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Effects of the spatial configuration of trees on urban heat mitigation: A comparative study

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ABSTRACT

Urban greenspace has significant cooling effects on urban heat. Recent studies investigating the effects of spatial configuration of greenspace show significant, but inconsistent results, including both positive and negative effects. To investigate the causes of this inconsistency, we compared Baltimore, MD and Sacramento, CA, USA, two cities with very different climatic conditions. We quantified and compared the relationships between the spatial configuration of trees and land surface temperature (LST) using different statistical approaches, and conducted the analyses using spatial units of different sizes, based on trees mapped from 1 m high resolution imagery. We found: (1) trees' cooling efficiency was higher in Baltimore than in hotter and drier Sacramento. Additionally, percent cover of trees was more important than their spatial configuration in predicting LST in Baltimore, but the opposite was found in Sacramento. (2) Spatial configuration of trees affects LST more in Sacramento than in Baltimore, and the effects of spatial configuration of trees on LST varied greatly in terms of magnitude, significance, and even direction, between the two cities. Notably, mean patch size had significantly positive effects on LST in Baltimore, but negative effects in Sacramento. In contrast, edge density had negative effects on LST in Baltimore, but positive effects in Sacramento. (3) Different statistical approaches resulted in dramatic changes in the relationships between LST and configuration metrics. Our results underscore the necessity of controlling the effects of percent cover of trees, when quantifying the effects of spatial configuration of trees on LST. (4) Spatial autocorrelation may influence relationships between landscape metrics and LST, particularly when the unit of analysis is relatively small. (5) The relationships between spatial configuration metrics and LST are stronger with an increase of the size of the analytical unit. This study can enhance our understanding of the effects of spatial configuration of greenspace on urban heat island (UHI). It also provides important insights to urban planners and natural resource managers on how to mitigate the impact of urbanization on UHI through urban design and vegetation management.

1. Introduction

Urban heat island (UHI) describes the phenomenon by which urban areas are warmer than surrounding non-urban areas (Voogt and Oke, 2003). Increased temperatures due to the UHI effect may increase water consumption and energy use in urban areas (Santamouris et al., 2015; Wan et al., 2012), alter species composition and distribution (Niemelä, 1999; White et al., 2002), and lead to an increase in the production of ground level ozone which has direct consequences for human health (Akbari et al., 2001; Akbari et al., 1996). In addition, excess heat affects the comfort of urban dwellers and leads to greater health risks (Poumadere et al., 2005). In fact, extreme heat increases mortality and morbidity in cities worldwide (Fouillet et al., 2006; Harlan and Ruddell, 2011). Consequently, how to mitigate and adapt to the UHI has become a major research focus in urban climatology and urban ecology (Arnfield, 2003; Sun and Chen, 2017; Weng, 2009; Zhou et al., 2011).

Considerable research has demonstrated the significant cooling effects of urban greenspace on urban heat (Fan et al., 2015; Jenerette et al., 2007; Kong et al., 2014; Li et al., 2016; Ma et al., 2010; Weng et al., 2004; Zhou et al., 2011). Increasing the percent cover of greenspace can greatly reduce ambient air temperatures and land surface temperatures (Bowler et al., 2010; Connors et al., 2013; Fan et al., 2015; Li et al., 2012; Weng et al., 2004; Zhou et al., 2011; Zhou et al., 2014). In addition, the spatial configuration (or arrangement) of greenspace, can also have significant effects on land surface temperature (LST) (Chen et al., 2014; Fan et al., 2015; Kong et al., 2014; Li et al., 2013b; Li et al., 2012; Maimaitiyiming et al., 2014; Myint et al., 2015; Zhou et al., 2011). Because cities have limited space for greening, managers and decision-

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makers would benefit from knowing how to optimize the spatial configuration of greenspace to further alleviate urban heat stress (Huang et al., 2011; Li et al., 2016; Myint et al., 2015; Zhou et al., 2011).

We know that simply increasing the percent cover of greenspace leads to a reduction of temperatures; this relationship is very consistent. What is less known, however, is the effects of the spatial configuration of that greenspace on urban temperatures. Research results are, in some cases, contradictory. For example, greater patch density of greenspace reduced LST in studies conducted in Shenzhen (Li et al., 2010) and Shanghai, China (Li et al., 2011), Baltimore, USA (Zhou et al., 2011), and Berlin, Germany (Dugord et al., 2014), but was associated with increased LST in Beijing, China (Li et al., 2013b; Li et al., 2012). Similarly, edge density of greenspace was found to be negatively correlated to LST in many cities (Dugord et al., 2014; Li et al., 2011; Li et al., 2014; Maimaitiyiming et al., 2014; Rhee et al., 2014; Zhang et al., 2009; Zhou et al., 2011), but positively correlated in others (Li et al., 2013b; Wu et al., 2014). This inconsistency prevents the application of results to urban greenspace planning and management (Li et al., 2013b).

The reasons for this inconsistency remain largely unaddressed. It may be because these studies have been conducted 1) in cities with contrasting climatic conditions; 2) using a variety of statistical analysis (Fan et al., 2015; Kong et al., 2014; Li et al., 2013b; Li et al., 2012; Myint et al., 2015; Zhou et al., 2011); 3) based on maps from image data with spatial resolution ranging from sub-meter to1000 m (Li et al., 2013b; Rhee et al., 2014; Wu et al., 2014; Zhou et al., 2011); and 4) using a variety of analytical units with different sizes such as grids or pixels (Peng et al., 2016; Rhee et al., 2014), city blocks (Dugord et al., 2014), sub-districts (Li et al., 2013b), or self-defined polygons (Zhou et al., 2011). Does spatial configuration of greenspace affect temperatures differently in cities with different climatic conditions? Or, is this inconsistency due to the varied statistical approaches applied, or different units of analysis, or different resolutions of data to map greenspace?

