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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 groups) based on the time period in which they were developed in order to understand how present-day urban spatial pattern varies based on when areas of the city became developed.

Material and methods

Study area

Phoenix's urban history did not begin in earnest until the start of the twentieth century. The city's 1915 boundaries, generally considered to be the "original townsite" (York et al., 2014) encompass 10.4 square kilometers, while its 2012 boundaries include 2079 square kilometers. Residential land use dominates the city in terms of land area, comprising 69% of the built-up area in its historic core in 1915 and 62% of the built-up area in 2012 (Kane, York, Tuccillo, Ouyang, & Gentile, 2014). The urban (developed) extent of the entire metropolitan area increased similarly from 48 square kilometers in 1934 to 2537 square kilometers in 2010 (Knowles-Yanez et al., 1999 and authors' calculations).

Early growth in Phoenix followed a relatively concentric pattern extending outward from the Central Business District (CBD), facilitated by the limited presence of existing manmade features and the fact that automobile transportation was adopted fairly early in the city's history (VanderMeer, 2002). This pattern began to change in the early 1960s when the CBD ceased to be a major draw and growth became more polycentric and dispersed (Kane, Tuccillo, York, Ouyang, & Gentile, 2014). Development styles contrast dramatically across time periods, in Phoenix and in general (Gober, 2006; Judd & Swanstrom, 2008). Early homes and businesses of the 1920s, localized near downtown, were largely built in the same manner as in older cities. Mass-produced single-story tract homes characterized residential construction following World War II, while gated and master-planned communities became popular beginning in the 1970s. During the latter period, large shopping malls and office parks supplanted older commercial space in Phoenix's CBD. Discussion of more recent changes typically focuses on fringe development, with the real estate boom that began in the late 1990s taking place most prominently farther from the city center (Gober & Burns, 2002). This happened in "boomburbs" such as Chandler and Gilbert but also in the far northern and southern parts of the City of Phoenix. Atkinson-Palombo (2010) finds that growth during the early 2000s was more varied than the prior decade, with denser, multifamily housing near the urban fringe augmenting single-family development there. Conversion of former agricultural land ground to a halt during the 2006–2008 recession (Kane et al., 2014).

Delineating historical periods

The purpose of this study is to investigate how spatial indicators of urban sprawl vary across areas within a city based on the time period during which present-day structures were built. While a city-wide indicator of sprawl may be interesting in a cross-site context, our goal is to capture sub-metropolitan variation in sprawl indicators, following the idea within urban design that geographic pattern informs a sense of place and drives the experiences of individuals (see, e.g., Talen, 2011), and that environmental implications of development such as the urban heat island are often localized (see, e.g., Connors, Galletti, & Chow, 2012). Furthermore, the surroundings of an individual are not confined to a single land parcel, but also include the streets, public spaces, and other land uses nearby. Thus it is necessary to define an appropriate areal unit at which to analyze sprawl.

Prior studies such as Shrestha, York, Boone, & Zhang (2012) and Zhang et al. (2013) use a grid or a rectangular moving window. Instead, we chose to use US Census Block Groups because they are intentionally delineated by the Census Bureau such that they contain between 600 and 3000 people. While a block group certainly does not define an actual neighborhood, this characteristic ensures that each block group represents some functional urban space. Furthermore, block groups are the closest census aggregation unit to the optimal moving window size suggested by Zhang et al. (2013). The City of Phoenix is comprised of 977 block groups. Excluding 19 unusually large (larger than 11.5 km^2) block groups which represented large conservation areas or unoccupied desert, block groups in this study range in size from 0.08 km^2 to 11.3 km^2, with a mean of 1.02 km^2 and standard deviation of 1.20 km^2 ($N = 958$). Our study calculates landscape metrics for all block groups and does not rely on random sampling.

Reliable data on buildings and structures for the city of Phoenix are available from the Maricopa County Assessor's Office and were cross-checked with the Maricopa Association of Governments, a regional planning body. These data record the construction year of the buildings on each land parcel as of 2012. In order to identify the historical time period during which development in a block group began to resemble its present-day form, we describe each block group using the decade by which half of the present-day structures had been built. While some buildings in Phoenix date back to the 1880s, the oldest block group using this classification technique is actually from the 1920s (Fig. 1). However, only one block group is dominated by 1920s construction, two are dominated by 2010s construction, and nine block groups date principally from the 1930s. In contrast, defining historical zones by the age of the oldest building in an area, or by the time period during which the most construction occurred is less consistent with the path-dependent nature of development. Our goal is to identify when a sub-metropolitan area became "substantially developed" relative to its present-day land cover characteristics.

This study compares present-day land cover characteristics (2010) with the age of the present-day building stock, as described above. In general, development in Phoenix is continually characterized by a desire for new construction in new areas (Gober, 2006). Infill development is comparatively rare: buildings are not often knocked down, which makes this method of using public records from 2012 to identify historical zones a reasonably accurate indicator of when an area was originally developed.

Image classification

The satellite images were classified using object-based image analysis (OBIA) and classification methods. OBIA methods are increasingly favored for the classification of high-resolution images because they can take advantage of the spatial and contextual information present at finer scales (Benz, Hofmann, Willhauck, Lingenfelder, & Heynen, 2004; Blaschke, 2010). OBIA methods have two stages: segmentation and classification. Image segmentation involves grouping adjacent pixels with similar values into objects (Baatz & Schape, 2000). Once formed, objects may then be assigned various values based on spectral and spatial properties calculated from all of the encapsulated pixels (e.g., averaging the reflectance of all pixels in the object). Objects are then assigned to discrete land cover classes using decision-based rule sets or automated algorithms. We used a set of decision-based rules to classify the objects. Seven land cover classes were extracted from the classified NAIP image: buildings, roads, trees, grass, soil, shrubs, and croplands. After the classification, the results were inspected and obvious errors were manually corrected. Using this approach, we were able to achieve 91.86% accuracy (Li et al., submitted for publication).

