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Remote sensing of the surface urban heat island and land architecture in Phoenix, Arizona: Combined effects of land composition and configuration and cadastral–demographic–economic factors

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ABSTRACT

This study seeks to determine the role of land architecture—the composition and configuration of land cover—as well as cadastral–demographic–economic factors on land surface temperature (LST) and the surface urban heat island effect of Phoenix, Arizona. It employs 1 m National Agricultural Imagery Program data of land-cover with 120 m Landsat-derived land surface temperature, decomposed to 30 m, a new measure of configuration, the normalized moment of inertia, and U.S. Census data to address the question for two randomly selected samples comprising 523 and 545 residential neighborhoods (census blocks) in the city. The results indicate that, contrary to most other studies, land configuration has a stronger influence on LST than land composition. In addition, both land configuration and architecture combined with cadastral, demographic, and economic variables, capture a significant amount of explained variance in LST. The results indicate that attention to land architecture in the development of or reshaping of neighborhoods may ameliorate the summer extremes in LST.

1. Introduction

The urban heat island (UHI) effect refers to the higher air and surface temperature in urban areas compared to that of the surrounding rural hinterland, generated by high levels of near surface energy emission, solar radiation absorption of ground objects, and often, low levels of evapotranspiration in cities (Buyantuyev & Wu, 2010; Oke, 1982, 1997; Rizwan, Dennis, & Liu, 2008). The UHI of large cities has increased substantially since the middle of the 20th century (Akbari, Pomerantz, & Taha, 2001; Oke, 1976; Stone, 2007), with urban conglomerations generating modeled and observed changes in regional temperatures (Georgescu, Moustaoui, Mahalov, & Dudhia, 2011; He, Liu, Zhuang, Zhang, & Liu, 2007; Kalnay & Cai, 2003; Li, Wang, Shen, & Song, 2004). Extensively examined, the UHI draws increasing attention owing to its effects on energy and water consumption, human health, environmental (ecosystem) services, especially in the context of global warming (e.g. Gober, Kirkwood, Balling, Ellis, & Deitrick, 2009; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Harlan, Declet-Barreto, Stefanov, & Petitti, 2013; Hondula, Vanos, & Gosling, 2013; Hondula et al., 2012). For these and other reasons, attention to the means to mitigate the UHI effect have garnered considerable attention, especially through model simulations (e.g. Golany, 1996; Sailor, 1995), but increasingly through the use or remote sensing data that permit novel assessments (e.g., Zhou, Huang, & Cadensasso, 2011).

Remote sensing technology has been a boon to the study of the UHI in at least two fundamental ways: [1] direct observation of land surface thermal radiance converted to land surface temperature to address the Surface UHI (SUHI) (e.g. Lo, Qiattrochi, & Luvall, 1997; Streutker, 2002); and [2] direct spatial linkages of ground features, both their vertical dimensions and patterns, to land surface temperature at fine spatial resolutions (e.g. Arnfield, 2003; Buyantuyev & Wu, 2010; Chow, Chuang, & Gober, 2012; Nichol, 1996; Unger, 2004). To date, this research has focused on the relationship between land surface temperature (LST) and particular land-cover types (or land composition) (e.g. Chow & Brazel, 2012; Li, Song, Cao, Meng, & Wu, 2011; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Stone & Rodgers, 2001; Zheng, Myint, & Fan, 2014; Zhou et al., 2011), and between spatial thermal patterns and social economic factors (Buyantuyev & Wu, 2010; Harlan et al., 2006; Hondula et al., 2013; Huang, Zhou, & Cadenasso, 2011; Jenerette, Harlan, Stefanov, & Martin, 2011). Recently, however, attention to land system architecture (Turner, Janetos, Verburg, & Murray, 2013)—the composition and configuration (e.g., size, shape, patterns, and connectivity) of the urban land cover—on SUHI has been examined in regard to possible UHI mitigation strategies (Chen, Zhao, Li, & Yin,

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2006; Connors, Galletti, & Chow, 2013; Li, Zhou, Quyang, & Zheng, 2012; Li et al., 2013b; Zhou et al., 2011).

Briefly summarizing, this research informs us that increasing greenspace, water, and skyview (open area ventilation) tend to ameliorate the UHI effect, while dark-colored impervious surfaces tend to amplify it, with larger impacts on nighttime temperatures (e.g. Chow & Brazel, 2012; Li et al., 2011; Maimaitiyiming et al., 2014; Weng, Lu, & Schubring, 2004; Xian & Crane, 2006; Zheng et al., 2014; Zhou, Qian, Li, Li, & Han, 2014). These relationships tend to hold across different urban areas and environments, but vary in magnitude diurnally and seasonally. Specific linkages to human outcomes demonstrate that UHI impacts tend to be registered most highly among those parts of city that have dense occupation with low levels of shade, either from buildings or trees, and greenspaces. These conditions, at least in the U.S. cities examined, tend to be related to lower levels of income, often linked to neighborhoods dominated by certain ethnic groups (Buyantuyev & Wu, 2010; Harlan et al., 2006; Hondula et al., 2012; Jenerette et al., 2007, 2011). Finally, the land architecture of urban areas, from the parcel to larger levels of assessment, has been hypothesized to amplify or ameliorate ecosystem services, such as those related to SUHI effects (Turner et al., 2013). Nascent research suggests that, controlling for land composition, edge and patch densities, landscape shape index, and fractal dimensions (FRAGSTAT metrics) of land covers hold significant consequences for land surface temperatures (Buyantuyev & Wu, 2010; Connors et al., 2013; Li et al., 2011; Li et al., 2012; Middel, Brazel, Kaplan, & Myint, 2012; Middel et al., 2014; Stone & Rodgers, 2001; Zhang, Odeh, & Ramadan, 2013; Zhang, Zhong, Feng, & Wang, 2009; Zhou et al., 2011).

