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Spatio-temporal non-uniformity of urban park greenness and thermal characteristics in a semi-arid region

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A B S T R A C T

Thermal characteristics of urban parks often vary city-wide due to different landscape properties of parks themselves or their surrounding environments. Understanding such heterogeneity is critical for strategic use of urban forest elements to mitigate extreme heat and provide various ecological amenities; however, relatively few studies to date have assessed such variability at the whole-city scales and across different seasons. This study investigated seasonal variation, statistical association and local spatial clustering in satellite image-based proxies of vegetation greenness and surface temperature (normalized difference vegetation index (NDVI) and at-sensor surface brightness temperature (T_b), respectively) among 135 parks in a part of California, USA on ten different-season dates in 2014. Both metrics varied among parks and dates and exhibited a significant negative linear relationship which was stronger on warmer-season dates. Regressions with NDVI explained 2–17% more variance in T_b when they also included the proportion of woody plant cover (negative effect on T_b) or the proportion of grass cover (positive effect on T_b) on all dates, and park area on some dates (negative effect on T_b). The analysis of spatial variation in park properties revealed several significant local clusters of parks with higher T_b that persisted among warmer dates and had significantly smaller area and warmer neighborhoods than did significant clusters of greener or cooler parks. These results highlight potential under-provisioning of park microclimatic benefits in the associated neighborhoods and calls for further research on environmental and social implications of these results to inform mitigation of urban heat in this region and similar climates.

1. Introduction

Urban parks provide numerous ecological, climatic, recreational and social benefits that become even more significant with globally increasing urban population and extent (Bowler et al., 2010; Ibes, 2015; Kong et al., 2014a). Many previous studies have demonstrated the importance of parks and other urban forest elements for heat mitigation, provision of versatile ecosystem services and support of ecological communities (Bowler et al., 2010; Brown et al., 2015; Chang and Li, 2014; Cheng et al., 2015). However, spatial and temporal variation in these benefits affected by park characteristics and regional spatial configuration remain less well understood at whole-city scales (Bao et al., 2016; Chen et al., 2014; Kong et al., 2014a; Kong and Nakagoshi, 2006, Li et al., 2016; Pataki et al., 2011). Advancing this knowledge is critical for strategic use of parks in urban heat regulation and provision of important ecological, recreational and health amenities (Brown et al., 2015; Georgescu et al., 2015; Ibes, 2015; Norton et al., 2015).

A key determinant of a park's cooling potential is photosynthetically active vegetation providing shade, evapotranspiration and regulation of atmospheric movement (Feyisa et al., 2014; Hamada et al., 2013; Kong et al., 2014b). Cooling benefits become especially important during the hottest times of the year, but can be difficult to maintain in water-limited regions, such as dry-summer arid and Mediterranean-type climates (Barradas, 1991; Feyisa et al., 2014; Potchter et al., 2012; Spronken-Smith and Oke, 1998; Zoulia et al., 2009). Previous studies have also acknowledged the importance of park distribution at the neighborhood and city scale for urban cooling (e.g., Bao et al., 2016; Kong et al., 2014a; Li et al., 2016). However, the implications of differences in park characteristics within green space networks are less well known, and several important uncertainties contribute to these gaps.

First, most previous analyses of park thermal performance have been based on limited samples, especially in field studies (Bowler et al., 2010; Jaganmohan et al., 2016), due to logistical difficulties in

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synchronizing multi-park measurements. In the review of green space cooling effect by Bowler et al. (2010), median number of parks among 24 studies was 1.5. Very few field studies have included larger sets, such as the analysis of 62 urban parks and forests in Leipzig, Germany (Jaganmohan et al., 2016) and 61 parks in Taipei, Taiwan (Chang et al., 2007). In response to this challenge, satellite remote sensing data have been increasingly used to characterize thermal effects of green spaces for whole cities (Cao et al., 2010; Cheng et al., 2015; Kong et al., 2014b; Lin et al., 2015; Spronken-Smith and Oke, 1998) and even globally (Clinton and Gong, 2013). In such studies vegetation is often represented by estimated plant cover fraction or spectral indices of greenness (Clinton and Gong, 2013; Powell et al., 2007; Weng, 2012), while thermal properties are derived from satellite-measured emitted energy converted to proxies of surface temperature (Kong et al., 2014b; Weng et al., 2004). Broad-scale landscape coverage by remote sensing data allows analyzing larger sets of green spaces. For example, Feyisa et al. (2014) compared 21 parks in Addis Ababa, Ethiopia with ground measurements in only 9 of them; Lin et al. (2015) studied on 30 parks in Beijing, China, and Cao et al. (2010) assessed cool island intensity of 92 parks in Nagoya, Japan. Such studies often corroborate the cooling potential of urban parks (Cheng et al., 2015; Kong and Nakagoshi, 2006; Spronken-Smith and Oke, 1998); however, they also show that cooling effects can be non-uniform (Chang et al., 2007; Chen et al., 2014; Monteiro et al., 2016; Potchter et al., 2012). Understanding this non-uniformity requires more comprehensive city-scale analyses in different climates.

