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A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA

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Abstract

Urbanization is arguably the most dramatic form of land transformation that profoundly influences biological diversity and human life. Quantifying landscape pattern and its change is essential for the monitoring and assessment of ecological consequences of urbanization. Combining gradient analysis with landscape metrics, we attempted to quantify the spatial pattern of urbanization in the Phoenix metropolitan area, Arizona, USA. Several landscape metrics were computed along a 165 km long and 15 km wide transect with a moving window. The research was designed to address four research questions: How do different land use types change with distance away from the urban center? Do different land use types have their own unique spatial signatures? Can urbanization gradients be detected using landscape pattern analysis? How do the urban gradients differ among landscape metrics? The answers to these questions were generally affirmative and informative. The results showed that the spatial pattern of urbanization could be reliably quantified using landscape metrics with a gradient analysis approach, and the location of the urbanization center could be identified precisely and consistently with multiple indices. Different land use types exhibited distinctive, but not necessarily unique, spatial signatures that were dependent on specific landscape metrics. The changes in landscape pattern along the transect have important ecological implications, and quantifying the urbanization gradient, as illustrated in this paper, is an important first step to linking pattern with processes in urban ecological studies.

Introduction

Urbanization has profoundly transformed natural landscapes throughout the world, which inevitably has resulted in various effects on the structure, function, and dynamics of ecological systems at a wide range of scales. For example, land transformations associated with urban expansion can significantly affect biodiversity, energy flows, biogeochemical cycles, and climatic conditions at local to regional scales (Sukopp 1990; McDonnell et al. 1997; Breuste et al. 1998; Baker et al. 2001). With accelerating urbanization throughout the world, therefore, it is becoming increasingly important for large-scale ecological research and applications (e.g., natural resource management, land use planning, and biodiversity conservation) to consider these most dramatic land transformations and their ecological consequences.

The morphology and evolution of cities have been extensively studied by geographers, economists, and social scientists for centuries (e.g., von Thünen (1825) and Burgess (1925), Christaller (1933), Hoyt (1939), Harris and Ullman (1945), Lösch (1954)). Three classic theories of urban morphology were developed: the concentric zone theory (urban pattern as concentric rings of different land use types with a central business district in the middle; see Burgess (1925)), the sector theory (concentric zone pattern modified by transportation networks; see Hoyt (1939)), and the multiple nuclei theory (patchy urban pattern formed by multiple centers of specialized land use activities). Since the 1960s, a variety of new theories and methods have been used for describing the form and formation of urban systems. These include catastrophe theory (Wilson 1976), chaos theory (Wilson 1981; Wong and Fotheringham 1990), dissipative structure theory (Allen and Sanglier 1979), fractals (Batty and Longley 1989; White and Engelen 1993), cellular automata (Tobler 1979; Couclelis 1985; Batty 1997), and theory of self-organization (Schweitzer 1997; Portugali 2000). In contrast with the static theories of urban morphology discussed above, these new approaches emphasize the dynamics of the urban form and its relation to generating processes. Also in sharp contrast with the traditional views, these new approaches are based on non-equilibrium and nonlinear systems perspectives. In addition, from fractals to cellular automata and to self-organization, bottom-up and local interactions are viewed essential for the formation of urban systems.

No matter how cities are formed, their spatial pattern undoubtedly affects physical, ecological, and socioeconomic processes within their boundaries and beyond. A major goal of urban ecology is to understand the relationship between the spatial pattern of urbanization and ecological processes (Sukopp (1990, 1998); Loucks 1994; Breuste et al. 1998; Wu and David 2002 (in press)). Urban ecological studies date back to more than 50 years ago when plant ecologists documented the spatial distribution of plants in and around cities–notably the ‘Berlin school’ of urban ecology (see Sukopp (1990, 1998) for reviews). In the same time, social scientists applied the concepts developed in plant and animal ecology (e.g., competition, invasion, and succession) to “the study of the relationship between people and their urban environment”–the definition of urban ecology rendered by the Chicago sociologists (Park et al. 1925). Today, a diverse spectrum of perspectives on urban ecology, from bio-ecological to socioeconomic and from basic research to land use planning, exists worldwide (see Breuste et al. (1998)). Although urban ecology is not new, a resurgence of interest in the ecology of urban environment is evident in recent years (e.g., Pickett et al. (1997) and Breuste et al. (1998), McIntyre et al. (2001), Collins et al. (2000)). This is marked by the unprecedented enthusiasm from bio-ecologists who traditionally regarded urban areas as extremely ‘disturbed’ sites that were not desirable for ecological research. In particular, landscape ecology in Europe has historically emphasized human-environmental interactions (e.g., Naveh and Lieberman (1984)), and it seems that this more humanistic ecological perspective has finally begun to penetrate into the ‘mainstream’ ecology in North America (Wu and Loucks 1995; Pickett et al. 1997; Collins et al. 2000; Grimm et al. 2000; Luck et al. 2001).

