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Research Paper

Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona

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ABSTRACT

The urban heat island effect is especially significant in semi-arid climates, generating a myriad of problems for large urban areas. Green space can mitigate warming, providing cooling benefits important to reducing energy consumption and improving human health. The arrangement of green space to reap the full potential of cooling benefits is a challenge, especially considering the diurnal variations of urban heat island effects. Surprisingly, methods that support the strategic placement of green space in the context of urban heat island are lacking. Integrating geographic information systems, remote sensing, spatial statistics and spatial optimization, we developed a framework to identify the best locations and configuration of new green space with respect to cooling benefits. The developed multi-objective model is applied to evaluate the diurnal cooling trade-offs in Phoenix, Arizona. As a result of optimal green space placement, significant cooling potentials can be achieved. A reduction of land surface temperature of approximately 1–2 °C locally and 0.5 °C regionally can be achieved by the addition of new green space. 96% of potential day and night cooling benefits can be achieved through simultaneous consideration. The results also demonstrate that clustered green space enhances local cooling because of the agglomeration effect; whereas, dispersed patterns lead to greater overall regional cooling. The optimization based framework can effectively inform planning decisions with regard to green space allocation to best ameliorate excessive heat.

1. Introduction

As cities grow, changes in urban land cover and geometry/morphology/architecture coupled with intensifying human activities have led to a modified thermal climate, particularly at night, forming an urban heat island (UHI) (Fan & Sailor, 2005; Voogt & Oke, 2003). This effect has significant implications for sustainability, with consequences for energy and water consumption, emissions of air pollutants and greenhouse gases, human health, and the emergence of regional heat islands (Arnfield, 2003; Georgescu et al., 2014; Hondula et al., 2012, 2014; Huang, Zhou, & Cadenasso, 2011; Sailor, 2001). The UHI effect is intense in Phoenix, Arizona, amplified by rapid and extensive urbanization with resulting temperature increases approximating 0.5 °C per decade (Grimm et al., 2008). Summers in Phoenix are characterized by peaks in energy use and increased residential water consumption as well as the emergence of extreme UHI "riskscapes" (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Jenerette, Harlan, Stefanov, & Martin, 2011; Ruddell, Harlan, Grossman-Clarke, & Buyantuyev, 2010; Wentz, Rode, Li, Tellman, & Turner, 2016).

Green space, an area partially or completely covered by grass, trees, shrubs, and/or other vegetation in the form of parks, golf courses, large gardens, and yards, can effectively reduce temperature through shading and evapotranspiration (Balling & Lolk, 1991; Chang, Li, & Chang, 2007; Spronken-Smith & Oke, 1998). Recognizing the potential to mitigate UHI, the City of Phoenix has launched a master plan that aims to increase the amount of green space (City of Phoenix, 2010). Consequently, an important question is where to site new green space in order to best realize potential cooling benefits. Improvements in measuring and modeling cooling benefits of green spaces are required, however, to make informed decisions.

On the measurement side, air temperature based studies have found that green space can be 1–3 °C, and sometimes even 5–7 °C, cooler than surrounding built-up areas (Chow, Pope, Martin, & Brazel, 2011; Spronken-Smith & Oke, 1998; Upmanis, Eliasson, & Lindqvist, 1998), with cooling impacts extending as much as several hundred meters beyond green space boundaries (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Eliasson & Upmanis, 2000; Spronken-Smith, Oke, & Lowry,

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2000). Air temperature measurements are not suitable for citywide studies, however, due to their small sample size and limited spatial coverage (Bowler et al., 2010). Derived from remotely sensed thermal infrared imagery, land surface temperature (LST) measures surface UHI (SUHI). LST shows significant correlation with air temperature and provides complete spatial coverage across an entire cityscape (Fung, Lam, Nichol, & Wong, 2009; Klok, Zwart, Verhagen, & Mauri, 2012; Nichol, Fung, Lam, & Wong, 2009). Extensive research has explored relationships between SUHI and urban land cover, especially with regard to vegetation (Buyantuyev & Wu, 2010; Li, Li, Middel, Harlan, & Brazel, 2016; Myint, Wentz, Brazel, & Quattrochi, 2013; Ren et al., 2013; Weng 2009; Zhou, Huang, & Cadenasso, 2011). Studies have suggested that land cover composition and configuration of the green space are strong predictors of its cooling effect (Cao, Onishi, Chen, & Imura, 2010; Li et al., 2013; Lin, Yu, Chang, Wu, & Zhang, 2015; Maimaitiyiming et al., 2014; Ren et al., 2013 Ren et al., 2013). Furthermore, local context and adjacent green space also have impacts on cooling (Cheng, Wei, Chen, Li, & Song, 2014; Lin et al., 2015; Spronken-Smith & Oke, 1998, 1999). Explicit linkages between cooling effects and the locations of green spaces are missing, however, causing difficulties for location model construction.

On the modeling side, micro-climate numerical models deal with surface energy balance, simulating thermodynamic processes for canopy layer UHI assessment (Chow et al., 2011; Erell, Pearlmutter, & Williamson, 2012; Fernández, Alvarez-Vázquez, García-Chan, Martínez, & Vázquez-Méndez, 2015; Middel, Chhetri, & Quay, 2015; Ng, Chen, Wang, & Yuan, 2012). Results from such models are rich in temporal scale but are limited in spatial extent, thus fail to capture intra-urban temperature variations. Combining broader scale spatial data, multi-objective optimization models have been applied recently to determine green space locations in the city, balancing various kinds of environmental benefits. Neema and Ohgai (2013) developed a multi-objective heuristic technique for optimizing the configuration of parks and open space with respect to air and water quality improvement as well as noise and temperature reduction. Zhang and Huang (2014) sought to minimize LST in the allocation of land uses within a multi-objective heuristic, where temperature is a regressed function of land use intensities. As yet, however, no current model has attempted to account for the agglomeration of cooling resulting from adjacent green spaces, which greatly affects their spatial allocation.

