Addressing Climate Change through Design: A Land Systems Science Approach to Assessing Microclimate Regulation in New Urbanist Developments

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INTRODUCTION

Global urbanization driven by an ever increasing proportion of the world population residing in cities contributes to climate change and exposes urban areas and inhabitants to its impacts (Grimm et al. 2008, Seto 2010). Scientists, non-governmental organizations, and a coalition of cities around the world agree that managing urban environments is one of the most important challenges of the 21st century and many cities are moving forward with climate change adaptation plans (Rozenweig et al. 2010, Solecki et al. 2013, UN, WHO, C40). Land change—alteration of the composition and configuration of the environment—driven by urbanization is one of the central ways that cities contribute to the causes and are exposed to the consequences of climate change (Kalnay and Cai 2003, Grimm 2008). Yet, there is great opportunity to intervene in current urban land change trajectories through design interventions that mitigate urban contributions and vulnerability to climate change (Rozenweig et al. 2010, Seto et al. 2010, Childers et al. 2015). The capacity to address climate change and its impacts through New Urbanist design specifically were recently articulated in the *Canons of Sustainable Architecture and Urbanism: A Companion to the Charter of the New Urbanism*, which outlines “action-oriented tools” to be “continuously developed and refined” through “information sharing” (Canons 2017). We argue that an important component of information sharing implied in the Canons is monitoring the performance of New Urbanist design interventions and that such efforts can best be accomplished by strengthening the nexus between design and empirical science. Moreover, we contend that built examples of New Urbanist design constitute experiments in climate change adaptation and offer important opportunities for empirical study and learning to inform future design. Here we extend well developed methods from land systems science, the study of “human-induced transformations of ecosystems and landscapes and the resulting changes in land cover,” (Verburg et al. 2013; 433) to develop a method for assessing the temperature regulating potential of New Urbanist design and apply it to Civano, a development in Tucson, Arizona, as a case study.

MEASURING THE ENVIRONMENTAL PERFORMANCE OF NEW URBANIST DEVELOPMENTS

The environmental agenda of New Urbanism posits that urban design via a combination of urban density, mixed-used development, multi-modal transit, greenbelts, green buildings, and context sensitivity to the natural environment will reduce a range of environmental problems associated with sprawl from open space consumption to carbon emissions (Farr 2008). Here, we focus on what Trudeau (2013) describes as the “technical” dimensions of environmental sustainability, the direct ecological benefits of the built environment (as opposed to indirect benefits such as behavioral changes, like walking over driving, encouraged by design), at the neighborhood scale. Although New Urbanist design principles can theoretically be applied to any scale—site, city, region—large emphasis is placed on the importance of the neighborhood unit (Talen 2005). Critics have argued that New Urbanism is “greenwashed” conventional suburban sprawl (Zimmerman 2001) or that design features such as dense and compact development or a tendency for many developments to be greenfield developments at the urban periphery, undermine the potential to protect ecosystems and land consumption, respectively (Audirac et al. 1990, Grant et al. 1996). Importantly, however, these studies do not directly measure the ecological functioning of the biophysical environment and, therefore, are basing those assessments on assumptions about linkages between design and environmental performance. A few studies measure the location (infill versus greenfield) and configuration of the built environment in New Urbanist developments (Song and

Knaap 2004, Conway 2009, Trudeau and Malloy 2011), but do not quantify environmental impacts associated with location and design. In partnership with the Green Building Council and the Natural Resources Defense Council, the Congress of the New Urbanism (CNU) helped create the third party rating system, Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND), to assess the extent to which neighborhood design promotes environmental sustainability (Green Building Council 2017). Similar to academic studies, LEED-ND offers insight into the potential environmental performance of neighborhoods by rating the design and configuration of built structures, but stops short of monitoring actual environmental performance (Garde 2009). In sum, New Urbanism endorses environmental sustainability through design principles that respond to the natural environment and partnerships with environmental groups to create the LEED-ND assessment system but, "there is no comprehensive inventory of the environmental impacts, either positive or negative, that the built New Urbanist projects have created," (White and Ellis 2007, 129). The handful of studies have attempted to directly measure environmental performance (2008, Turner and Galletti 2015) are discussed in the sections that follow. Additionally, several studies directly measure local (Crewe et al. 2016) or regional urban forms similar to those promoted by New Urbanism (e.g., Stone and Rodgers 2001, Stone et al. 2010), but not actual New Urbanist sites. There is a need for studies of *actual* New Urbanist developments that assess *actual* environmental impacts in order to substantiate or refute claims about the environmental performance of neighborhood design.