The decision to use these seven land cover classes (buildings, roads, trees, grass, soil, shrubs, and cropland) is based on changing

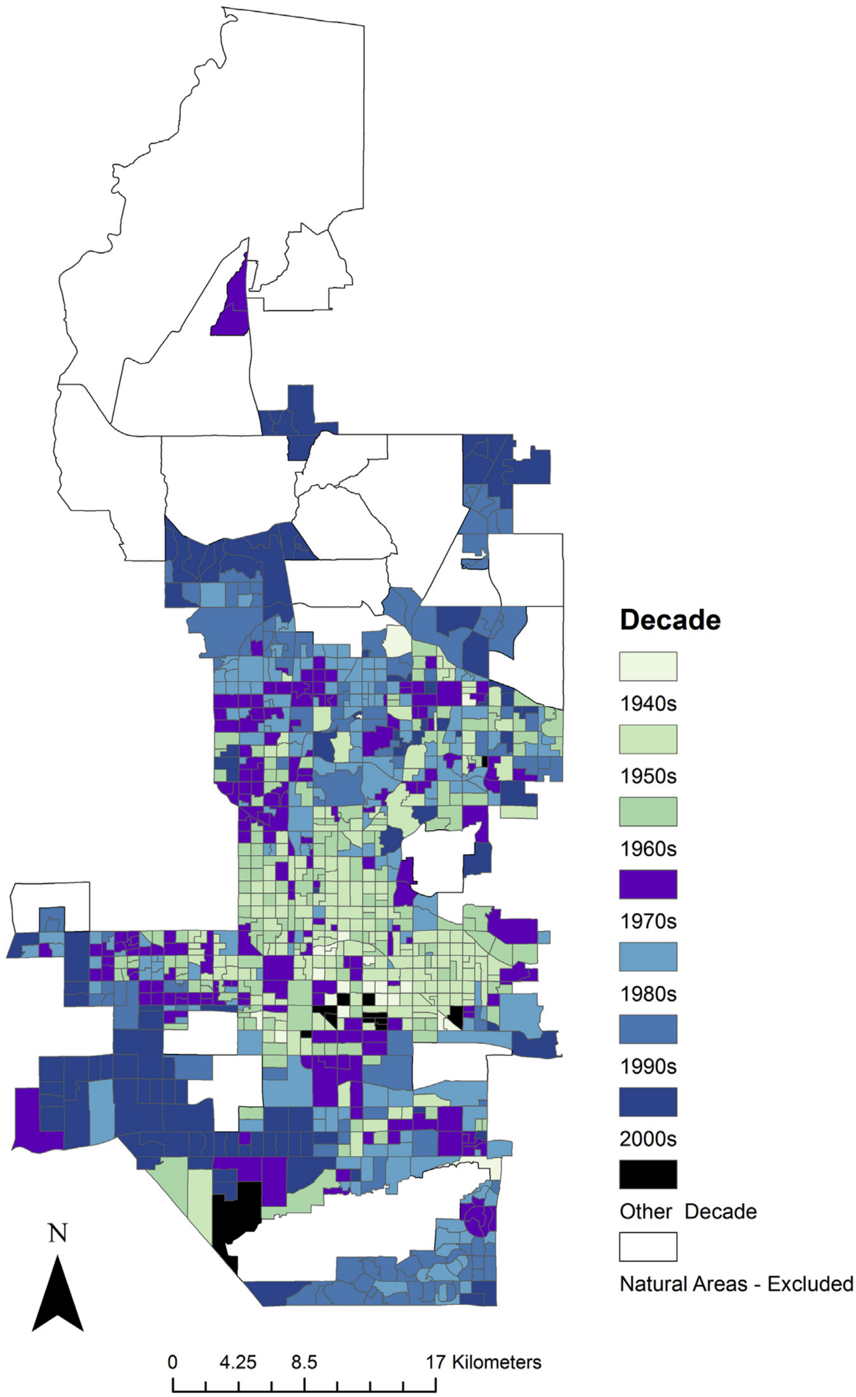

Fig. 1. Phoenix block groups by dominant construction decade.

development patterns in Phoenix and previous studies (e.g., Myint, Wentz, Brazel, & Quattrochi, 2013). These land cover classes were chosen to capture the heterogeneity of urban parcels in Phoenix, particularly the variation in residential landscaping. This finer thematic resolution, identifying land covers beyond the urbanized–nonurbanized dichotomy, provides the ability to examine detailed patterns in urban form and development. The land cover scheme includes some land covers that are natural to the American Southwest, such as desert soil and shrubs, but these features were largely replaced by turf lawns and non-native vegetation during earlier development periods (particularly in the 1960's and 1970's). New trends in development, however, have encouraged so-called xeric landscaping, which changes the land cover in residential areas from what would have been turf grass and trees to something that might mimic natural desert, such as soils. Because cropland and shrub classes represented only a very small proportion of the total land area within the Phoenix city limits, we excluded them from our subsequent statistical analyses.

