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Research Paper

On the association between land system architecture and land surface temperatures: Evidence from a Desert Metropolis—Phoenix, Arizona, U.S.A

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HIGHLIGHTS

- Land system architecture affects land surface temperature (LST) of residential parcels.
- Land-cover composition has the largest effect on LST but land-cover configuration is significant.
- Compact and concentrated land-covers, foremost vegetation, improves nighttime cooling.
- Large land-cover units of irregular shape improve daytime cooling.
- Parcel level land architecture can be used to mitigate the LST of residences.

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ABSTRACT

The relationship between the characteristics of the urban land system and land surface temperature (LST) has received increasing attention in urban heat island and sustainability research, especially for desert cities. This research generally employs medium or coarser spatial resolution data and primarily focuses on the effects of a few classes of land-cover composition and pattern at the neighborhood or larger level using regression models. This study explores the effects of land system architecture—composition and configuration, both pattern and shape, of fine-grain land-cover classes—on LST of single family residential parcels in the Phoenix, Arizona (southwestern USA) metropolitan area. A 1 m resolution land-cover map is used to calculate land architecture metrics at the parcel level, and 6.8 m resolution MODIS/ASTER data are employed to retrieve LST. Linear mixed-effects models quantify the impacts of land configuration on LST at the parcel scale, controlling for the effects of land composition and neighborhood characteristics. Results indicate that parcel-level land-cover composition has the strongest association with daytime and nighttime LST, but the configuration of this cover, foremost compactness and concentration, also affects LST, with different associations between land architecture and LST at nighttime and daytime. Given information on land system architecture at the parcel level, additional information based on geographic and socioeconomic variables does not improve the generalization capability of the statistical models. The results point the way towards parcel-level land-cover design that helps to mitigate the urban heat island effect for warm desert cities, although tradeoffs with other sustainability indicators must be considered.
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1. Introduction

Over a quarter century ago, Forman (1990) called for ecological research on landscape mosaics (land-cover composition and configuration) in regard to the environmental performance and sustainability of landscapes (also Wu, 2013), and more recently has championed this approach for urban ecology (Forman, 2014). Urban

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climatology, in turn, has long considered the impacts of urban morphology or geometry on the urban heat island (UHI) effect. Much attention has been given to the vertical dimensions and spacing of buildings (e.g., urban canyon height-to-width ratios), sky-views, and the density of general types of land covers, such as vegetation and impervious surfaces (e.g., Stewart & Oke, 2012). In addition, landscape architecture has long addressed the structure of outdoor spaces, foremost parks and common and reclamation areas, with a strong orientation towards their aesthetics attributes. It has drawn on ecological principles in landscape design, however, more so than examining the environmental dynamics of existing landscape conditions (Brown & Corry, 2011; Yu, Li, & Ji, 2001).

Joining these research interests and the approaches applied to them, but differing somewhat from each, is the transdisciplinary subfield of land system (change) science, focused on the causes and consequences of land change (Turner et al., 2007). Land system science, partly a product of global environmental change and sustainability interests, seeks to provide a science-based understanding of land-use and –cover change, increasingly with an eye towards informing decision making. Land system architecture (henceforth, land architecture) is one dimension of this effort (Janetos, Verbug, & Murray, 2013). It addresses the composition and configuration of land covers, including pattern, shape and connectivity, and their impacts on social-environmental system performance (Turner, 2017). It differs slightly from landscape mosaic approaches in its attention to fine-grain spatial analysis (i.e., 1–30 m), and detailed categories of land covers (e.g., among various categories of vegetation cover) and, in some cases, land uses. These distinctions make the land architecture orientation well fit to address the heterogeneous character of urban land cover, and compatible with calls for land system science to address urbanization-land relationships (e.g., Seto and Reenberg, 2014). Land architecture explores configuration metrics derived from the spatial sciences rather than relying solely on those developed in ecology (see below). Urban land architecture has focused on the UHI effect (Turner, 2017), but differs from urban morphology or geometry in regard to the array of land-cover categories examined and the details of configuration. Finally, the focus of land architecture (as defined here) on base research to inform decision making about sustainability problems (Clark, 2007) distinguishes it from the primary motivation of activities within the subfield of landscape architecture.

The UHI effect increasingly captures the attention of administrators and decision makers concerned with mitigating urban temperature extremes and their impacts on energy and water use, human health, and thermal comfort (e.g., City of Phoenix, 2010; Kleerekoper, van Esch, & Baldiri Salcedo, 2012; Shashua-Bar, Pearlmutter, & Erell, 2009, Shashua-Bar, Pearlmutter, & Erell, 2011; Solecki et al., 2005; Wentz, Rode, Li, & Tellman, 2016). This concern, in turn, has drawn insights from UHI research undertaken in the subfields and approaches discussed above as well as in remote sensing (e.g., Gago, Roldán, Pacheco-Torres, & Ordoñez, 2013; Hart & Sailor, 2009; Oke, 1981; Taha, 1997). The problem and the research given to it are particularly acute for urban areas worldwide situated in warm and hot climates where the UHI effect is expected to be significantly amplified by global climate warming (e.g., Grossman-Clarke, Schubert, Clarke, & Harlan, 2014; McCarthy, Best, & Betts, 2010; Saha, Davis, & Hondula, 2014).