Land systems science (formerly known as "land change science") examines the role of land use (human activities associated with the land) and land cover (the physical composition and arrangement of land features) change to explain human-environment relationships (Turner et al. 2007, Verburg et al. 2013). It has traditionally focused on themes relevant to global environmental changes and relied on remote sensing technology, sensors mounted to satellites that detect energy reflected from the earth's surface, to provide environmental data (NOAA). Early remote sensing technology developed in late 20th century provided coarse resolution data capable of distinguishing urban areas based on the presence of built materials, but unable to describe intra-urban variation (Turner et al. 2007). New high resolution remote sensing data available in the 21st century is capable of detecting fine scale variation in urban environments, ushering in a new wave of land systems science focused on urban areas (Wentz et al. 2011). Following in the tradition of earlier work, urban land system science has largely focused on urban regions (c.f., Seto et al. 2012) and has not been widely applied at finer-scales, like the neighborhood, of central interest to urban planners. This may be due to data challenges; extracting fine-scale information about variability across a single land cover type is more difficult to do than to compare different land cover types (Kuemmerle et al. 2013). One exception is, perhaps, urban climate research, which is well suited to land system science approaches due to the importance of information about the land that is easily extracted from remote sensing data including vegetation, impervious surface, and temperature information. Urban climate is also a major environmental challenge that can be addressed through urban design.

URBAN CLIMATE IN THE SOUTHWEST

Urban areas are warmer and warming at a faster rate than their rural counterparts due to the Urban Heat Island (UHI) effect (Oke 1982; Brazel et al. 2007). A longitudinal study of urban and rural temperatures in the United States found that cities are on average 1.2-1.8° C warmer than their rural hinterlands and that the mean decadal rate of warming has increased from 0.08 C between 1951-2000 to 0.20° C over the most recent 20 years of the study (Stone 2009). Another study found that cities were 0.37° C warmer than their rural counterparts in 2010 (Debbage and Shepherd 2015). It should be noted, however, that while longitudinal and comparative analysis of UHI across cities are helpful for pointing out the general UHI signal, there is large variability in the approach and quality of data collection and analysis in these studies (Stewart 2011).

In arid-land cities, where water is scarce, climate regulation services are particularly salient due to tradeoffs between vegetated landscapes that lower land surface temperatures (LST) and the water resources required to irrigate them (Jenerette et al. 2011, Gober et al. 2012). In these cities, the urban climate constitutes a public health concern due to heat illness and morbidity, especially during extreme heat events, which have been increasing over time (Ruddell et al. 2012, Saha et al. 2014). Vegetation can provide a cooling effect in arid cities in which built areas have similar or lower temperatures than the surrounding desert due to the introduction of non-native vegetation such as turf grass (Brazel et al. 2000). Mitigating rising temperatures through increased vegetative cover, however, creates trade-offs with water availability in these regions (Gober et al. 2009). Studies have demonstrated that small increases in temperature correlate with large increases in water and energy consumption (Guhathakurta and Gober 2007; Aufhammer and Mansur 2014). Light colored, high albedo surfaces and building morphology can provide similar climate regulation benefits without irrigation (Akbari et al. 1997; Lindberg and Grimmond 2011), but do not provide the full range of co-benefits (e.g., habitat, recreation, carbon sequestration) that vegetated landscapes might provide.

Urban design plays a role in regulating climate and mitigating extreme heat events (Rosenzweig et al. 2006, Stone et al. 2001) and within cities there is large variability in microclimates between neighborhoods (Harlan et al. 2006). Such findings point to the importance of neighborhood design in climate regulation. Yet, until recently, most UHI studies examine general land use and land cover categories (e.g., urban, peri-urban, rural) and do not consider the role of fine-scale differences in urban form (Buyantuyev and Wu 2010, Su et al. 2010, Zhang 2014). Recent studies find that land composition as measured by percent paved surfaces, buildings, and green space are determinants of LST (Fan et al. 2011, Li et al. 2011, Connors et al. 2013, Middel et al. 2014, Zheng et al. 2014, Myint et al. 2015). Additionally, several of these studies found that land configuration also determined LST (Connors et al. 2013, Middel et al. 2014, Lin et al. 2016). One study found that at micro-scales, compact urban form provided more cooling than type of vegetative cover (Middel et al. 2014). Another found that composition explained LST in grass lawn residential areas, while configuration of vegetative and impervious surfaces explained LST in industrial and commercial areas (Connors et al. 2013). These studies underscore the complex relationship between form (land composition and configuration) and micro-climate in urban lands.