Our study follows from but extends these lines of research. It seeks to determine if LST among residential neighborhoods during the summer season, specifically June, is related to the land architecture and certain cadastral, demographic, and socioeconomic characteristics of the neighborhoods in the metropolitan area of Phoenix, AZ. We employ fine resolution spatial data and a compactness pattern measure—the normalized moment of inertia—applied for the first time in land architecture assessments. We test the following hypotheses drawn from or implied in the body of research reviewed above:

[1] [1] *The composition and configuration* (i.e., *land architecture*) *of land-cover types affect summer daytime LST and thus the SUHI*. Research to date has yet to explicate adequately the configuration dimensions of multiple land covers on SUHI.

[2] [2] *Land composition is more strongly related to summer daytime LST than configuration*. Most of the research results to date, typically using FRAGSTATS metrics, indicate the stronger role of composition, or area of land covers, on the SUHI.

[3] [3] *Land architecture has more impact on summer daytime LST than do cadastral–demographic–socioeconomic factors*. Some research implies that these factors and land architecture may be linked, but assessing their relative roles has yet to be examined fully. In our study, cadastral data provide information on parcel size, which are used as ancillary data for the economic dimension in question.

2. Study area, data, and methods

2.1. Study area

The City of Phoenix, AZ, is the center of an expansive metropolitan area located on the northern edge of the Sonoran Desert (Fig. 1). June maximum daily temperatures average 40 °C, with the highest recorded temperature reaching 48.3 °C (Middel et al., 2012). Temperatures are amplified by the UHI effect, especially in regard to an enlarged minimum night time temperature (Chow et al., 2012; Hawkins, Brazel, Stefanov, Bigler, & Saffell, 2004; Stabler, Martin, & Brazel, 2005). This effect has been triggered by the massive growth in the metropolis. Since the middle of the 20th century, there have been major increases in the area of impervious surface and numbers of residential parcels and neighborhoods with different levels of vegetation and bare soil (including rock and desert surfaces). Residential landscape composition—variations of turf lawns to xeric- and desert-scapes—are associated with the period of development, rules of Home Owner Associations (HOAs), and income levels, among other factors (Chow & Brazel, 2012; Kane, Connors, & Galletti, 2014; Larson, White, Gober, Harlan, & Wutich, 2009b; Sha & Tian, 2010; Shrestha, York, Boone, & Zhang, 2012; Turner & Ibes, 2011). For the most part, the presence of vegetation and open greenspaces beyond residential parcels (e.g., parks and golf courses) varies across the city, with lower levels of both apparently related to lower income and Hispanic neighborhoods in Phoenix proper (Harlan et al., 2006; Jenerette et al., 2011).

2.2. Data and methods

2.2.1. Parcel and neighborhood selection

This study draws on residential census blocks (Fig. 1), our surrogate for neighborhoods, composed primarily, but not exclusively, of single family residential parcels and for which cadastral data provide land-use information for each parcel. Two random samples (A and B) were employed in order to verify the results of the exercise, and each sample was drawn by the same method (Fig. 1). The Create Random Points function in the GIS software ArcMap selected 1000 single family residential parcels (0.2% of such parcels in the city) for both samples. To ensure spatial independence, both samples were reduced by applying a distance filter in which each parcel had to be at least 1000 m from the others. The census block (neighborhood) for each parcel was identified, and another distance filter was applied: each census block had to be at least 500 m from one another. This sampling and filtering procedure yielded 21,505 and 24,167 single family parcels that are distributed over 523 and 545 census blocks, respectively, across the city. The parcel and census block selection outcomes are provided in Table 1 and the distributions of the A and B sample census blocks are mapped in Fig. 1.

At least two issues are noteworthy in our sample. First, parts of the metropolitan area with the highest SUHI were excluded from consideration because they are predominately nonresidential in composition. Nevertheless, the sample included neighborhoods within the higher SUHI zones adjacent to the central commercial district and to native-vegetation parklands, both of which tend to have high LST (Fig. 2). Second, census block data were employed because of our focus on the land architecture–LST relationship, which is more accurately captured at the fine-spatial grain of the census block rather than at the more coarse-spatial grain of the census block group. In a few cases, our sampled census blocks had 10 or fewer households, and household income data provided by the census are derived at the census block group level and applied to block level for our entire sample. These two issues may affect our results.

2.2.2. Land-cover classification

To examine the heterogeneous land architecture of neighborhoods requires detailed land-cover data. These data were derived through the image classification of the National Agricultural Imagery Program (NAIP) data, 1 m orthorized aerial photography taken from June 8–10, 2010. The NAIP dataset includes four spectral bands (red, green, blue, and near infrared band) with their radiances converted to a Digital Number ranging from 0–255, mosaicked at the county scale. The dataset was cookie-cut to the extent of the Central Arizona-Phoenix Long-term Ecological Research program (www.caplter.asu.edu), which covers most of the metro-Phoenix area, and preprocessed with pixel-based spectral transformations, which included *red*, *green*, and *blue* to *intensity*, *hue*, and *saturation*, *principal components analysis*, and Normalized Difference Vegetation Index (NDVI). An Object-Based Image Analysis (OBIA) was utilized to produce the land-cover classification (Li et al.,