The spatial pattern of land use reflects underlying human processes and influences the ecology of urban environment (Redman 1999). Humans have the ability to greatly modify their environment, which tends to increase landscape fragmentation by generating more and smaller patches. To relate the spatial pattern of urbanization to ecological processes, quantitative spatial analysis methods are needed. Among others, gradient analysis and landscape pattern analysis seem appropriate for such studies. Gradient analysis, developed in the context of vegetation analysis (Whittaker 1975), has been used to investigate the effects of urbanization on plant distribution (e.g., Kowarik (1990) and Sukopp (1998)) and ecosystem properties (McDonnell and Pickett 1990; Pouyat and McDonnell 1991; Pouyat et al. 1995; Blair 1996; Zhu and Carreiro 1999). McDonnell and Pickett (1990) indicated that the ‘urban-rural’ gradient, similar to the ‘city-country gradient’ used by European urban (plant) ecologists (e.g., Kowarik (1990)), provides an unplanned field experiment in which study plots can be arranged in a transect along the gradient of urbanization. On the other hand, many landscape metrics have been developed and widely applied for characterizing various landscape patterns in the past few decades (O’Neill et al. 1988; Turner 1989; Frohn 1998; Wu et al. 2000), but their use in urban ecology is yet to be fully explored.

In this study, we integrated gradient analysis with landscape pattern metrics to quantitatively characterize the urbanization pattern of the metropolitan area of Phoenix, USA. We aimed to address several questions: 1) How do different land use types change with distance away from the urban center? 2) Do different land use types have their own unique spatial signatures (e.g., the shape of the change curve along an urban-rural transect)? 3) Can urbanization gradients be detected using landscape pattern analysis? 4) How do the urban gradients differ among landscape metrics? Identifying these gradients or patterns is an important first step to related urban morphology to ecological and socioeconomic processes.

Study area

The Phoenix metropolitan region is located in the northern Sonoran Desert, with a very warm, arid climate (mean summer high temperature = 40 °C; mean annual precipitation = 193 mm). Although many areas of the desert region are sparsely populated, Phoenix has become the sixth largest, and fastest growing city in the United States. Phoenix is the home of the Central Arizona-Phoenix Long Term Ecological Research (CAP-LTER) site, which was established in 1997 to study the relationship between urbanization and ecological conditions using interdisciplinary approaches. Since the beginning of the 20^{th} century, Phoenix has experienced a tremendous land transformation from an agricultural to urban area (Knowles-Yanez et al. 1999). Both the human population and urbanized area in this region have increased exponentially with a correlation coefficient of larger than 0.95 between the two (Jenerette and Wu 2001; Wu and David 2002 (in press)). Most of the development, including local agriculture and nearly all of the urban (industrial and commercial) and residential areas, occupies a relatively flat basin along the Salt River within the boundary of Maricopa County. The county covers approximately 2.4 million ha, with a maximum north-south length of 171 km and east-west distance of 216 km. The metropolitan area is located primarily in the northeast quadrant and is bordered by several large Native American reservation lands to the south and northeast that are agricultural or relatively undeveloped. Almost all of the residential and urban land uses and most of the agricultural land occur in the northern half of Maricopa County.