New Urbanist design may potentially mitigate UHI effects and increase thermal comfort due to its emphasis on clustering urban development alongside urban greening. Studies analyzing the relationship between UHI and urban forms associated with New Urbanism at the city scale uncover complexity. Early work associated dense urban development with the most pronounced UHI effects (e.g., Oke 1982, 1987). Recent studies have returned mixed results, finding that both sprawl (Stone and Rogers 2001, Stone et al. 2010, Stone 2012) and density (Coutts et al. 2007, Martilli 2014, Schwarz and Manceur 2014) increase UHI and extreme heat events. Another study found that contiguous urban land cover increases the UHI effect in both sprawling and compact cities (Debbage and Shephard 2015). New Urbanism emphasizes both compactness (aka., contiguity) and density (ratio of people or dwellings to land area), which may increase UHI, but also emphasizes mixed land uses that suggest heterogeneous spatial composition and configuration and urban greening, which may mitigate UHI (Jabareen 2006). It may be misleading, therefore to focus on one aspect of New Urbanist design to the exclusion of all others, due to the mixed effect of the various urban form prescriptions. The climate regulation and thermal comfort benefits of actual built examples of New Urbanist design at the neighborhood scale for which it is frequently implemented are relatively unknown.

A few nascent studies have examined climate regulation and other environmental benefits of New Urbanist developments or developments that use many of the principles of New Urbanism at the neighborhood scale. One study examined a downtown, urban infill project that used design principles similar to those advocated by New Urbanism and found the infill had lower daytime temperatures (but not always nighttime temperatures) (Crewe et al. 2016). A study testing watershed protection benefits found that New Urbanist greenfield developments were more likely to increase green space and New Urbanist infill developments are more likely to reduce impervious surfaces than conventional counterparts (Berke et al. 2008); New Urbanism, therefore, was associated with urban forms that could reduce UHI effect. Each of these studies suggests that the nuances of urban form can be vital to understanding relationship between New Urbanist design and temperature, especially at the scale of development.

RESEARCH DESIGN

Our goal was to compare the relative effect of different urban designs on local climate at the neighborhood scale. This approach stands intentionally in contrast to many studies in the environmental sciences that compare urban areas to a natural area baseline because no urban area can reasonably be expected to achieve the same level of environmental performance as natural areas. Using the planned development of Civano as a case study, we compared the influence of urban design on microclimate in a series of analysis. The first analysis examined the relationship between urban design and temperature and several environmental factors that influence or are influenced by temperature: vegetation, albedo, and water use. The second analysis focused on diurnal and seasonal differences in micro-climate at the neighborhood scale. Together, the analysis provides a comprehensive first look at the relationship between design and temperature, the potential to use land system science approaches at the neighborhood scale, and the potential to use New Urbanism to address urban climate issues in the arid Southwest United States. Case study background and greater detail on the data and methods used in this approach follow.

Case Study Background

Civano is a planned development built in two phases on the urban periphery of Tucson, Arizona and came out of planning efforts begun in the 1980s to build a "solar village" (Figure 1). The first phase, Civano I, used New Urbanist design principles such as regionally appropriate architecture and dense building configuration and even incorporated a Charette process led by leaders of the then burgeoning New Urbanist movement. The second phase, Sierra Morado, was developed by national builders, Pulte Homes, that focused on building technology to enhance energy efficiency did not use New Urbanist design principles. Civano is also adjacent to a conventional subdivision and otherwise flanked by semi-natural Sonoran Desert land. Due to the relatively similar size and adjacency, the three developments are well suited for studying the comparative effect of different urban designs against while holding the backdrop of the pre-development landscape relatively constant.