Subset images

We conducted our analysis at the block group level to provide an approximation of neighborhood areas, and in order to facilitate future comparison to census data. Using an automated process in a

Python code, we extracted 958 image subsets, each conforming to the boundary of one census block group. In other words, using the boundaries of each individual block group in the City of Phoenix, we clipped the classified image, creating 958 separate images for analysis. To illustrate this process, Fig. 2 shows a selection of these subset land cover images for six different block groups from different historical zones.

Spatial metrics

In order to characterize the spatial pattern within each block group, we calculated spatial metrics for each of the 958 images using the FRAGSTATS package (McGarigal & Marks, 1994). FRAGSTATS calculates three types of spatial metrics. Patch metrics are measures assigned to each individual patch, or contiguous area of a single land cover type. Class metrics provide a measure of spatial structure for all patches of the same class within the image – for example, the proportional area of tree cover for the entire census block group would be a class metric. Landscape metrics incorporate all patches of all land cover classes, for example to measure diversity or interspersion. This analysis calculates class and landscape metrics.

Schneider and Woodcock (2008) identified four urban growth indicators: size of built-up area and rate of change, density of built-up land, fragmentation, and population density. Whereas they conducted an interurban analysis, we are concerned with intra-urban characteristics and therefore modify this framework to suit the higher spatial and thematic resolution of our one-city analysis. Rather than looking at size and density of built up areas, we consider the size and density of each land cover class because we are concerned with variation within built-up areas. Similarly, we consider the fragmentation of each land cover type rather than fragmentation of non-built up areas en masse. Following Herold, Liu, and Clark (2003), who use 4-m Ikonos imagery to analyze urban areas, we also investigate fractal dimension and contagion indices as measures of shape complexity. We additionally consider interspersion and diversity because these metrics are widely used to characterize fragmentation, particularly in studies of lower thematic resolution examining encroachment on non-urban lands. In sum, we selected metrics that concern the 1) area and density of

Table 1
Basic description of spatial metrics used in our study.

Metric	Level	Basic description
Simpson's Diversity (SIDI)	Landscape	The square of the proportion of the landscape occupied by a patch type, summed over all patch types. In other words, the probability that any 2 randomly selected pixels would be of a different class.
Simpson's Evenness (SIEI)	Landscape	The Simpson's Diversity Index divided by the maximum possible Simpson's Diversity. It approaches zero when the landscape is dominated by a single class.
Contagion Index (CONTAG)	Landscape	A measure often used to determine the level of fragmentation between pixels. Contagion is high when a single class occupies a very large percentage of the landscape. It increases with an inequitable distribution of pairwise adjacencies.
Fractal Dimension (FRAC)	Landscape and Class	A measure of landscape complexity or fragmentation based on perimeter-to-area relationships. The area-weighted mean version is used.
Interspersion and Juxtaposition Index (IJI)	Landscape and Class	Measures the level of intermixing of patch types. The maximum value is achieved when all patch types are equally adjacent to all other patch types.
Patch Density (PD)	Landscape and Class	The number of patches in the landscape divided by the total area.
Percent of Landscape (PLAND)	Class	The percent of the total landscape represented by this class.
Contiguity Index (CONTIG)	Class	An assessment of the spatial connectedness (contiguity) of pixels based on a 3x3 pixel neighborhood. The area-weighted mean version is used.

Descriptions based on McGarigal and Marks (1994).

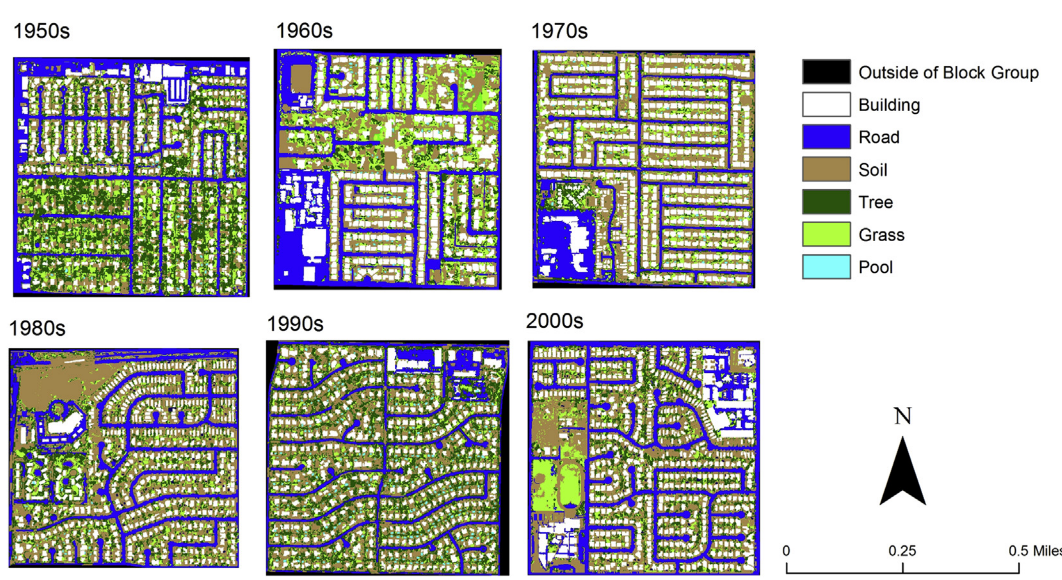

Fig. 2. Samples of block group land cover by decade. These examples show subsets of our image, depicting the land cover for six different block groups. For illustration purposes, we selected images from different historical zones, although these may not be representative of all block groups in each given historical zone.

land covers 2) fragmentation/scatter, 3) shape complexity, and 4) diversity. These characteristics were selected because of their relevance to the broader definitions of urban sprawl, discussed above, and the specific metrics were selected because of their use in prior studies, thus facilitating comparison. The six landscape and five class metrics chosen are outlined in Table 1.