Methods

The analysis of structural characteristics of the Phoenix metropolitan landscape was based on the 1995 Maricopa County land use data set produced by the Maricopa Association of Governments (Figure 1). First, the land use data set was reclassified from twenty-four patch types into six patch types (or classes): agriculture, desert, residential, urban, roads, and water (Table 1). The two linear types, roads and water, comprised a total of less than 1% of the total area, and thus were not included in the results. The desert category includes undeveloped land, vacant lots, and open space; the residential class includes various dwellings such as neighborhoods, apartments, and rural lots; and the urban class includes commercial, industrial, and public institutions (e.g., educational and correctional facilities). The vector data were then converted to raster format at the pixel size of 50×50 m^2 using ESRI's ArcView Spatial Analyst. To capture some of the synoptic features of the landscape, several landscape-level metrics were calculated using the raster version of FRAGSTATS (McGarigal and Marks 1995).

To detect the urbanization gradient of landscape pattern, we conducted a series of analyses along a west-east transect cutting across the entire Phoenix metropolitan area (Figure 1). The transect had three adjacent rows each composed of thirty-three 5×5 km^2 blocks (i.e., the transect spanned 165 km long). The orientation of the transect was chosen to include the most continuous transect that was not interrupted by native American Indian Reservation lands. Both class and landscape level metrics were computed using a 3×3 (i.e., 15×15 km^2) overlapping moving window across the transect from west to east with FRAGSTATS. This procedure, similar to the derivation of moving averages for a time series, smoothed out much of the noise caused by fine-scale, local variations. For the landscape-level metrics, a smaller window size of 1×1 (i.e., a single block) was also used for the middle row of the transect to get a sense of the effect of changing the moving window size.

Data quality and accuracy assessment is an important and rather difficult problem in landscape analysis, which has received little attention (Hess 1994; Hess and Bay 1997). In our study, the MAG land use map was digitized and classified based on 1990 aerial photographs from various sources. In 1995, individual cities in Maricopa County were responsible for updating their own portion of the map, and the final land use map for the entire county was a mosaic of several authoring groups. As a result, information on both the classification accuracy and the resolution of the original data was lacking. This problem might affect the accuracy of landscape metrics (Hess 1994; Wu 2000; Wu et al. 2000) if a high-resolution and detailed classification map would be used. However, by using a coarse-resolution and highly aggregated classification scheme and by focusing on general trends instead of absolute values, the requirement for data accuracy was significantly relaxed, and thus our results should be robust.