Second, previous studies have often focused on the contrast between green spaces and built-up areas (Bowler et al., 2010; Hamada et al., 2013; Kong et al., 2014b; Spronken-Smith and Oke, 1998) and less on the heterogeneity among parks themselves (Bowler et al., 2010; Cao et al., 2010; Jaganmohan et al., 2016). Differences in park origin, design and use (Cranz and Boland, 2004; Ibes, 2015) may translate into varying surface properties and thermal performance. For instance, cooling potential may increase with greater park size (Chang et al., 2007; Chang and Li, 2014; Feyisa et al., 2014; Jaganmohan et al., 2016; Monteiro et al., 2016; Upmanis et al., 1998), certain aspects of shape (Feyisa et al., 2014; Jaganmohan et al., 2016), greater tree cover (Chang et al., 2007; Potchter et al., 2006), lower proportion of paved area (Barradas, 1991; Chang et al., 2007) and sometimes lower grass cover (Cao et al., 2010). At the same time, similarities in park design and management (Cranz and Boland, 2004) may lead to convergence in composition and microclimatic performance. This resonates with the broader issue of urban ecological homogenization (Groffman et al., 2014) and calls for more comparative analyses of existing parks. Such analyses are also needed to assess the impacts of urban green spaces in other contexts, e.g., fear of crime related to the type of green space (Maruthaveeran and van den Bosch, 2014) and equity in access to park amenities (Byrne and Wolch, 2009; Ibes, 2015; Macedo and Haddad, 2016; Wolch et al., 2014).

Finally, many studies have assessed park thermal properties within relatively narrow time frames, typically the hottest times of the year (Potchter et al., 2006; Spronken-Smith and Oke, 1998; Zoulia et al., 2009). Yet, seasonality of park environments can also strongly affect their thermal performance in different climates. For example, a study in the subtropical central Taiwan found that the correlation between park thermal properties and human visitation tended to be lower in hotter conditions with excessive solar radiation (Lin et al., 2012). Similarly, a comparison between winter and summer in Tel-Aviv, Israel (Cohen et al., 2012) showed differences in park potential to reduce warmer daytime temperatures and improve thermal comfort. Importantly, in drier climates, limited water resources may constrain park management for heat mitigation due to, e.g., reduced irrigation (Christian-Smith and Heberger, 2015; Johnson and Belitz, 2012), making the role of vegetation phenology in microclimate regulation especially critical.

This study examined spatial and temporal variability of microclimate-relevant remotely sensed urban park characteristics in a portion of the East San Francisco Bay, California, USA. Despite relatively mild summer temperatures in this region (Section 2.1), intensifying urban heat presents an increasing concern. It is recognized that cities most vulnerable to thermal stress are not those from historically hot climates, but rather cooler areas, such as coastal regions, that are not designed to alleviate growing temperatures and resident heat stress (CA EPA, 2013). For example, Residential Energy Consumption Survey (U.S. EIA, 2013) reported that the proportion of homes with air conditioning in the marine climate covering the USA's West coast and our study area was only 38.1% in 2009 compared to 87.1% for the whole USA. For California, increases in mean and maximum atmospheric temperature have been projected from 1 to 5 °C and up to 9 °C by the end of 21st century (Hayhoe et al., 2004). In 2017 alone, study area endured two massive heat waves breaking historical records and exceeding typical temperatures by up to 20–30 ° (Fritz, 2017; Samenow, 2017). However, even small increases pose risks to human health: a 1 °C increase in maximum temperatures corresponded to 1–3% increase in human mortality risk in a meta-analysis by Hajat and Kosatky, (2010) and to ~29% increase in ambulance response calls for heat-related illnesses in a Toronto, Canada study (Bassil et al., 2010). Finally, intensifying drought risks (Diffenbaugh et al., 2015) may amplify thermal stresses due to restrictions on water use and thus outdoor cooling.

To better understand the potential contributions of urban parks to such concerns, our study estimated proxies of vegetation greenness and surface temperature from a one-year time series of Landsat satellite imagery and examined their spatial and temporal non-uniformity among parks and their neighborhoods. Our main objective was to assess the relative heterogeneity in park characteristics, spatial distribution and seasonality, which, to our knowledge, has not been previously done in the study region and only to a limited extent in other similar locations. We asked the following specific questions: To what extent are local urban parks similar in their proxies of surface temperature and greenness at different seasons? Are any of these similarities manifested in the form of significant local grouping of higher or lower values of greenness and surface temperature at the city scale and, if yes, do such patterns persist over time? Finally, to what extent are thermal properties and greenness associated between parks and their adjacent urban areas?

2. Methods

2.1. Study area

This study focused on urban parks in the portion of the East San Francisco Bay, California, USA including the adjacent cities of Berkeley, Oakland and Piedmont (Fig. 1). This region has a subtropical, dry-summer climate with the average annual temperature of 14.5 °C and annual precipitation of ~698 mm, most of which falls between November and March (Western Regional Climate Center, 2017). The warmest months are July–September (average maximum temperature ~23 °C), the coldest – December and January (average minimum temperature ~6.6 °C). Variable summer cloudiness and influence of maritime fog also contribute to shorter-term variation in atmospheric and surface temperatures in a given season (Iacobellis and Cayan, 2013). Fog typically enters the area through the Golden Gate Bridge gateway located directly across the city of Berkeley, and its eastward movement is further prevented by the California Coast Range hills (Fig. 1). As a result, northern part of the study area more directly in the fog's way may experience stronger influence depending on local topographic properties and specific location.

Urban parks in this region share similarities due to their year-round recreational use and common presence of grass cover and evergreen woody vegetation; however, a number of historical and present-day factors also contribute to their heterogeneity (Kibel, 2010; Simon, 2014). There is a pronounced topographic variability with elevation ranging from ~420 m in the upper parklands to 1–2 m near the Bay