ANOVA

In order to analyze the differential impact of the timing of development on present-day land cover, we used Analysis of Variance (ANOVA) to identify statistically significant differences in spatial metrics between development periods. Tukey's HSD post-hoc test creates a confidence interval and significance value (*p*-value) for each pair of decades, using block groups as the unit of analysis. Since very few block groups became substantially developed (relative to their present-day form) prior to the 1940s or since the 2000s, we compare decades from the 1940s until the 2000s. Our statistical analysis, therefore, is performed on a total of 946 block groups.

Results

Comparing the historical zones, the results reveal that more recently constructed areas differ in several ways from their older counterparts. In general, many landscape and class metrics appear to significantly vary based on the time periods during which areas were developed, which have in turn shaped variation in Phoenix's spatial structure. Many metrics, however, remain consistent across the different historical zones. Below, we discuss the specific differences in urban morphology among the historical areas.

The results of our ANOVA are presented in the form of cross-tabulation matrices. Each position within the matrix represents a comparison between two historical periods, and indicates whether the mean values were higher or lower in later construction periods compared to earlier construction periods. Each position also notes the statistical significance of the comparison through ANOVA post-hoc tests. Landscape metrics are presented in Table 2 and class metrics are shown for each individual land cover class in Table 3. Fig. 3 also shows landscape metrics as boxplots, which display the variation in each landscape metric by development decade. The percent of the total landscape occupied by each class is shown as a stacked bar plot in Fig. 4. These results are discussed in detail below.

Area and density of land covers

Comparing the various historical zones, there is evidence of significant differences in the area and density of impervious features (buildings and roads). Buildings, in particular, show a notable decrease in their proportional cover (PLAND) across the historical zones as the construction data advances in time. The highest proportional area of buildings is found in block groups dominated by 1950s construction, occupying an average of approximately 19 percent of the total area. In contrast, the 2000s historical zone has an average proportional area of only 11 percent. The ANOVA results corroborate, indicating that this decrease was significant when comparing more recently constructed areas (1990s and 2000s) with areas built between the 1950s and 1980s. The same pattern is apparent for patch density (PD) of buildings, indicating a lower density of buildings in more recent construction zones as well. Similarly, the proportional area of roads is lower in the 1990s and 2000s block groups than in block groups constructed in earlier periods. Road density, however, is not discernibly different among the different periods.

Comparing the different historical periods, we also see notable differences in the proportional area and density of soil patches. The proportional area of soil remains fairly consistent across the historical zones, except for the 1990s and 2000s zones, which show slight increases in mean soil area. As indicated by the ANOVA results, the area of soil in the 2000s zone is significantly different from most of the areas of earlier construction (except the 1940s and 1990s zones). Patch density of soil, however, is highest for the 1940s and 1950s zones, and is significantly different from all zones dominated by later construction.

Although some differences in the area and density of tree and grass cover can be seen in the data, these differences were only significant when comparing areas built during the 1940s and 1950s to later construction periods. Specifically, 1950s zones have higher average tree cover than areas constructed in the 1970s, 1980s, and 2000s, but the patch density of trees is not significantly different

Table 2
ANOVA pairwise post-hoc tests for landscape-level metrics ($^{*}p < 0.05$,$^{**}p < 0.01$) presented as a cross-tabulation matrix. Pluses and minuses indicate whether the metric's value is higher or lower in the subsequent (more recent) decade. Descriptions of landscape metrics can be found in Table 1.

Simpson's Diversity							Simpson's Evenness						
SIDI	50	60	70	80	90	00	SIEI	50	60	70	80	90	00
40	−	−	−	−	−	−**	40	−	−	−	−	−*	−**
50		−	−*	−**	−**	−**	50		−	−*	−**	−**	−**
60			−	−	−	−*	60			−	−	−	−**
70				+	−	−	70				−	−	−**
80					−	−*	80					−	−**
90						−	90						−
Fractal Dimension							Contagion Index						
FRAC	50	60	70	80	90	00	CONTAG	50	60	70	80	90	00
40	−	−	−	+	+*	+**	40	+	+	+	+*	+	+**
50		+	+	+*	+**	+**	50		+*	+*	+**	+*	+**
60			+	+	+**	+**	60			−	+	+	+*
70				+	+**	+**	70				+	+	+*
80					+**	+**	80					−	+
90						+	90						+
Interspersion/Juxtaposition							Patch Density						
IJI	50	60	70	80	90	00	PD	50	60	70	80	90	00
40	+	−	−	−	−	−**	40	−	−	−	−	−	−
50		−	−	−*	−**	−**	50		−	−	−	−	−
60			−	−	−**	−**	60			+	−	+	+
70				−	−**	−**	70				−	+	+
80					−	−**	80					+	+
90						−**	90						+

Table 3
ANOVA pairwise post-hoc tests for class-level metrics (*p < 0.05,**p < 0.01) presented as a cross-tabulation matrix. Pluses and minuses indicate whether the metric's value is higher or lower in the subsequent (more recent) decade. Descriptions of class metrics can be found in Table 1.