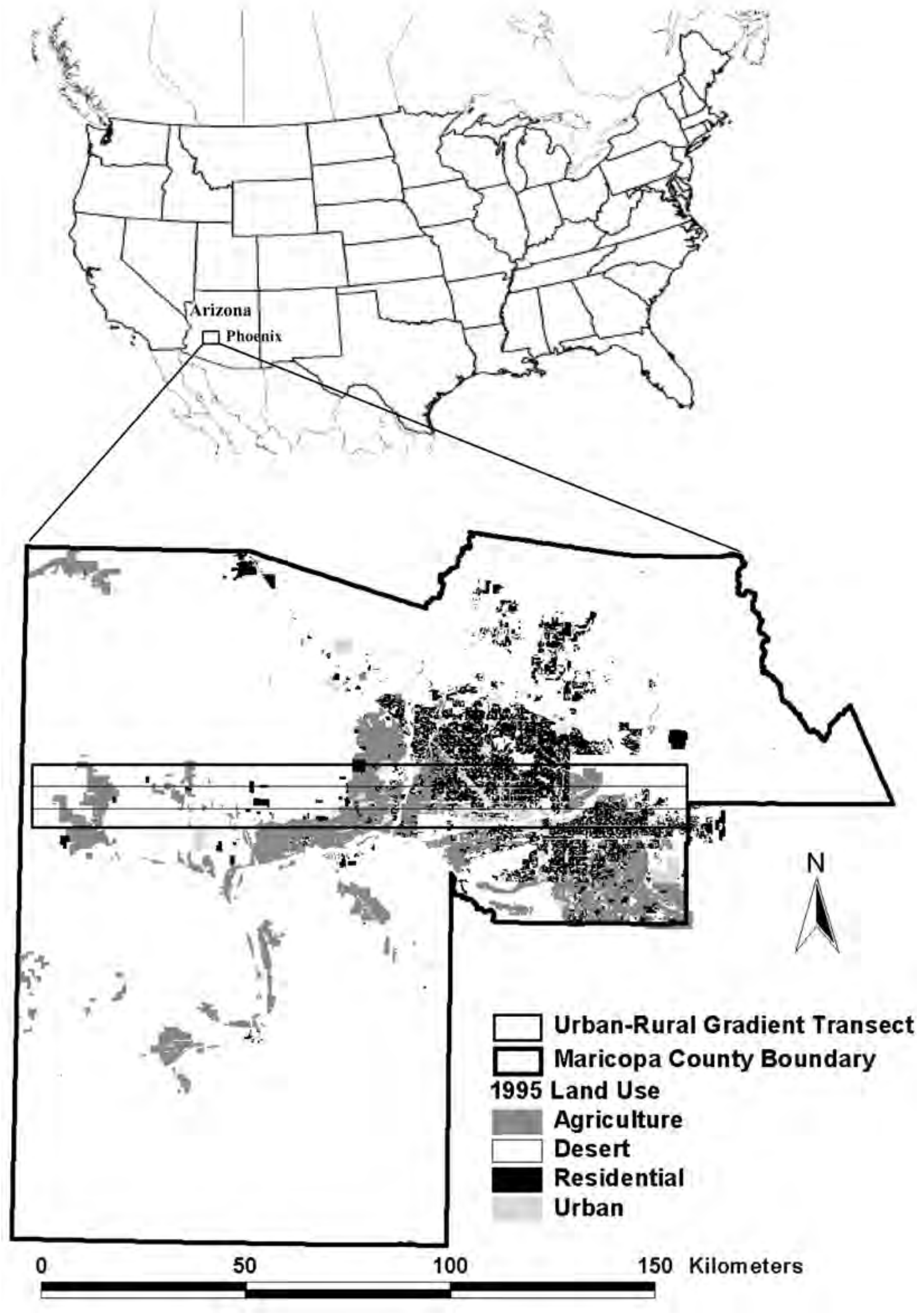

Figure 1. 1995 land use map of the Phoenix metropolitan area, Maricopa county, Arizona, USA (data from the Maricopa Association of Governments). The transect was east-west oriented, and 165 km long and 15 km wide.

Table 1. Land use reclassification scheme.

Reclassified patch type	Original land use type (by Maricopa Association of Governments)
Agriculture	Agriculture
Desert	Vacant
	Recreational Open Space
	Dedicated or Non-developable Open Space
Residential	Rural
	Large Lot Residential
	Small Lot Residential
	Medium Density Residential
	High Density Residential
	Hotel, Motel, or Resort
Urban	Neighborhood Retail Center
	Community Retail Center
	Regional Retail Center
	Warehouse/Distribution Center
	Industrial
	Business Park
	Office
	Educational
	Institutional
	Public Facility
	Large Assembly Area
	Airport
Roads	Roads
Water	Water

Table 2. Definitions of landscape metrics (adapted from McGarigal and Marks (1995)).

Name of landscape metric	Description
Patch richness	The number of patch types in the landscape; a measure of diversity of patch types.
Class percent of landscape	The proportion of total area occupied by a particular patch type; a measure of dominance of patch types.
Largest patch index	The proportion of total area occupied by the largest patch of a patch type.
Patch density	The number of patches of per 100 ha.
Mean patch size	The area occupied by a particular patch type divided by the number of patches of that type.
Patch size coefficient of variation	Patch size standard deviation divided by the mean patch size; a measure of relative variability.
Landscape shape index	The landscape boundary and total edge within the landscape divided by the total area, adjusted by a constant for a square standard.
Area-Weighted Mean Shape Index	A mean patch-based shape index weighted by patch size.