With these concerns in mind, the role of urban land composition and configuration on the UHI and its capacity to mitigate the phenomenon has been examined in regard to both air and land surface temperature, including the role of "smart buildings", green and white roofs, urban street canyons, green spaces, shade, impervious surfaces, bare soil, and sky-views (e.g., Coseo & Larsen, 2014; Donovan & Butry, 2009; Erellet al., 2012; Giridharan, Lau, Ganesan, & Givoni, 2007; Li, Bou-Zeid, & Oppenheimer, 2014; Oke, 1981; Santamouris, 2013). Configuration has largely been addressed in terms of the spatial distribution or pattern of general types of land covers (Buyantuyev & Wu, 2010; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Myint, 2012; Myint, Wentz, Brazel, & Quattrochi, 2013; Stewart and Oke, 2012), with abundant attention to Chinese cities (e.g., Huang, Li, Zhao, & Zhu, 2008; Li, Wang, Wang, Ma, & Zhang, 2009; Su, Gu, & Yang, 2010; Zhang et al., 2013).

Complementing recent research that treats land configuration in rural, forest landscapes (Mitchell, Bennett, & Gonzalez, 2013; Wu, Jenerette, Buyantuyev, & Redman, 2011) and consistent with Forman's (1990) call, nascent efforts are underway to determine the role of land architecture, as defined here, on the UHI effect. Most studies to date tend to employ 30 m or coarser resolution satellite data to calculate daytime land surface temperature (LST) of urban land units, address one or two land-covers at the neighborhood or larger level, use FRAGSTATS metrics (McGarigal and Marks, 1995; McGarigal, Cushman, & Ene, 2012) to determine land-cover configuration, and apply regression models to assess the land cover-LST relationship (e.g., Turner, 2017). The results indicate that the concentration of different land covers in Phoenix and Las Vegas (USA) increased heating or cooling effects (Fan, Myint, & Zheng, 2015; Myint et al., 2015; Zheng, Myint, & Fan, 2014), whereas different elements of shape (e.g., edge density) have a strong effect on land-cover temperature in Beijing, China (Li, Zhou, Ouyang, Xu, & Zheng, 2012), Baltimore, USA (Zhou, Huang, & Cadenasso, 2011), and Phoenix (Connors, Galletti, & Chow, 2013). Indeed, at least one study in Phoenix found land-cover shape at the parcel level, as measured by the Normalized Moment of Inertia, trumped land-cover pattern in terms of effects on LST at the neighborhood level (Li, Li, Middel, Harlan, & Brazel, 2016).

In addition to the overall work on the UHI effect, land architecture approaches increasingly point to the significant role that both the pattern and shape of small-size land covers have on temperature extremes. Here we extend this line of research by exploring the role of land configuration on LST at the single-family residential (SFR) parcel level for the metropolitan area of Phoenix, Arizona, U.S.A., using 2010–2011 data (Fig. 1). Consistent with most other studies, FRAGSTATS serve as the metrics of composition and configuration. Following Li et al. (2016), multiple land covers and their mosaics are examined. These land covers are linked to 6.8 m MASTER data in order to match the fine-resolution, heterogeneous land cover of the residential parcels. New to this assessment, both daytime and nighttime LST are analyzed. In addition, the neighborhood effect (Cox, 1969; Johnston, Propper, Sarker, Jones, & Bolster, 2005) on individual parcels is investigated using linear mixed effect models (LMEs). LMEs allow us to identify significant predictors related to land configuration while accounting for nested, neighborhood-specific data structures and controlling for land composition, socioeconomic neighborhood characteristics and spatial correlation of neighboring parcels. Evaluation of LMEs emphasized their generalization capability based on their performance in predicting outcomes on neighborhoods not used to estimate model parameters. Taken together, this study constitutes a novel attempt to determine the role of residential land architecture on the UHI effect, specifically the surface urban heat island (SUHI). The results have the potential to inform how a redesign or reshaping of the land units could mitigate the extremes of the SUHI.

2. Study site, data, and methods

2.1. Study site

The Phoenix metropolitan area (Fig. 1) consists of 26 joined cities and towns that housed about 4.2 million people in 2010 and covered over 7600 km^2 of the northern Sonoran Desert of

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