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Beyond fragmentation at the fringe: A path-dependent, high-resolution analysis of urban land cover in Phoenix, Arizona

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A B S T R A C T

A common critique of urban sprawl is that it leads to increased land fragmentation, which has negative social and ecological implications. Consistent with theory, empirical research generally finds increased levels of fragmentation near the urban fringe. We apply landscape metrics to 1-m resolution remotely sensed imagery of the City of Phoenix, Arizona from 2010 in order to analyze urban sprawl based on the area, fragmentation, shape complexity, and diversity of land covers at a resolution finer than that of an individual land parcel. While previous work typically defines areas by how far they are from the central city, we identify census block groups in Phoenix based on the decade during which they became developed in order to observe landscape variation based on the age of a neighborhood area. Results confirm substantial variation in present-day land cover patterns based on the timing of development: landscape structure in Phoenix is heavily path-dependent. While land covers in newer-developing regions generally appear more fragmented, more homogeneous, and less diverse, the complexity of shapes and incidence of desert landscaping appear to be higher as well. Areas that developed principally during the 1990s and 2000s appear noticeably different than their older counterparts across many measures used. We speculate that institutional changes and evolving preferences for various development types explain much of this present-day variation.

Introduction

Patterns of human settlement are changing rapidly around the world as the global population becomes increasingly urban. In addition, economic and social changes affect the pattern of land use and land cover within cities, altering the structure and form of urban environments. These changes in spatial structure in turn transform ecological functions, such as hydrological systems and biogeochemistry (Grimm et al., 2008). Changes in land cover and ecological process have far reaching impacts for ecosystem services, which in turn shape various social and economic outcomes (Bolund & Hunhammar, 1999; Tratalos, Fuller, Warren, Davies, & Gaston, 2007). As urbanization continues and urban spatial pattern evolves, research is needed to inform planning and management of urban areas, addressing the causes and impacts of different urbanization patterns (Klosterman, 1999; Longley & Mesev, 2000), which are heavily impacted by policy (Carruthers, 2003; Newburn & Berck, 2006).

Urban form and patterns of urban growth have long been of interest to geographers. This topic has been widely explored in relation to socioeconomic activities (see, e.g., Knox, 1991), but more recently scholars have become interested in environmental implications: namely, how different spatial patterns in cities may impact ecosystem processes with implications for ecosystem services and adaptation to environmental change (e.g., Alberti, 2005; Alberti & Marzluff, 2004; Turner, Janetos, Verburg, & Murray, 2013). Concerns for both socioeconomic and biophysical implications of urban spatial pattern are often aired in conjunction with critiques over urban sprawl. Definitions of urban sprawl vary, but the term generally refers to the excessive spatial growth of cities (Brueckner, 2000), which is characterized by low-density development and automobile-dominated infrastructure and lifestyles (Bruegmann, 2005). Considering the variety of phenomena encompassed, Ewing, Pendall, and Chen (2002) suggest three specific spatial dimensions of sprawl: low-density population, new development on the periphery without a clear activity center, and widely separated built structures.

Additionally, the form and style of agglomeration is highly dependent on place and historical context (Bruegmann, 2005). Urban spatial structure is heavily path-dependent (Arthur, 1988),

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continuously characterized by the infrastructure and planning of past periods of development. The way a neighborhood looks today is largely reflective of the era during which it was built, "locking in" the effect of short-term housing booms, the principal economic activities of the time, and the dominant communication and transportation technology (Adams, 1970; Anas, Arnott, & Small, 1998). Given these legacy effects of urbanization, understanding the characteristics of historical time periods during which growth occurred can inform the understanding of present-day landscape variation.

Research analyzing the detailed characteristics of patterns of sprawl has been supported by the increasing availability of spatial data and the development of new methods of spatial analysis. Whereas earlier geographic analyses were often limited by data availability, recent studies have benefited from the proliferation of earth observing (EO) sensors to examine specific changes in urban landscapes, and to evaluate theories of urban development (e.g., Dietzel, Herold, Hemphill, & Clarke, 2005; Taubenböck et al., 2014). EO methods provide the ability to examine regional, continental, and even global scales. At regional scales, sprawl studies have employed EO data to examine agglomeration around urban cores (Dietzel et al., 2005; Taubenböck et al., 2014) and to facilitate comparison between urban areas (Burchfield, Overman, Puga, & Turner, 2006; Schneider & Woodcock, 2008), examining changes in the extent of built-up areas or even changes in vertical structure across different cities (Frolking, Milliman, Seto, & Friedl, 2013). These comparisons of urbanization around the world reveal distinct patterns of growth, suggesting that growth trajectories vary across cities (Schneider & Woodcock, 2008). To facilitate such comparison and to capture the more nuanced characteristics of urbanization, Seto and Fragkias (2005) call for a diverse set of quantitative measurements that describe various facets of urban growth and that help to infer the underlying processes that drive observed urban forms. Similarly, Siedentop and Fina (2010) suggest that a multi-indicator approach should be used to identify three aspects of sprawl: urban density, pattern, and composition.