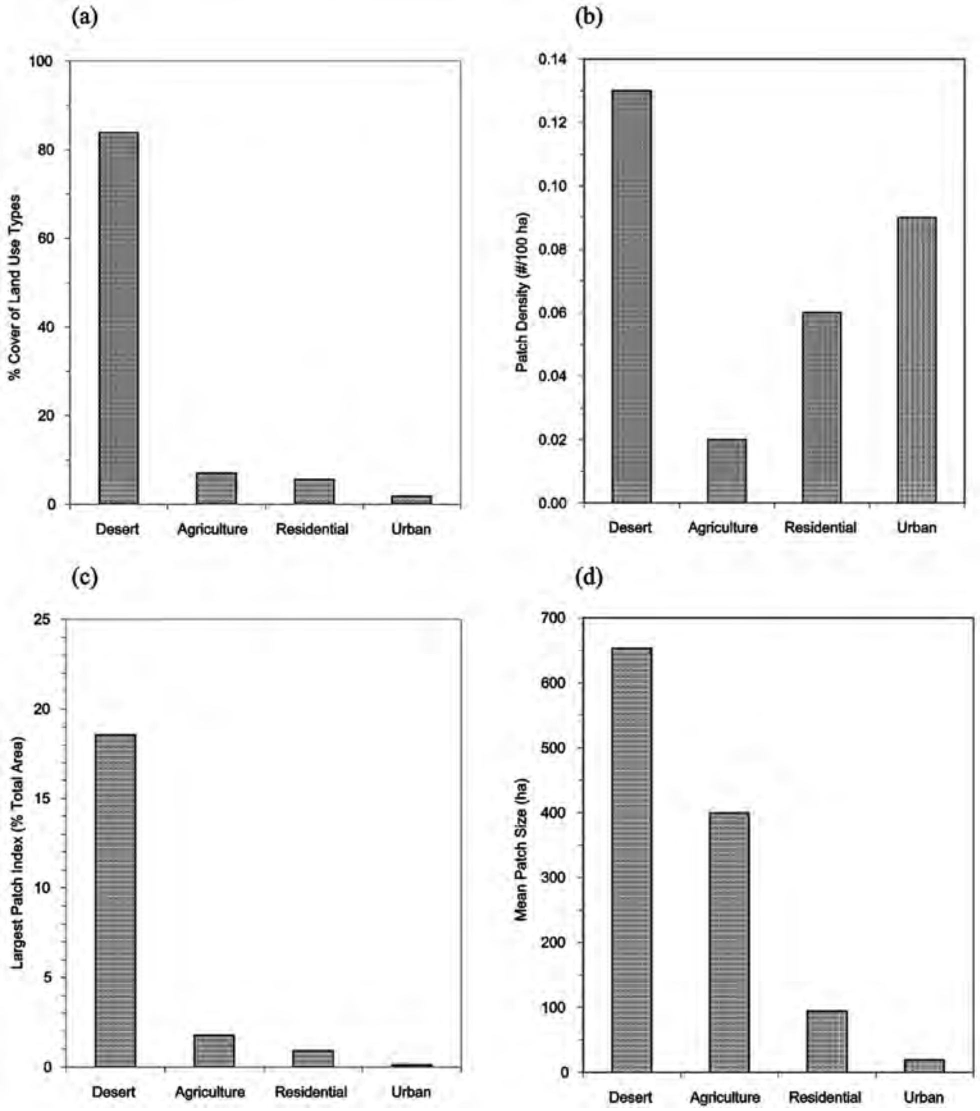

Figure 2. Synoptic landscape characteristics for Maricopa County, Arizona: (a) patch type percent cover (% of the total landscape area); (b) patch density, (c) mean patch size, and (d) largest patch index (%).

Results

Synoptic characteristics of the Phoenix urban landscape

In 1995 most of the land of Maricopa County was yet undeveloped, with native desert occupying 84% of the area, while agricultural, residential, and urban land uses accounted for 7%, 6%, and 2%, respectively (Figure 2a). The mean patch size (MPS) for the entire landscape was approximately 193 ha, and the mean patch density (PD) was 0.52 patches/km^2. Patch density increased progressively from agricultural, to residential, and to urban land use, but desert had the highest patch density over the landscape defined by the boundary of Maricopa County (Figure 2b). Similar to the pattern of the relative area of patch types (Figure 2a), desert had the highest values of largest patch index (LPI) and mean patch size, and from agricultural to residential and then to urban land use both largest patch index and mean patch size continued to decrease (Figures 2c and 2d).