Buildings																																		
PLAND	50	60	70	80	90	00	PD	50	60	70	80	90	00	IJI	50	60	70	80	90	00	CONTIG	50	60	70	80	90	00	FRAC	50	60	70	80	90	00
40	+	+	+	+	−	−	40	−	−	−	−	−*	−**	40	−	−	−*	−*	−*	−**	40	+	+	+*	+	+	−	40	−	+	+	+	+	−
50		−	−	−	−**	−**	50		−	−	−*	−**	−**	50		−	−*	−*	−**	−**	50		+	+	−	−	−*	50		+	+	+**	+	+
60			−	−	−**	−**	60			−	−	−**	−**	60			−	−	−	−**	60			+	−	−	−**	60			−	+	+	−
70				−	−**	−**	70				−	−**	−**	70				+	−	−**	70				−	−	−**	70				+	−	−
80					−**	−**	80					−*	−**	80					−	−**	80					−	−	80					−	−
90						−	90						−	90						−	90						−	90						−
Soil																																		
PLAND	50	60	70	80	90	00	PD	50	60	70	80	90	00	IJI	50	60	70	80	90	00	CONTIG	50	60	70	80	90	00	FRAC	50	60	70	80	90	00
40	+	+	+	+	+	+	40	−	−*	−**	−*	−**	−*	40	+	+	+	−	−	−	40	+	+	+	+	+	+	40	+	+	+	+	+**	+**
50		−	−	−	+	+*	50		−**	−**	−**	−**	−*	50		−	−	−**	−	−**	50		+	+	+	+	+**	50		+	+	+	+**	+**
60			−	−	+	+**	60			−	+	−	+	60			−	−*	−	−**	60			−	−	+	+	60			+	+	+**	+**
70				−	+	+**	70				+	−	+	70				−	−	−**	70				−	+	+	70				+	+**	+**
80					+	+**	80					−	−	80					+	−**	80					+	+*	80					+**	+**
90						+	90						+	90						−**	90						+	90						+
Tree																																		
PLAND	50	60	70	80	90	00	PD	50	60	70	80	90	00	IJI	50	60	70	80	90	00	CONTIG	50	60	70	80	90	00	FRAC	50	60	70	80	90	00
40	−	−	−	−	−	−	40	−	−	−	−	−	−	40	−	−	−	−	−	−**	40	+	−	−	+	+	−	40	−	−	−	−	+	+
50		−	−*	−**	−	−**	50		−	+	−	−	−	50		−	−	−	−**	−**	50		−	−*	+	+	−**	50		−	+	+	+	+*
60			−	+	+	−	60			+	−	−	−	60			−	−	−	−**	60			−	+	+	−**	60			+	+	+	+**
70				+	+	−	70				−	−	−	70				−	−	−**	70				+**	+	−**	70				+	+	+*
80					−	−	80					−	+	80					−	−**	80					−	−**	80					+	+
90						−	90						+	90						−	90						−**	90						+
Grass																																		
PLAND	50	60	70	80	90	00	PD	50	60	70	80	90	00	IJI	50	60	70	80	90	00	CONTIG	50	60	70	80	90	00	FRAC	50	60	70	80	90	00
40	−	−**	−*	−*	−**	−**	40	−	−*	−*	−*	−*	−**	40	+	+	−	−	−	−**	40	+	+	+	+	+	+	40	−	−	−	−	−	−
50		−*	−	−	−**	−**	50		−	−	−	−	−**	50		−	−**	−**	−**	−**	50		−	+	+	+	+	50		−	+	+	+	+
60			+	+	−	−	60			+	−	−	−	60			−**	−**	−**	−**	60			+	+	+	+	60			+	+	+	+
70				+	−	−	70				−	−	−	70				−	−**	−**	70				+	+	+	70				−	+	+
80					−	−	80					−	−	80					−	−**	80					+	−	80					−	+
90						−	90						−	90						−**	90						−	90						+
Roads																																		
PLAND	50	60	70	80	90	00	PD	50	60	70	80	90	00	IJI	50	60	70	80	90	00	CONTIG	50	60	70	80	90	00	FRAC	50	60	70	80	90	00
40	+	+	+	+	−	−	40	−	−	−	−	−	−	40	−	−	−	−	−	−**	40	+	+	+	+	+	+	40	+	+	−	−	+	+
50		+	−	−	−**	−**	50		−	−	−	−	−	50		−	−	−	−**	−**	50		+	+	+	−	−	50		−	−**	−*	−	−
60			−	−	−**	−**	60			+	+	−	−	60			−	−	−*	−**	60			+	−	−	−*	60			−	−	+	+
70				−	−**	−**	70				+	+	−	70				−	−	−**	70				−	−*	−**	70				+	+	+
80					−**	−**	80					+	−	80					−	−**	80					−	−	80					+	+
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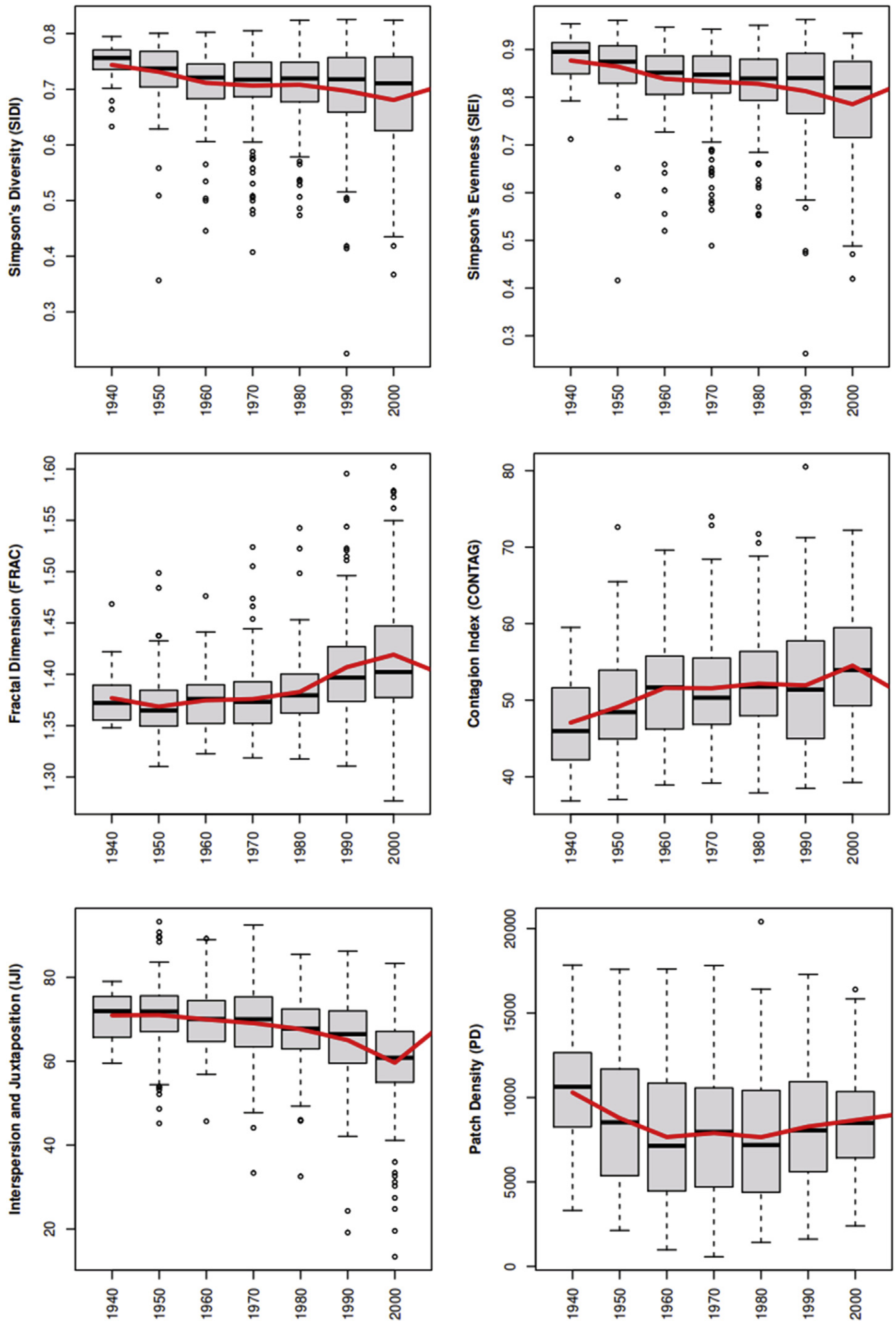