In order to characterize such aspects of urban spatial pattern, an increasing number of urban studies have employed an array of spatial metrics common in landscape ecology (Turner, 1989). Spatial metrics provide measures of landscape pattern derived from the analysis of thematic-categorical maps, which first segment the observed landscape into patches of adjacent pixels of the same class and then use this information to quantify landscape patterns. Spatial metrics commonly provide descriptive measures of the spatial characteristics of individual patches, all patches in a given class, or all patches in the landscape. Various metrics have been developed (Li & Reynolds, 1993; Turner, O'Neill, Gardner, & Milne, 1989) and implemented in different software packages, most notably FRAGSTATS (McGarigal & Marks, 1994). Ecologists have long employed these tools because changes in the shape, size, prevalence, and connectivity of different land cover patches, as well as the positions of these land covers relative to each other, can have significant impacts on various ecological processes (Turner, 1989; Turner, Gardner, & O'Neill, 2001). Studies of sprawl commonly incorporate these metrics, but often only identify two thematic classes that distinguish between "developed" and "undeveloped" patches. Nonetheless, EO datasets can support more complex classification schemes, which can be useful to characterize specific features of certain regions (for example, identifying structure types within informal settlements in the developing world, see Banzhaf & Hofer, 2008; Kuffer & Barros, 2011), but these are partially dependent on the resolution of the EO data.

In recent years, numerous studies have applied landscape metrics to the study of urban morphology (e.g., Wu & Webster, 2000; York & Munroe, 2010), most commonly employing moderate resolution data, such as Landsat and the National Land Cover Dataset (NLCD), which consist of 30 m × 30 m pixels. For example, York et al. (2011) and Zhang, York, Boone, & Shrestha (2013) used Landsat-derived data to estimate metrics of fragmentation in several rapidly growing US cities and demonstrated that fragmentation typically increases with distance from the city center. McDonnell and Hahs (2008) review 300 papers that rely on the variation of urban intensity along an urban–rural gradient in order to understand differences in ecosystem processes, but little of this research has empirically assessed differences in detailed spatial patterns of land cover (beyond general categories of land use) or small scale habitats.

Moderate resolution analyses offer important information on regional scale change, but increasingly complex use of urban space necessitates a scale-sensitive, micro-level approach (Irwin, Jayaprakash, & Munroe, 2009) – a perspective shared by ecologists (Pickett et al., 1997; Wu & Loucks, 1995). The moderate resolution imagery relied upon for most prior studies has proven useful for tracking the expansion of urban areas, but is ill-suited for capturing the fine details that characterize urban landscapes (Herold, Couclelis, & Clarke, 2005; Irwin & Bockstael, 2007; Theobald, 2001). For example, Burchfield et al. (2006), develop an index of sprawl using NLCD data and find that, across the entire US, the extent of scatteredness in urban areas was essentially unchanged from 1976 to 1992. Irwin and Bockstael (2007) challenge their conclusions, augmenting NLCD data with land use records in Maryland to demonstrate that fragmentation (using landscape metrics) is not static over time, does vary across an urban–rural gradient, and requires a finer resolution approach. Recognizing this need, some studies have begun to use landscape metrics to analyze finer resolution data to identify and characterize specific components of urban form. Taubenböck and Kraff (2013) used spatial metrics of high resolution data to identify the physical properties of slums in Mumbai using Quickbird imagery (0.6 m resolution). Kuffer and Barros (2011) used Quickbird and Ikonos (4 m resolution) in Dar es Salaam and Delhi to identify unplanned areas in cities. Similarly, Banzhaf and Hofer (2008) used object-based methods on aerial photographs to identify specific types of urban structures. In combination, these examples illustrate the potential application of high-resolution datasets and pattern analysis techniques to improved characterization of urban landscape features.

This paper analyzes fine-grained aspects of sub-metropolitan spatial pattern in Phoenix, Arizona based on when an area within the city was developed, relying on the path-dependent nature of cities to understand variation in present-day patterns of land cover. Urban morphology is largely the product of historical development trends, while the durability of built capital means that the environmental consequences of development will persist for several decades after the process that led to their construction has played out. In particular, Boone et al. (2012) argue that the timing of development is crucial for urban ecosystem structure and function. Put simply, different areas within a city are expected to have different landscape characteristics based on when they were built. This study adds to the literature above because it 1) uses higher resolution spatial data, 2) uses high thematic resolution (i.e., beyond developed/undeveloped), and 3) considers variation in spatial pattern by historical development periods rather than by intrametropolitan location. We use 1-m resolution NAIP (National Agriculture Imagery Program) images of Phoenix, Arizona from 2010, which has the ability to identify variation within parcels of land – including, for example, individual trees, sidewalks, and patches of lawn. We use spatial metrics to identify four characteristics of land cover relevant to urban sprawl: area and density, fragmentation, shape complexity, and diversity. We analyze these metrics across 946 sub-metropolitan units in Phoenix (census block