Overall, urban land use had the smallest values for mean patch size and largest patch index and the largest patch density, together suggesting a high degree of fragmentation. The fragmentation of the residen-

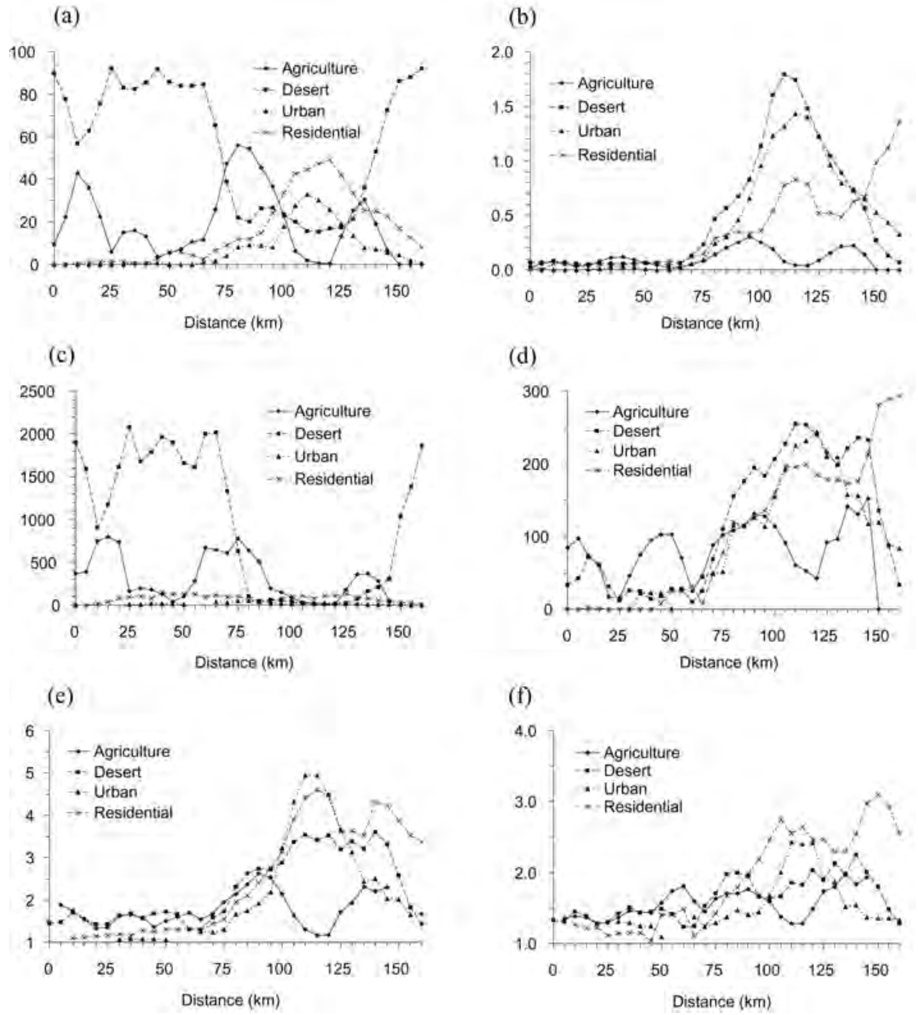

Figure 3. Changes in landscape pattern along the transect by patch type: (a) patch type percent cover, (b) patch density, (c) mean patch size, (d) patch size coefficient of variation, (e) landscape shape index, and (f) area-weighted mean shape index. The values were averages obtained using a 3 × 3 overlapping moving window. See text for explanations.

tial land use was lower than urban but higher than agricultural land use. The desert patch type had the highest proportion of cover and the highest values of largest patch index and mean patch size, indicating its dominant and least fragmented status outside the urban core and within the country boundary. However, its largest patch density value suggested a high degree of fragmentation which, most likely, occurred within the metropolitan area. This interpretation was corroborated by transect analysis presented below (Figures 3a and 3b).

