic (the most common) and polar (especially polar Atlantic) systems, and these modify the regional climate (Nunes, 1997).

2.2. Sites and observations

The scales adopted in field measurement for this research were instantaneous and microclimatic, which allowed for assessing weather conditions and not climate. However, the "*in loco*" climate, mainly within 1 km, was influenced by local environmental parameters (solar radiation, air temperature, relative humidity and wind speed), and by macroclimatic and mesoclimatic conditions. In studies concerned with qualifying and quantifying trees and their benefits at the micro scale, similar surrounding conditions should be considered: no shade from buildings or other trees; uniformity of conditions around trees related to topography, lack of pavement and buildings nearby; standardization of the surface at the measuring points; and time of exposure, with few or no clouds. The criteria for the choice of species to be studied were those most used in tree planting programs of the Campinas city government. Trees were required to meet the following conditions: mature; their physical characteristics were representative of their species; they were located in areas suitable for measurement; specifically unshaded by nearby trees or buildings; accessible topography and sufficient area for equipment around the species; and no interference by passers. The large gap of study different trees species is because they behave in different ways in microclimate. As well, it is necessary to consider the biodiversity for sustainability of urban green on cities.