Landscape and Urban Planning 123 (2014) 87–95

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa

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HIGHLIGHTS

- We evaluated relative cooling effects of urban parks and observed significant cooling differences.
- Cooling effects of green spaces mainly depended on species, canopy cover, size and shape of parks.
- Variation in cooling influence of urban parks was highest in the afternoon hours.
- Appropriate choice of species, geometry and size of parks may improve efficiency of urban warming.

ARTICLE INFO

Article history:
Received 25 May 2013
Received in revised form 6 December 2013
Accepted 13 December 2013
Available online 15 January 2014

Keywords:
Cooling intensity
Cooling distance, Microclimate
Surface temperature
Urban heat island
Vegetation

ABSTRACT

Urban green infrastructure can to a certain extent mitigate urban warming. However, the cooling effect of plants varies with space, time and plant-specific properties. To contribute to our understanding of the cooling effect of vegetation on urban surface and air temperature, 21 parks in Addis Ababa were studied. Air temperature and humidity were measured for 60 plots in nine of the parks for 15 days. Furthermore, the thermal band of Landsat ETM+ was used to examine the cooling impact of all 21 parks on a larger spatial scale. Linear mixed-effects models were used to examine the relationship between characteristics of the vegetation and observed temperature. It emerged that *Eucalyptus* sp. had a significantly higher cooling effect than any other species group ($P < 0.05$) and the species with the least effect on temperature were Grevillea and Cupressus. On a larger spatial scale, the cooling effect of parks on their surroundings (Park Cooling Intensity, PCI) was positively related to the NDVI and area of parks ($P < 0.01$). A negative relationship was observed between PCI and park shape index (SI). The range within which the cooling effect could be observed (Park Cooling Distance, PCD) was positively related to SI and park area. The maximum PCI was 6.72 °C and the maximum PCD was estimated at 240 m. We conclude that the cooling effect is mainly determined by species group, canopy cover, size and shape of parks. Thus, the study provides insights regarding the importance of species choice and spatial design of green spaces in cooling the environment.

Published by Elsevier B.V.

1. Introduction

Urbanization has brought about several undesirable environmental changes. In the process of urbanization, land cover changes and natural surfaces are replaced by the urban fabric which is characterized by higher temperatures than the surrounding rural environment, a pattern described as urban warming. A large body of urban climate studies have shown that thermal, optical and geometric properties of urban surfaces affect heat absorptive and radiative properties and lead to the so-called Urban Heat Island (UHI) effect (Coutts et al., 2007; Gartland, 2008; Krayenhoff & Voogt, 2007; Voogt & Oke, 2003).

High temperatures in urban areas affect health, economy, leisure activities and wellbeing of urban dwellers. In particular, the health of vulnerable people, such as the old and poor, is highly affected by thermal stress caused by warming (Hajat, Kovats, & Lachowycz, 2007; Patz, Campbell-Lendrum, Holloway, & Foley, 2005; Tan et al., 2010). Urban warming may also enhance air pollution, for example by increasing surface ozone concentration with several negative impacts on human health (Jacob & Winner, 2009; Weaver et al., 2009). Furthermore the magnitude and adverse effects of UHI may be intensified as a consequence of global warming (Corburn, 2009). In many tropical countries, where rapid urbanization is undergoing, the intensity and negative impacts of UHI are likely to be substantial (McGregor & Nieuwolt, 1998).

Various strategies are being implemented to improve thermal comfort of outdoor and indoor urban environments. Indoor air conditioning facilities may efficiently eliminate thermal stress. However, this strategy may, at the same time, enhance UHI by

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0169-2046/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.landurbplan.2013.12.008

releasing additional heat to the outdoor environment (Tremeac et al., 2012). A study by Shen, Chow, and Darkwa (2013) indicated that in the summer the cooling demand of a typical office building in Hangzhou metropolitan area of China would increase by 10.8% due to ambient temperature increasing by 0.5 °C. Similarly, a study by Akbari, Pomerantz, and Taha (2001) indicated that electricity consumption in US cities on average increases by 2–4% for every 1 °C increase in temperature and estimated that 5–10% of the urban electricity demand is spent on cooling buildings to compensate for 0.5–3.0 °C warming. The increased energy use for cooling may therefore cause other environmental problems such as increased carbon emission. In the context of global climate change, urban buildings are reported to be a major source of greenhouse gas emission (McKibben, 2007). Adaptive strategies of improving thermal environments, therefore, need to aim at lowering energy use in buildings, thereby also reducing carbon emissions (McKibben, 2007; Smith & Levermore, 2008).

Earlier studies have shown that urban green spaces such as parks can considerably mitigate the UHI effect (Georgi & Zafiriadis, 2006; Oliveira, Andrade, & Vaz, 2011; Susca, Gaffin, & Dell'Osso, 2011). The green vegetation can improve both indoor and outdoor thermal comfort, while at the same time providing multiple environmental services, such as carbon storage (Escobedo, Varela, Zhao, Wagner, & Zipperer, 2010; Jana, Biswas, Majumder, Roy, & Mazumdar, 2010; Ren et al., 2011), reduced air pollution (Tallis, Taylor, Sinnett, & Freer-Smith, 2011; Yin et al., 2011) and act as urban biodiversity hotspots (Cornelis & Hermy, 2004). Urban vegetation can also contribute to improving the quality of life and enhancing human well-being through exposure to the nature (Dallimer, Irvine, et al., 2012; Dallimer, Rouquette, et al., 2012). Integration of green spaces in urban planning and building designs may, therefore, be essential for adaptation to and mitigation of thermal impacts of both local and global warming processes.

