Landscape and Urban Planning 128 (2014) 35–47

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Effects of spatial pattern of greenspace on urban cooling in a large metropolitan area of eastern China

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HIGHLIGHTS

- An optimal spatial scale for examining greenspace cooling effects was identified.
- The effect of greenspace configuration on the land surface temperature was quantified.
- Spatial configuration of a mainland-island greenspace enhances the cooling effect.
- Fragmented greenspace is also effective for cooling given a fixed amount of forest cover.
- Greenspace cooling intensity can indicate cool island characteristics well.

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form 16 April 2014
Accepted 24 April 2014
Available online 22 May 2014

Keywords:
Cooling effect
Landscape metrics
Landscape pattern
Urban greenspace
Urban heat island

ABSTRACT

Urban areas will experience the greatest increases in temperature resulting from climate change due to the urban heat island (UHI) effect. Urban greenspace mitigates the UHI and provides cooler microclimates. Field research has established that temperatures within parks or beneath trees can be cooler than in non-greenspaces, but little is known about the effects of the spatial pattern of greenspace on urban temperatures or the optimal spatial patterns needed to cool an urban environment. Here, urban cool islands (UCIs) and greenspace in Nanjing, China were identified from satellite data and the relationship between them analyzed using correlation analyses. The results indicate the following: (1) Areas with a higher percentage of forest-vegetation experience a greater cooling effect and a 10% increase in forest-vegetation area resulted in a decrease of about 0.83 °C in surface temperature; (2) A correlation analysis between mean patch size, patch density, and an aggregation index of forest vegetation with temperature reduction showed that for a fixed amount of forest vegetation, fragmented greenspaces also provide effective cooling; (3) The spatial pattern of UCIs was strongly correlated with greenspace patterns; a mainland-island greenspace spatial configuration provided an efficient means of enhancing the cooling effects; and (4) the intensity of the cooling effect was reflected in cool island characteristics. These findings will support better prediction of the effects of specific amounts and spatial arrangements of greenspace, helping city managers and planners mitigate increasing temperatures associated with climate change.

1. Introduction

Climate change predictions indicate that, in the near future, temperatures will rise and there will be an increased frequency and intensity of heat waves; as a result there will be negative effects on both human health and the environment (Luber & McGeehin, 2008; Oliveira, Andrade, & Vaz, 2011; Stott, Stone, & Allen, 2004; Tan et al., 2007; Yuan & Bauer, 2007). Large urban areas are warmer than the surrounding countryside – a phenomenon known as the urban heat island (UHI). The higher temperatures in an UHI result in reduced thermal comfort with an associated increased in energy consumption as measures are taken to cool homes and offices. UHIs can also serve as a trap for atmospheric pollutants, contribute to increased urban smog formation, and generate socioeconomic impacts on

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http://dx.doi.org/10.1016/j.landurbplan.2014.04.018
0169-2046/

communities all of which affect the quality of life of those living and working in urban areas (Alghannam & Al-Qahtnai, 2012; Gobakis et al., 2011; Mihalakakou, Santamouris, Papanikolaou, Cartalis, & Tsangrassoulis, 2004; Ng, Chen, Wang, & Yuan, 2012; Price, 1979, 1983). The predicted magnitude and speed of climate change over the next 30–40 years (Gill, Handley, Ennos, & Pauleit, 2007; Hulme et al., 2002), suggests an urgent need for the development of strategies to adapt to and mitigate the expected continual increase in temperature (Bowler, Buyung-Ali, Knight, & Pullin, 2010). Consequently, the role of urban greenspace in moderating urban climates is being studied extensively (Chen & Wong, 2006; Dimoudi & Nikolopoulou, 2003; Eliasson, 2000; Georgi & Dimitriou, 2010; Givoni, 1991; Hamada & Ohta, 2010; Oliveira et al., 2011; Zoulia, Santamouris, & Dimoudi, 2009) with researchers consistently suggesting that an effective way to reduce or alleviate the effects of UHIs is to increase tree cover area and density (Rosenfeld et al., 1995; Semrau, 1992). Vegetation, mainly through direct shading and evapotranspiration, can reduce temperatures and create a local cool island within an urban area (Oke, Crowther, McNaughton, Monteith, & Gardiner, 1989; Tyrväinen, Pauleit, Seeland, & de Vries, 2005). Vegetation in a city can also achieve other environmental benefits such as reduced storm water runoff, greater urban biodiversity, and improved esthetics (Kong, Yin, & Nakagoshi, 2007; Kong, Yin, Nakagoshi, & Zong, 2010).