Fig. 3. Boxplots of landscape-level metrics. The trend line connects mean values.

among the other historical zones. The proportional area of grass is generally lower in more recently constructed areas, but as with trees, this difference is only significant when comparing recent construction to the 1940s and 1950s areas. The areas constructed in the 1940s and 1950s also have a higher density of grass patches than later-constructed periods. In sum, more recently constructed areas generally have less tree cover and less grass cover than their older counterparts.

Fragmentation and scatter

The contagion index (CONTAG) provides a landscape-level measure of fragmentation, accounting for all land cover classes. The cross-tabulation matrix for the contagion index shows that the mean value for more recently constructed periods is almost always higher than preceding periods (with the exception of two points in the matrix). Newly constructed areas, thus, show greater fragmentation than older areas. Most notably, the 1950s had a significantly lower contagion than all later construction periods, and areas constructed in the 2000s have a significantly higher mean contagion than all areas built between the 1940s and 1970s. The interspersion and juxtaposition index (IJI) landscape-level metric (not to be mistaken for the IJI class-level metrics discussed later), which measures the overall intermixing of classes complements these results: there is significantly less intermixing in areas developed during the 1990s and 2000s.

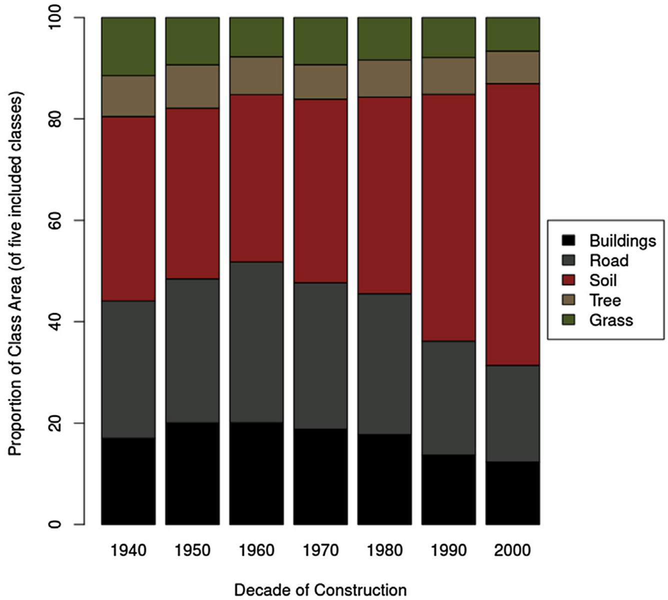

Fig. 4. Proportion of identified landscape cover occupied by each class, by construction decade (cropland and shrub classes excluded).