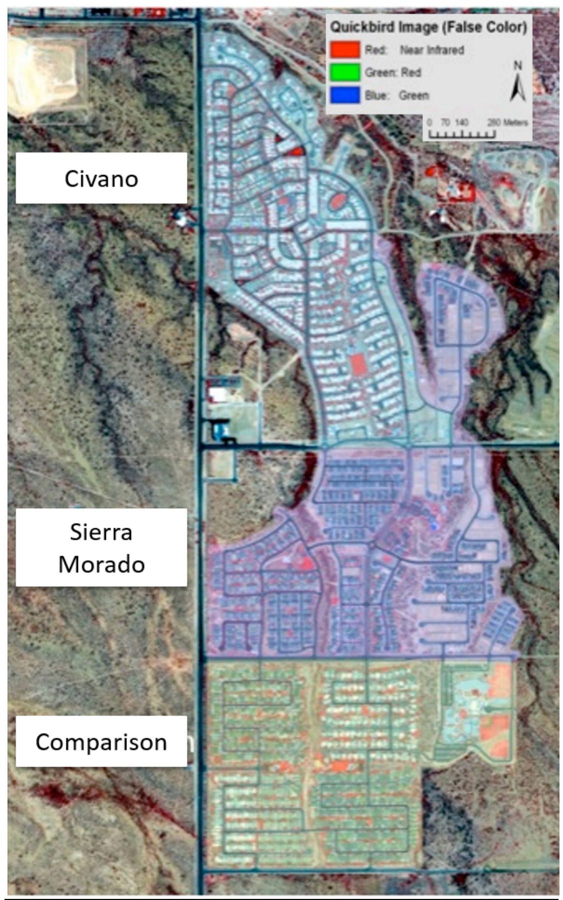

Figure 1: Quickbird Image of Study Area (2010)

Study 1 Data and Methods: Relating Neighborhood Design to Temperature and Environment

In order to characterize urban design and environmental outcomes, we leveraged several well established land system science methods to analyze fine-resolution remote sensing data. First, we used a traditional 'band ratio' approach to (1) classify land cover and (2) characterize environmental performance using higher resolution Quickbird (2.4m) and lower resolution Landsat (60m) June 2010 daytime remote sensing images. We used the following standard urban land cover classes: impervious surface, trees and shrubs, low and medium albedo buildings, high albedo buildings, exposed soils, grass, pools, and other water bodies (Mynt et al. 2013). We characterized environmental performance using the following metrics: vegetative cover (SAVI – soil adjusted vegetation index), albedo (ratio of solar short wave radiation reflected from the surface versus the amount absorbed), and temperature (land surface temperature). All environmental data was derived from the higher resolution Quickbird image except for temperature, which can only be derived from the lower resolution Landsat image. In addition, we obtained potable and non-potable water consumption data from the City of Tucson Water utility (city block scale). Next, we calculated 'landscape metrics' (percent composition, patch density per hectare, average building area) to characterize land composition and configuration. We calculated each variable at the city block scale to determine means for each neighborhood, Civano I, Sierra Morado, and the conventional subdivision, and to conduct multinomial logistic regression analysis. This approach allowed us to identify differences in design and environmental outcomes across neighborhoods as well as relationships between design and outcomes that were statistically significant. For a detailed description of data and analysis methods see (Turner and Galletti 2015).

Study 2 Data and Methods: Day-Night and Seasonal Differences in Neighborhood Microclimate
In the second analysis, we used geospatial methods to identify patterns of high and low temperature in the study area across day and night and seasons. We collected land surface temperature for June, April, and January 2014, using Landsat (30m) for daytime and ASTER (90m) for nighttime images. Similar to the first study, we used traditional band-ratio methods to characterize albedo and vegetation (NDVI – Normalized Difference Vegetation Index) in addition to temperature. In this study, we used Local Indicators of Spatial Association (LISA) to identify "hot spots" of high and low temperature values across the three communities. Finally, we used two analytic methods, spatial regression models and spatial lag models, to determine relationships between land surface temperature and albedo and vegetation. For a detailed description of data and analysis methods see (Galletti et al. *under review*).

RESULTS

Cumulatively, the results from these two studies reveal that the New Urbanist design of Civano I more successfully regulated microclimate than both the green building approach used in Sierra Morado and conventional subdivision development. Moreover, these findings hold across time of day and season.

Neighborhood Design
Civano I had the lowest impervious surface coverage and density, highest coverage and density of high albedo area, lowest coverage and density of low albedo area, and the highest coverage and density of trees and shrubs (Table 1). Overall, these findings indicate that by clustering buildings, Civano was able to achieve design that minimized impervious surfaces and maximized green space. Interestingly, Sierra Morado had the highest impervious surface coverage, which was dominated by low albedo area, and the lowest tree and shrub coverage and density. These findings suggest that the urban design of Sierra Morado was unable to achieve impervious surface and vegetation coverage commensurate with even conventional subdivision sprawl.