Traditionally, on-site observation using fixed stations or mobile equipment has been widely used to investigate the cooling effect of greenspace. The type, size, and shape of greenspace patches, as well as tree shade area have been identified as important factors in determining the cooling effect of greenspaces (Chang, Li, & Chang, 2007; Fahmy, Sharples, & Yahia, 2010; Giridharan, Lau, Ganesan, & Givoni, 2008; Jauregui, 1990; Jusuf, Wong, Hagen, Anggoro, & Yan, 2007; Katayama, Ishii, Hayashi, & Tsutsumi, 1993; Potchter, Cohen, & Bitan, 2006; Shashua-Bar & Hoffman, 2000; Spronken-Smith & Oke, 1998; Upmanis, Eliasson, & Lindqvist, 1998). In terms of the cooling effect of vegetation, researchers typically rank trees, followed by bushes and then grass, as having the greatest effect – even a single tree can affect the air temperature of the immediate area (Rosenfeld, Romm, Akbari, Romm, & Pomerantz, 1998; Saito, Ishihara, & Katayama, 1990–1991; Shashua-Bar & Hoffman, 2000). However, most research provides only qualitative descriptions of cooling effects and fails to establish quantifiable effects and statistically significant relationships (Cao, Onishi, Chen, & Imura, 2010; Hemiddi, 1991; Honjo & Takakura, 1990; Jonsson, 2004; Kawashima, 1994; Narita et al., 2004; Wong et al., 2007). On-site studies often take measurements in only a small number of green sites; but confirm that vegetation lowers air temperatures by shading, by absorbing heat, and by converting ambient heat to latent heat through evapotranspiration at a local scale (Cao et al., 2010). A consensus has also developed among researchers that the relationship between the cooling effect and the size of greenspace may not be linear (Cao et al., 2010; Chang et al., 2007; Jauregui, 1990). Yet conclusions drawn from an individual study cannot be easily verified or transferred (Bowler et al., 2010) and hence quantifiable cooling effects and statistical relationships at the urban scale cannot be established from these site-specific studies (Chang et al., 2007; Spronken-Smith & Oke, 1998). Consequently, the current body of evidence base does not allow recommendations to be made on how to best incorporate greening in an urban area for reducing temperatures (Bowler et al., 2010).

The effects of greenspace on cooling can be measured using remote sensing at all scales from a greenspace patch to a city and beyond. Rao (1972) first demonstrated the possibility of detecting the thermal footprint of urban areas from satellite images. Subsequently, a wide range of remote sensing images and GIS technology has been used to retrieve spatially explicit land-surface temperature (LST) datasets. Significantly, remote sensing images provide detailed spatial land-use and land-cover (LULC) information that can be combined with LST datasets (Cao et al., 2010; Schwarz, Lautenbach, & Seppelt, 2011; Small, 2006; Tran, Uchihama, Ochi, & Yasuoka, 2006). Relating LST data to surface cover characteristics and assessing thermal conditions has enabled the development of city level climate strategies (Amiri, Weng, Alimohammadi, & Alavipanah, 2009; Carlson & Arthur, 2000; Keramitsoglou, Kiranoudis, Ceriola, Weng, & Rajasekard, 2011; Kim, 1992; Nichol, 2005; Stathopoulou & Cartalis, 2007;Weng, Lu, & Liang, 2006; Weng & Lu, 2008; Xiao et al., 2008).

Two decades of urban surface temperature studies have advanced our understanding of spatial thermal patterns, and greenspace is now recognized as one of the most important land-use types that contributes to reducing urban thermal effects (Buyantuyev & Wu, 2010; Gallo et al., 1993; Lu & Weng, 2006; Mackey, Lee, & Smith, 2012; Nichol, 1998; Owen, Carlson, & Gillies, 1998; 1999; Quattrochi & Ridd, 1998; Sobrino, Raissouni, & Li, 2001; Sobrino, Jiménez–Muñoz, & Paolini, 2004; Weng & Larson, 2005; Weng, Lu, & Schubring, 2004; Wilson, Clay, Martin, Stuckey, & Vedder-Risch, 2003; Xian & Crane, 2006). However, most previous remote sensing studies of urban areas focused on providing qualitative descriptions of thermal patterns and simple correlations between LST and LULC types (Keramitsoglou et al., 2011; Voogt & Oke, 2003), and provide only a limited exploration of how the composition and spatial arrangement of greenspaces affect cooling (Chang et al., 2007; Li et al., 2011; Li, Zhou, Ouyang, Xu, & Zheng, 2012; Weng, 2009).

Recent developments in landscape ecology have made it possible to characterize composition and spatial arrangement and to quantitatively link greenspace spatial heterogeneity to its cooling effects (Cao et al., 2010; Li et al., 2011, 2012; Zhou, Huang, Mary, & Cadenasso, 2011). For example, numerous studies have shown that increased greenspace cover has a positive relationship with cooling effects. Li et al. (2012) reported that a 10% increase in greenspace cover produced a 0.86 °C decrease in LST. However, the urban greenspace cooling effect is scale dependent and the optimal spatial scale for its study is not yet known (Li et al., 2011; Liu & Weng, 2009). Using landscape metrics, Weng, Liu, and Lu (2007) assessed the effects of LULC patterns on thermal conditions, while Li et al. (2011) did the same at pixel and landscape scales. Li et al. (2012) investigated the impact of greenspace spatial patterns on LST using a census tract method and recommended that multi-scale research be conducted, a conclusion with which we concur.

As past research illustrates, the characteristics of the urban greenspace cooling effect are not fully understood; this limits the planning and design of such space to mitigate thermal effects at the city level. Consequently, the main objectives of our study are to: (1) investigate the sensitivity of the cooling effect associated with greenspace to changes in scale; (2) identify urban cool islands (UCIs) associated with greenspace – greenspace cool islands (GCIs) – and identify any relationships between GCIs and greenspace spatial patterns; and (3) characterize the intensity of the effects of GCIs.

2. Study area

Nanjing (31°14′–32°37′ N, 118°22′–119°14′ E), the capital of Jiangsu Province, China, is located in the western edge of the Yangtze River Delta (Fig. 1). The Nanjing metropolitan region, comprising 11 districts, covers an area of 4733 km^2, and in 2010 had a population of about 6.3 million (Nanjing Municipal Bureau Statistics, 2011). Nanjing has a subtropical monsoon climate with four seasons and a mean annual temperature of 15 °C (Jim & Chen, 2003). Since 1951, the mean daily maximum temperature between June and August has been 37.3 °C, and on three occasions