In addition to these landscape metrics, class-level measures of interspersion (IJI) and contiguity (CONTIG) provide class-specific measurements of scatteredness, which can also be indicative of fragmentation. Specifically, IJI provides information on the relationship between different types of land covers and how frequently they come in contact with each other. This is indicative of landscape heterogeneity and the degree of segregation among land covers. Like its landscape-level counterpart, the IJI for each individual class also shows that the interspersion of land covers is significantly lower in more recently constructed areas.

The position of buildings relative to other land cover classes also differs significantly across the zones. This is reflected in the contiguity and class-level IJI indices: the 2000s historical zone differs significantly from most preceding periods. Thus, buildings in newer areas interface with fewer types of land covers. Roads, similarly, appear to interact with fewer types of land covers in areas of newer construction. The 2000s construction period, in particular has significantly lower IJI than past periods. Roads, in contrast, do not show significant differences in contiguity.

Soil patches also show a significantly lower IJI in areas developed during the 2000s, indicating less interspersion with other land covers, but show a higher level of contiguity in later periods. This difference in contiguity is significantly higher when comparing the 2000s zone to areas constructed in the 1950s and 1980s. In combination, these results suggest that later-constructed areas are characterized by continuous patches of soil that do not frequently intersect other land cover types. In contrast, tree covers, particularly in the 2000s, intersect less frequently with other use types but also are less contiguous, as indicated by the IJI and contiguity index, respectively. The IJI for grass cover is significantly lower in later-constructed areas across almost all pairs of decades though the contiguity index shows no significant patterns – that is to say, while grass patches in newer developing areas are no more or less fragmented, they consistently interface less with other land covers.

Shape complexity

The fractal dimension (FRAC) index is commonly used in studies of sprawl or fragmentation of urban areas (see, e.g., Herold et al., 2005), as it provides additional information about the complexity of land cover features. Specifically, the fractal dimension index provides a measure of the departure from Euclidean geometry, or straight-line edges. For our study area, this index is consistently higher in newer-developed areas. Considering the fractal dimension for all patches (i.e., landscape-level metric), landscape shapes appear more complex in more recently developed regions, with a significantly higher mean fractal dimension index in areas developed during the 1990s and 2000s.

Differences in shape complexity are also apparent for specific land cover classes across the various historical areas. In particular, tree and soil patches show much higher complexity in newer areas of the city. For trees, the fractal dimension in the 2000s zone is significantly different from areas constructed in the 1950s, 1960s, and 1970s. For soils, the fractal dimension index increases incrementally across the different historical zones, with the lowest value in the 1940s and the highest in 2000s – the mean values for the 1990s and 2000s zones are significantly different from the block groups in the preceding periods.

Diversity

Simpson's Diversity index (SIDI) indicates that areas developed in the 1950s have significantly higher diversity than newer areas, while areas that developed in the 2000s show significantly lower landscape diversity than older ones. This indicates a more homogenous landscape in newer areas. Simpson's evenness index (SIEI), which approaches zero when the landscape is dominated by a single class, shows the same pattern: while newer areas have continually lower evenness, differences are statistically significant when comparing the 1950s to subsequent decades (block groups developed during the 1950s have much higher evenness), and when comparing the 2000s to previous decades (the most recently developed block groups have much lower evenness than older areas).

Discussion

First, our results confirm that there is substantial variation in present-day land cover characteristics in sub-metropolitan areas based on dominant periods of development, supporting the hypothesis about path-dependence with respect to landscape structure. For many class-level and landscape-level metrics, block groups that developed principally during the 1990s and 2000s displayed significantly different values from earlier-developing regions. These areas tend to differ most significantly from areas that developed during the 1950s.

By analyzing sprawl across four distinct dimensions (area and density of land cover, fragmentation/scatter, shape complexity, and diversity), we are able to expand upon previous studies such as Irwin and Bockstael (2007), Shrestha et al. (2012), and Zhang et al. (2013). Those studies, using 30m data (which is more adept at detecting variation between parcels of land), have generally corroborated the traditional conceptualization of urban sprawl by providing evidence of increased fragmentation near the urban fringe. Comparison with these studies is complicated by the fact that our results involve more land cover classes and higher resolution; however, newer-developing areas in our study do appear more fragmented. Furthermore, landscape patches interface less frequently with different land cover classes, suggesting that newer-developing areas are actually more homogenous when we consider several types of land cover (buildings, roads, trees, grass, soil, shrub, and cropland). While it is not surprising that newer areas are also less diverse and are covered with fewer roads and buildings, the within-lot land cover classification that our high-resolution data affords also provides evidence of a shift from grass and tree covers to soil cover. Shape complexity appears higher in newer areas as well.

We speculate that certain institutional and economic changes in land use during the 1990s and 2000s explain some of our results. During the 1960s, commercial uses fled the downtown area in favor of decentralized office parks, shopping malls, and strip retail along arterial streets (Luckingham, 1989), resulting in a different style of business land use that not only has a larger footprint but more within-lot variation: shade trees, buildings, grass, and parking may depart more from Euclidean geometry than in a rectilinear downtown streetscape. Zoning and city ordinances also transformed residential areas during the latter half of the twentieth century. Increasing minimum lot sizes for residentially-zoned land, a trend that took place over this period in the Phoenix area and nationwide (Fischel, 2001; Talen, 2012) could result in increasing shape complexity within individual lots, especially when compared to a cookie-cutter 1950s-era ranch home. Atkinson-Palombo (2010) found that a wider variety of housing types were present at the urban fringe during the 2000s, which also corroborates some of our results: a wider variety of building styles could result in increased shape complexity in this category, while a higher proportion of multifamily housing would result in smaller building footprints and a lower percent landscape for buildings despite growth in the number of housing units. Newer construction is also more likely to abut agricultural lands, which may account for differences in proportional cover as well. In Phoenix, water rights could play a particularly important role in shaping the extent and pattern of land cover. Water rights are attached to a particular property and affect the types of irrigation permitted and cost of water associated with a particular property.