Table 1: Composition (percent) and Density (patches per hectare) of Impervious Surface, High and Low Albedo Area, and Trees and Shrubs at the Neighborhood Scale.

		Civano	Sierra Morado	Comparison
Impervious Surface	Composition	14.9829	22.0606	17.3324
	Density	194.6092	337.8262	307.9749
High Albedo Area	Composition	12.7938	0.1168	1.6521
	Density	957.6452	68.7104	325.8484

Low Albedo Area	Composition	8.7471	23.2316	25.8297
	Density	1771.0836	344.9836	537.5812
Tree and Shrub	Composition	29.1785	16.0748	22.9375
	Density	1176.0555	1238.219	1286.8951

Temperature and Relationship to Environmental Variables

In the first study, Civano had the lowest mean temperature (Table 2)—although differences were relatively small across the three neighborhoods—and city blocks with the lowest temperatures were concentrated in Civano. Civano also had the highest mean albedo and vegetative cover. Interestingly, the comparison community had a lower mean temperature, higher albedo, and higher vegetative cover than Sierra Morado. High albedo and vegetative cover were correlated with lower temperatures at the city block scale, however, the relationship between albedo and vegetation was stronger. Both Civano and Sierra Morado had lower potable water consumption than the comparison community due to non-potable water supply supplements for outdoor water use. Civano utilized non-potable water in common areas and individual lots and Sierra Morado only utilized non-potable water in common areas and in much higher amounts. Results of the multinomial regression analysis showed that differences in temperature, albedo, vegetation, and potable and non-potable water consumption between Civano and the other neighborhoods were statistically significant (Turner and Galletti 2015).

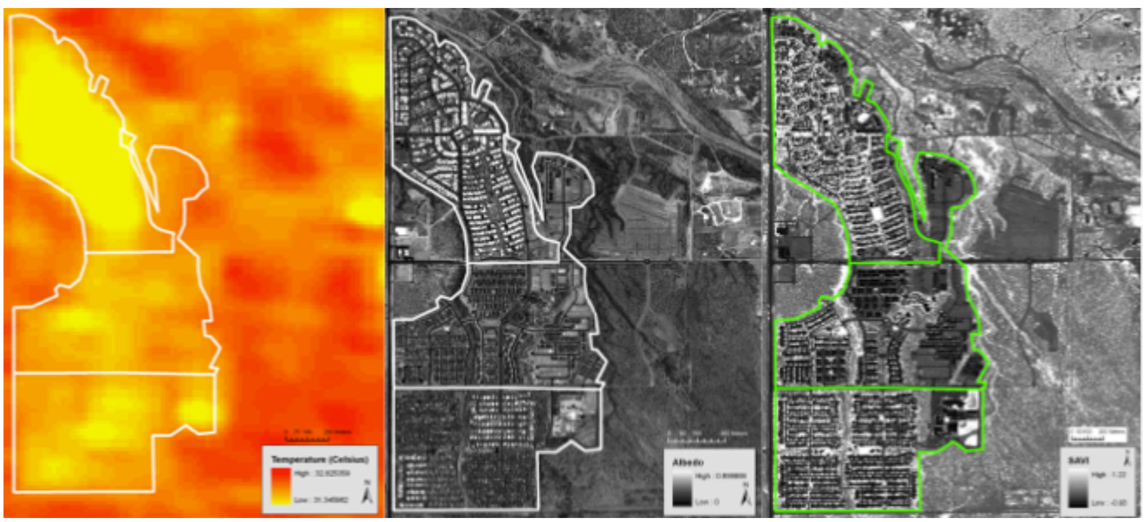

Figure 2: Remote sensing images for temperature (left - high red, low yellow), albedo (middle - high white, low black), and vegetation (right - high white, low black) for Civano (top), Sierra Morado (middle), and the comparison neighborhood (bottom) (Turner and Galletti 2015)

Table 2: Mean temperature, albedo (ratio), vegetation (index), potable and non-potable water consumption at the neighborhood scale (Turner and Galletti 2015)

	Temperature (Celsius)	Albedo	Vegetation	Potable Water (CCF)	Non Potable Water (CCF)
Civano	31.59	0.13	0.262	65.25	68.52
Sierra Morado	31.96	0.074	0.178	63.94	428.53
Comparison	31.91	0.08	0.237	103.56	N/A