Transect analysis with class-level metrics

Percent coverage (PC) for each land use type varied with distance from the west end of the landscape transect eastward (Figure 3a). In general, the relative dominance of land use types showed a somewhat symmetric pattern along the transect: shifting from desert to agriculture, residential/urban, agriculture, and then back to desert. Undoubtedly, the distances (between 100 and 125 km) where urban and residential land uses peaked indicated the location of the urbanization center in the metropolitan region. Natural desert was dominant at distances less than 75 km and again greater than 140 km, forming a 'U' shape. Agricultural land use exhibited two peaks on both sides of the urbanization center, and was the only other significant land use type at distances less than 75 km, indicating a second extensive agricultural zone farther away from the city. In contrast, residential and urban land use types increased gradually towards, and peaked prominently at, the urbanization center. The areal coverage of residential land use was consistently greater than that of urban land use in this area.

The patch density of all land use types was low from zero to 75 km, with desert, urban, and residential land uses reaching a maximum around 115 km (Figure 3b). Patch density of agriculture showed a similar pattern to its percent cover, with high values at 100 km in the west and 140 km in the east, and low values at and around the urban center. Patch density of all land use types decreased to the east of the urban center, with the exception of residential land use which continued to increase. At distances less than 40 km, the mean patch size of desert was high except in places where large patches of agriculture were present (Figure 3c). It then decreased to very low values at the urban center until 155 km and increased again rapidly beyond that distance. The mean patch size of agriculture was quite variable along the transect but was consistently small between 25 and 50 km and again between 100 and 125 km. The general pattern of mean patch size for both desert and agriculture mimicked the pattern of their percent cover (compare Figures 3a and 3c). The variation of the mean patch size for urban and residential land uses was less conspicuous along the transect partly because they were composed of relatively small patches.

Patch size coefficient of variation (PSCV) showed that all land use types, except agriculture, were relatively less variable west of the metropolitan center, but increased substantially toward the center (Figure 3d). Patch size coefficient of variation of desert, agriculture and urban land uses declined eastward after the urban center, but patch size coefficient of variation of residential continued to increase, resembling its patch density pattern (compare Figures 3b and 3d). Again, agriculture showed a more complex pattern with multiple peaks at different distances. Landscape shape index (LSI) and area-weighted mean patch shape index (AWMSI) were low for all land use types at distances less than 80 km and then increased eastward (Figures 3e and 3f). Landscape shape index and area-weighted mean patch shape index of three of the four land use types (desert, residential and urban) reached their peaks in the vicinity of the urban center, where agriculture, however, exhibited low values. The multiple-peaked pattern of agricultural land use along the transect was consistent for all the six indices.

From Figure 3, it is evident that an urbanization center, identified quantitatively using landscape metrics, existed between distances 110 km and 120 km. Within this urban core area, the rankings of desert (D), agriculture (A), residential (R), and urban (U) in terms of their relative dominance were different among landscape metrics. The rankings were R > U > D > A for percent cover; D > U > R > A for patch density; R > U > A > D for mean patch size; D > U > R > A for patch size coefficient of variation; U > R > D > A for landscape shape index; and R > U > D > A for area-weighted mean patch shape index. These results seemed to characterize the urban core of the Phoenix metropolitan area rather accurately and precisely: remnant desert patches and undeveloped lots were abundant, but highly fragmented; residential was even more extensive than urban, both having many small patches and high shape complexity; and agriculture was diminishing in area and simple in geometry.

Transect analysis with landscape-level metrics

The landscape-level metrics, combining all land use types (Figures 4a–4f), showed patterns resembling those of most of the individual land use types (Figures 3a–3f). The curves generated using two window sizes (1×1 and 3×3 blocks) exhibited qualitatively similar patterns. But, without the smoothing effect of the larger window size, the single block window (5×5 km) resulted in considerable fluctuations in the values of all metrics. This may be viewed as an example of effects of changing scale (Turner et al. 1989; Hunsaker et al. 1994; Jelinski and Wu 1996; Wu 2000; Wu et al. 2000). However, the general patterns of the six metrics examined here were apparently robust.