Here, we address these questions by conducting a comparison study of Baltimore, MD and Sacramento, CA, USA, two cities with very different climatic conditions. We quantified and compared the relationships between spatial configuration of trees and LST using different statistical approaches, and conducted the analyses at sampling units of different sizes. We mapped tree canopies using 1 m resolution imagery. This decision was based on the work of Li et al. (2013b), Zhou et al. (2014) and Zhou et al. (2016), which suggested that the spatial resolution of image data used to map greenspace influenced the statistical relationships between spatial configuration of greenspace and LST, and that high spatial resolution image data are more appropriate in such analysis. Results from the present study can enhance the understanding of the effects of spatial configuration of greenspace on UHI. In addition, important insights can be provided to urban planners and natural resource managers on how to mitigate the impact of urbanization on UHI through urban design and vegetation management.

2. Methods

2.1. Study area

The research focuses on two cities with contrasting climatic conditions, Baltimore, Maryland, USA, and Sacramento, California, USA. Baltimore is a temperate coastal city characterized by hot and humid summers (Brazel et al., 2000), while Sacramento has a Mediterranean climate characterized by hot, but dry summers. Baltimore is built in a biome dominated by temperate broadleaf and mixed forest, whereas Sacramento belongs to a biome dominated by grassland, with riparian forests only along the streams and shrub and woodlands that do not occur until in the sierra foothills and higher elevation (Imhoff et al., 2010).

Baltimore is the largest city in Maryland, with a total area of 239 km^2 and total population of approximately 0.62 million in 2014. Close to the Chesapeake Bay, its annual average temperature is 12.6 °C, and average precipitation is approximately 1070 mm. Sacramento is the capital city of California. It has a total area of 259 km^2, and total population of about 0.48 million in 2014. Located at the confluence of the Sacramento and American rivers, its annual average temperature is 16.2 °C and average precipitation is approximately 450 mm. The similarity in the sizes of total population and area, but the contrast in climatic conditions and biomes, make the two cities ideal for the comparisons conducted in this research.

2.2. Data

2.2.1. Land surface temperature

The LST data were derived from the thermal infrared (TIR) band (10.40–12.50 μm) of two Landsat-5 Thematic Mapper (TM) images with a spatial resolution of 120 m (Fig. 1 B_{LST}, S_{LST}). The TM data for Baltimore and Sacramento were acquired on August 11, 2007 (row 33/path 15), and August 14, 2010 (row 33/path 44), respectively. LST was derived for different years in order to coincide with the years the land cover for the two cities was collected – Baltimore in 2007 and Sacramento in 2010.

We first calculated the top-of-atmospheric (TOA) radiance based on the digital number (DN) of the TM TIR band (Chander and Markham, 2003; Landsat Project Science Office, 2009). We then calculated the surface-leaving radiance from TOA radiance by removing the effects of the atmosphere in the thermal region (Asgarian et al., 2015; Barsi et al., 2005; Sobrino et al., 2004; Yuan and Bauer, 2007; Zhou et al., 2014). Finally, LST was calculated from surface-leaving radiance using the Plank function (Chander and Markham, 2003; Chander et al., 2009).

2.2.2. Spatial pattern of tree canopy

We mapped the urban tree canopy based on 1-m resolution imagery from the National Agriculture Imagery Program (NAIP), using an object-based classification approach (MacFaden et al., 2012; Zhou and Troy, 2008). The imagery is 4-band color-infrared, with radiometric depth of 8 bits. Ancillary data, such as light detecting and ranging (Lidar) data and building footprint layers, were used to aid in classification. Six classes were included in the classification map: trees (i.e., tree canopy), grasses, pavement, buildings, water and bare soil (Fig. 1 B_{TC}, S_{TC}). The accuracies of the land cover classifications were assessed by visually referencing to sub-meter high-resolution imagery using protocol developed in Zhou and Troy (2008). The overall accuracies of the classifications were 95.7% for Baltimore and 93.6% for Sacramento. The user's and producer's accuracy of trees for Baltimore were 97.3% and 97.5%, and 98.2% and 96.7% for Sacramento.

There are numerous metrics that can be used to measure and describe spatial patterns of land cover features (Gustafson, 1998; McGarigal et al., 2002). Here, we chose 5 landscape metrics to measure the spatial pattern of urban trees, including one composition metric: percent cover of trees (PTree), and four configuration metrics: (1) mean patch size (AREA_MN), (2) edge density (ED), (3) mean patch shape index (SHAPE_MN), and (4) largest patch index (LPI) (Table 1). These metrics represent the primary characteristics describing the spatial pattern of trees, including the abundance of trees, size and shape of patches, edge density, and fragmentation. These metrics were chosen based on the following considerations: (1) importance in both theory and practice (Lee et al., 2009; Li and Wu, 2004; Peng et al., 2010; Zhou et al., 2011), (2) easily calculated and interpretable (Li et al., 2012; Zhou et al., 2011), and (3) minimal redundancy (Riitters et al., 1995; Li and Wu, 2004; Zhou et al., 2011). These metrics were calculated in ArcGIS™ 10.1.

2.3. Statistics analysis

We investigated the relationships among spatial patterns of tree canopy and LST at multiple scales, that is, using different sizes of analytical units. Specifically, 5 sizes of analytical unit were used: 1) 1 × 1 pixel