Day-Night and Seasonal Differences in Neighborhood Microclimate

The second study corroborated findings from the first that low temperatures were concentrated in Civano and higher temperatures were found in Sierra Morado than in the comparison neighborhood. Temperature differences were more pronounced during the day during which Civano was, on average, 1.5 C cooler than Sierra Morado and the comparison neighborhood, than at night when Civano was, on agerage, 1.0 C cooler. Low temperature areas were clustered almost entirely in Civano and this was true for all seasons (January, April, and June), day and night. The second study also found that low temperature was related to high albedo and vegetative cover and that, overall, Civano performed the best on each of these environmental variables.

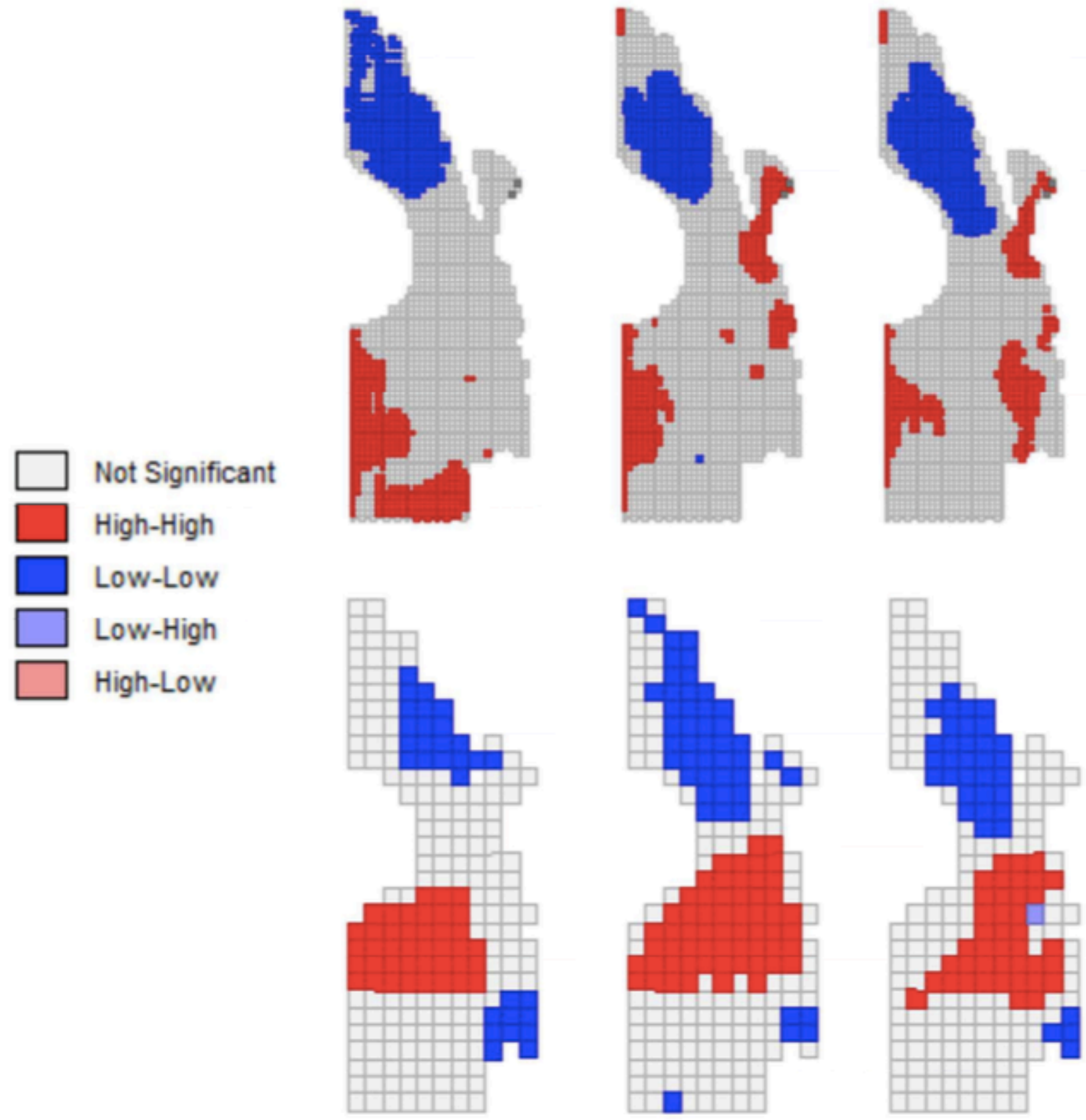

Figure 3: Clusters of high (red) and low (blue) land surface temperature in the study area for January (left), April (middle), and June (right) for day (top) and night (bottom) (Galletti et al. *under review*).