The above mentioned measuring and modeling gaps are addressed in this research using an integrated framework that combines remote sensing, GIS, spatial statistics and spatial optimization. Fine-scale remote sensing data can greatly improve model reality, allowing better representation of the intra-urban SUHI intensities. Incorporated with GIS, statistical and optimization models facilitate practical location decision making to enhance green space cooling. The study first quantifies and predicts direct and indirect cooling benefits of the green space using LST and land cover data, linking cooling effect with green space locations. The exact formulation and solution for green space allocation is developed next and explicitly accounts for agglomeration-based cooling. The multi-objective model developed here considers both daytime and nighttime cooling impacts, enabling trade-off solutions to be identified. The framework is applied to an area in central Phoenix.

2. Study area and data

The Phoenix metropolitan area, one of fastest growing urban regions in the U.S., is located on the northern edge of the Sonoran Desert. With a population approaching 1.5 million, the City of Phoenix comprises approximately 134,200 ha of land in the center of a much larger metropolitan area (Fig. 1). Dominated by a semi-arid climate, this region has mild winters and hot summers. The temperature in Phoenix commonly exceeds 38 °C on average for 110 days during the year, and reaches 43 °C or higher for 18 days. The average annual rainfall is about 210.82 mm. With rapid urbanization during the last 50 years, the mean daily air temperature has increased by 3.1 °C and the nighttime minimum temperature by 5 °C (Brazel, Selover, Vose, & Heisler, 2000). The city and metropolitan area confront major urban heat island effects and related water withdrawal problems, which are expected to be amplified by climate change over the coming years.

To address sustainability challenges, Phoenix adopted a master plan in 2010 that aimed to create a healthier and more livable city through strategic investment in more green space (City of Phoenix, 2010). Existing green space in the city varies in size, shape and vegetation cover, exhibiting different levels of cooling effects during the day and the night. As illustrated in Fig. 1, green space is distributed rather unevenly across the city. Low-income, ethnic minority neighborhoods tend to have less and smaller-sized green spaces, generally with sparse vegetation cover (Harlan et al., 2006). The aerial imagery in Fig. 1 shows the detailed study area, which is 8,800 ha in size. This area is low-income and has a mixture of low and high vegetation cover neighborhoods.

Associated data utilized in this study includes thermal temperature readings and a fine-scale land cover classification. The land surface temperature was derived from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data layers. The ASTER image consists of six bands for short-wave infrared, at 30 m resolution, and five bands of thermal infrared, at 90 m resolution (Yamaguchi et al., 1998). The ASTER_08 product was used for surface temperature extraction. In order to address the diurnal cooling effect variation, a consecutive night and day cloud-free image pair were selected (under clear and clam weather conditions) for a summer period: June 17, 2010 (22:00 at local time) and June 18, 2010 (11:00 at local time), respectively. Daytime and nighttime temperatures for these dates at 90 m resolution are shown in Fig. 2. The study area consists of 11,466 (126 by 91) pixels. The mean surface temperature of the area is 55.60 °C and 29.85 °C for day and night, respectively. According to the National Weather Service and the Arizona Meteorological network, five weather stations are located within the extent of the utilized ASTER image, and one is within the reported study area (Fig. 1). Table 1 shows the comparison between air temperature and corresponding LST values. This highlights significant daytime differences between the surface and air temperatures, because LST responds to direct solar radiation (Cao et al., 2010; Hartz, Prashad, Hedquist, Golden, & Brazel, 2006). During nighttime, the surface temperatures are slightly higher than air temperatures. Calm wind conditions enhance the positive association between LST and air temperature, whereas strong winds decouple the relationship (Stoll & Brazel, 1992).

Both daytime and nighttime effects are examined because of their combined impacts on human wellbeing, energy and water use, and environmental performance. The well-known consequences of extreme summer temperatures in the Phoenix area include human health (Harlan et al., 2006), increased demands on energy for cooling and water for landscaping (Wentz et al., 2016), and impacts on year-round tourism favored by the commercial sector (Gober et al., 2009). Perhaps less known are the nighttime UHI effects. These include extending energy use for cooling into evening, owing to daytime heat storage (Grimmond & Oke, 2002), and throughout the night, as well as providing a higher temperature base from which the daytime UHI effect builds (Stoll & Brazel, 1992). Interestingly, higher nighttime temperatures during the winter reduce the occurrence of frost and its dampening effect on insects and anthropods, which in turn increase pesticide use, among other impacts (Ruddell, Hoffman, Ahmad, & Brazel, 2013).

In addition, a 1 m land cover classification of metropolitan Phoenix was utilized. This data layer was created using aerial imagery from the National Agricultural Imagery Program. The 1 m aerial images have four bands (RGB and NIR) and were acquired for summer 2010. The images were classified using the object-based method, implemented using the eConigtion software (Li et al., 2014). The resulting land cover data layer included 12 land cover classes with an overall accuracy of