In addition to institutional and economic changes, the development style and preferences of residents living in Phoenix may also explain why the 1990s and 2000s zones appear distinctly different. The CBD influenced much of the early development of Phoenix and still has a great influence on the land use history (Keys, Wentz, & Redman, 2007). This could account for similar configurations seen up until the 1990s zones. However, it does not account for why the 1990s and 2000s zones change so distinctly, particularly in terms of fragmentation and shape complexity. Some further observations show that the development style in Phoenix changes with time. "Leapfrog" development was a large part of residential development in American cities between the 1950s and 2000s, particularly in Phoenix (Carruthers, 2003; Helm, 2001). This created patches of undeveloped land parcels that were filled in during later development periods, but it was not until after 1970 that leapfrogging in Phoenix occurred at greater distances from the CBD (Helm, 2001). Based on our observations, all of these factors are likely to manifest themselves in the configuration of the 1990s and 2000s zones, where a number of metrics become significantly different.

Finally, previous research has shown that natives of the Phoenix area seem to prefer mesic, or grassier, landscaping in backyards in contrast to more recent migrants who moved to the desert area in droves throughout the second half of the twentieth century. In addition, preferences for landscaping in Phoenix generally tend to exhibit a "legacy effect" wherein historically mesic landscape patterns persist in older areas (Larson, Casagrande, Harlan, & Yabiku, 2009). Grass covers are at their highest in the 1940s and 1950s zones. Grass patch density is highest in the 1940s zone and grass patches less likely to be near other cover types in newer areas. This may indicate that grasses that do exist in newer-developing areas are in large open spaces such as parks or golf courses, where patches are larger and less mixed-in with other land cover types. In contrast, newer areas feature more soil cover, it is less dense, and its shape complexity is higher, suggesting that desert-like land cover is more prevalent in backyards than larger public or undeveloped areas.

Conclusions

Land cover in urban areas is much more complex than the typical sprawl narrative of increasing fragmentation as one travels toward the urban fringe. The metropolis has long since ceased to be a monocentric entity; analysis of areas because of some particular characteristic may be better understood by delineating areas by when they were developed instead of based on their proximity to the urban core. Our results confirm that sub-metropolitan areas developing principally in different time periods have different present-day land cover characteristics. Legacy effects and historical development trends are important to understanding present-day landscape function and ecosystem services. While we find evidence suggesting that newly-developed areas of Phoenix are less diverse, more homogenous, and more fragmented, our higher-resolution approach goes beyond these traditional narratives, finding significant increases in shape complexity and differing preferences for landscaping in newer-developing areas. Generally speaking, though, our results corroborate prior research (e.g., Atkinson-Palombo, 2010) which has suggested that the most recent wave of development (1990s and onward) in Phoenix and elsewhere was distinct from past forms of urban development.

Resolution, both spatial and thematic, remains a very important consideration in analyzing what constitutes urban sprawl, especially given the increase in data and spatial analysis tools available. While an ecological understanding of landscape complexity and arrangement at the 1-m level is not yet as developed owing to the newness of such data, urbanization and the realization of the importance of urban areas to environmental outcomes suggest that this is a key area of future research (Turner et al., 2013). The definition of "fragmentation," for example, changes whether the research involves only individual lots, or whether it considers individual trees, sidewalks, and lawn patches. It also changes whether analysis concerns a simple developed/undeveloped dichotomy, or is attempting to observe more nuanced aspects of urban pattern. The scale of the aggregation unit merits careful consideration as well. Our choice of block groups as units of analysis was guided principally by theory: it makes sense in Phoenix for analyzing sub-metropolitan areas that are experienced by individuals, but a different aggregation unit may make more sense for different levels of spatial or thematic resolution, or if comparing between different cities. A future study exploring the sensitivity of results to changes in aggregation units would increase the utility of newly-available high-resolution data.

While much of our discussion linking landscape change to specific institutional, economic, and behavioral drivers remains speculative, our approach of linking fine-resolution land cover to development periods removes the assumption of monocentricity that is implicit in urban gradient studies and helps to avoid overlooking infill and leapfrog development patterns. A next step beyond using aggregated information from FRAGSTATS spatial metrics could use high-resolution land cover classifications to identify a typology of building and development styles (e.g., ¼-acre lot ranch homes versus McMansions; strip retail versus megamalls). Further, an explicit link to ecological outcomes, such as hydrology or urban heat island, could also move the discussion toward whether and why certain types of development may be better or worse. This information and similar analysis can support urban planning in Phoenix and elsewhere. By analyzing spatial and temporal pattern variation, it is possible to evaluate the impacts of land use institutions and changing development trends on the overall urban landscape. Nonetheless, greater understanding of the relationship between pattern and landscape ecology is required to assess the environmental implications of development types and institutional arrangements. By highlighting spatial pattern differences across Phoenix, this research hopes to move the discussion of urban landscape pattern beyond identifying homogeneity and fragmentation and toward an analysis of what it means and whether it matters.

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