DISCUSSION

The comparative approach taken in this series of studies confirms previous findings that large differences in microclimates can be detected between neighborhoods (Harlan et al. 2006) and that these differences are attributable to both land composition (Fan et al. 2011, Zhou et al. 2011, Li et al. 2011, Connors et al. 2013, Middel et al. 2014, Zheng et a. 2014, Myint et al. 2015) and configuration (Zhou et al. 2011, Connors et al. 2013, Middel et al. 2014, Lin et al. 2016). Findings from these two studies align with predictions that the diverse composition and configuration of New Urbanist design can successfully regulate climate (Jabareen 2006) by mitigating the heating effects of dense and contiguous urban land cover (Oke 1982, 1987, Coutts et al. 2007, Martilli 2014, Schwarz and Manceur 2014, Debbage and Shephard 2015, Middell et al. 2014)). New Urbanist design was able to regulate climate effectively by clustering buildings with high albedo surfaces, echoing findings from previous studies in non-New Urbanist study sites (Akbari et al. 1997, Lindberg and Grimmond 2011). While a reliance solely on albedo to regulate climate would ignore the ecosystem service benefits of vegetation, our studies found that New Urbanist design also provided dense vegetative cover successfully, echoing a previous study that found sites perform well in terms of green space provisioning (Berke et al. 2008). These findings are promising and suggest that the specific design mix articulate by New Urbanism can be an important tool in mitigating and adapting to the micro climate impacts of climate change, especially in the arid Southwest United States.

Future research would benefit from extending the approach developed here that borrowed from land system science methods to a larger number of New Urbanist developments and different contexts and environmental problem domains. One challenge to such an extension is that other New Urbanist developments may not be located near comparable sites. While this set of studies examined temperature in suburban, greenfield development, it would be beneficial to examine the performance of New Urbanist sites across the urban-to-rural transect. Ecologists for instance, have hypothesized peak performance of green infrastructure in suburban sites (Mitsch and Gosselink 2000). Similarly, the climate regulation benefits of New Urbanist sites undoubtedly depend on urban intensity. Moreover, climate regulation is only one environmental goal to consider with respect to climate change. Examining the effectiveness of New Urbanist design to deliver a range of environmental benefits, especially those enumerated in the Canons, could be done by extending the methods used here to examine, for instance, the impact of urban design on water quality, which can also be detected using remote sensing (e.g., Ortiz et al. 2013). The results presented here rely solely on remote sensing data, however, new research domains in land system science utilize “ground truthing” methods of collecting field data to corroborate findings. Adding field data on building height and wind speed as well as direct temperature measurement would increase the robustness of future studies. Finally, land system science recognizes the importance of human decision-making and management activities in influencing environmental performance. There are several well established frameworks for systematically relating human institutions to environmental outcomes to produce generalizable insights into the management pathways that are most likely to produce environmentally sustainable outcomes (e.g., Ostrom 2009). In the case of New Urbanism this would involve understanding how institutions such as land use policy, financing instruments, contractors, and property management companies influence land management during planning, implementation, and post-implementation phases of development (Hostetler and Drake 2009).

CONCLUSION

It is critical to produce empirical data linking design to environmental performance in order to build the case that New Urbanism should be an important component of climate change adaptation as articulated in the Canons and to promote learning when claims are not substantiated. It is especially critical to directly measure the environmental performance of actual built examples of New Urbanist developments because claims based on hypothesized environmental performance may not be sufficient to meet evidence criteria used by decision-makers and developers (Lubchenco 1998, Kingsley 2008). We have presented one approach to producing direct measurement of "technical" environmental sustainability that applies well developed methods from land system science to a New Urbanist case study and one environmental problem domain: urban climate. As recognized in the Canons, New Urbanism may be able to address myriad environmental problem domains related to climate change; however, there are trade-offs between various environmental goals inherent to specific design elements that will require decision-making processes for sorting between different normative objectives. It will be important for New Urbanists to be empowered with empirical data in order to meaningfully participate in decisions about climate adaptation moving forward.

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