Different levels of cooling by urban vegetation have been reported in the literature, depending on the methods used and the environments where under which studies are undertaken. Studies that involved ground-based air temperature measurements have shown park cooling effects of 1–7 °C (Chang et al., 2007; Shashua-Bar, Pearlmutter, & Erell, 2009). Studies involving remote sensing techniques where surface temperature data were derived from thermal infrared bands of satellite sensors also reported a large variation in cooling effects of urban green areas (Chen et al., 2012).

According to a review paper by Bowler, Buyung-Ali, Knight, & Pullin (2010), most studies on cooling effects of urban vegetation involved measurements within a single park, and only a limited number of studies have examined the cooling effect of parks on surrounding areas. An obvious factor limiting the application of time synchronized air temperature measurements within and at multiple distances from parks is the high cost of such study designs. Thermal remote sensors may, on the other hand, provide a time-synchronized estimate of surface temperature over entire urban surfaces. Estimation of surface temperature from remote sensors provides essential information regarding the thermal properties of land cover which modifies the air temperature of the lowermost part of the urban atmosphere (Voogt & Oke, 2003).

Recently, studies by Schwarz, Schlink, Franck, and Grossmann (2012) and Chen et al. (2012) showed that ground-based air temperature measurements and surface temperature estimated from thermal sensors are positively and significantly correlated. On the other hand, estimates of the cooling effects of vegetation from surface and air temperature measurements may produce different results. Urban climate studies clearly indicate a need for distinguishing between air temperature and surface temperature due to differences in the nature of the data acquisition and the information content of these data types (Arnfield, 2003; Voogt & Oke, 2003). Urban heat island studies based on surface temperature derived from thermal sensors such as those aboard the Landsat satellites are commonly used for assessing intensity of the surface heat island (SUHI), and for relating surface temperature with urban surface energy fluxes in order to characterize landscape properties, patterns, and processes (Quattrochi & Luvall, 1999). Surface temperature modulates the air temperature of the lowermost layers of urban atmosphere and determines surface radiation and energy exchange (Voogt & Oke, 1998). Analysis of thermal infrared data from satellite sensors offers essential information on thermal variation among vegetated surfaces and built-up and other non-vegetated environments by providing simultaneous observations and a dense grid of data across an entire city.

Complex processes are involved in determining the cooling effect of vegetation on daytime air and surface temperature. The vegetation cools the environment through evaporative cooling, shading effects, and its thermal and optical properties (Dimoudi & Nikolopoulou, 2003; Jonsson, 2004; Oke, 1988; Pearlmutter, Bitan, & Berliner, 1999). Compared to impervious surfaces, which generally have high thermal storage capacity and thermal conductivity, vegetation has low thermal storage and admittance (Oke, 1988; Spronken-Smith & Oke, 1999) and is therefore likely to emit less thermal radiation to the environment. However, the cooling impact of plants on air and surface temperature may vary with environmental factors and plant specific thermal and optical characteristics. Vegetation with highly reflective surfaces (high albedo) may reduce surface temperature by reducing the amount and intensity of thermal radiation which may also lower local and downwind ambient air temperatures because of smaller convective heat fluxes from cooler surfaces (Taha, 1997).

For instance, Oke (1988) indicated that coniferous forests have lower albedo compared to deciduous forests, the probable explanation being that conifers trap more radiation due to the rough leaf and canopy structure. An experimental study by Lin and Lin (2010) also indicated that the cooling efficiency of urban parks is mostly influenced by leaf color and foliage density. Plants growing in dry and hot environments have evolved to absorb less radiation through anatomical and physiological adaptations, thereby influencing the thermal environment in a different way than plants in more humid or colder environments (Oke, 1988). The amount of evaporative cooling and reduction in thermal infrared irradiation emitted from plant leaves likely vary with the evapotranspiration, which, among other things, varies considerably with season, climatic conditions and water availability at the local level (Debruin & Jacobs, 1993). Specific plant species have different adaptations and moisture conservation mechanisms (Pugnaire & Valladares, 2007); hence the thermal impact of different species on the environment is likely to vary.

Despite the contributions of research trying to understand the cooling effects of urban vegetation, generalization from the literature is difficult. In their systematic review of studies on thermal effects of urban green spaces, Bowler et al. (2010) noted that most studies have explored the cooling effects considering only one park. The same review paper also showed that only few studies provided data for sites located at different distances from park boundaries. Identifying the biophysical characteristics of vegetation which determine cooling efficiency may help urban planning to mitigate the UHI effect and improve quality of life in cities. Applying ground-based microclimate measurements and satellite remote sensing, the objectives of the present paper therefore are to: (1) examine the variation of the cooling effect of trees in parks and its relationship with tree species and biophysical site variables, (2) examine the thermal influence of green areas on surrounding environments and identify the main determinants of the thermal contrast and the maximum distance within which cooling can be detected.