Specifically, patch richness had a value between 1 and 3 patch types until 75 km, when it jumped to 5 and 6 at the urban center (Figure 4a). Patch density increased slowly up to 75 km and then rapidly to its highest value at 125 km, and subsequently decreased towards farther east (Figure 4b). Mean patch size was large up to 75 km, though with substantial fluctuations, declined to a minimal value between 75 km and 150 km, and then rose up again eastward away from the urban center (Figure 4c). Patch size coefficient of variation increased along the transect from west to east and reached the highest value at the urban core

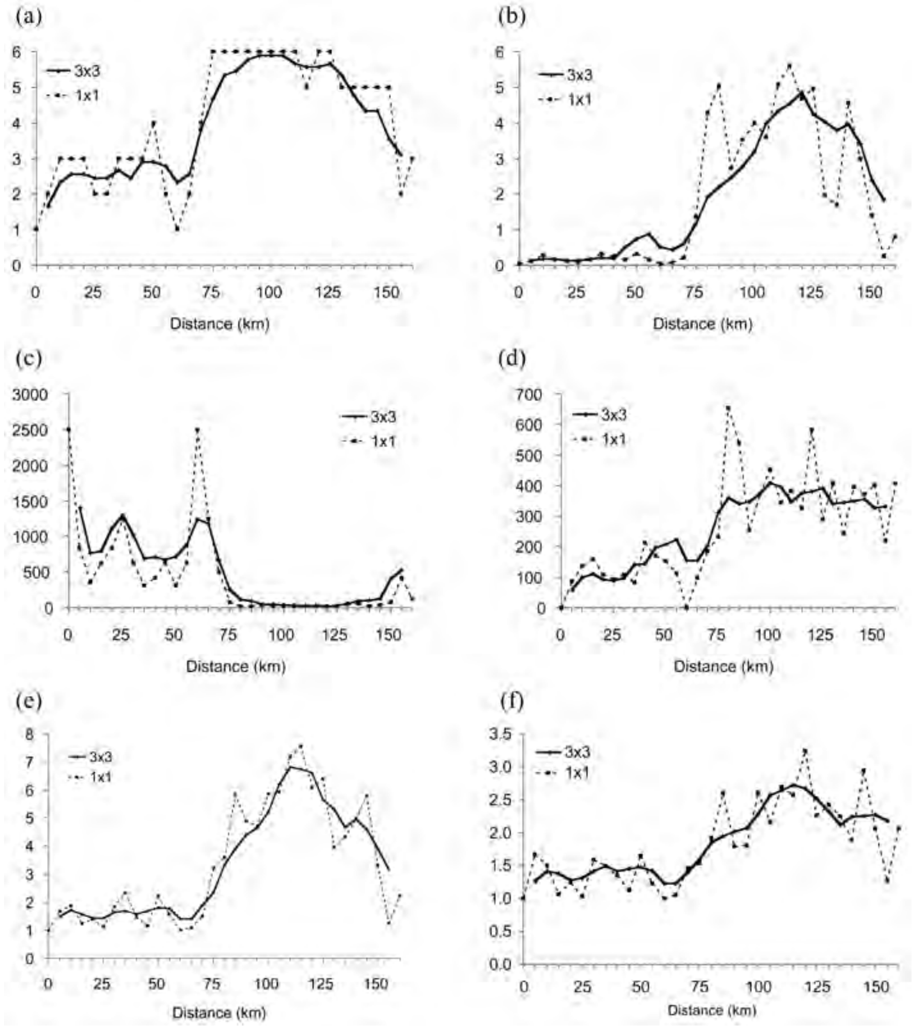

Figure 4. Changes in landscape-level metrics along the transect: (a) patch richness, (b) patch density, (c) mean patch size, (d) patch size coefficient of variation, (e) landscape shape index, and (f) area-weighted mean shape index. To examine the effect of changing scale of analysis, two window sizes were used: 1 × 1 and 3 × 3 blocks. See text for details.

(Figure 4d). Landscape shape index and area-weighted mean shape index indicated that the average patch shape complexity was low farther away from the urban center, and increased rapidly and substantially in the vicinity of the urban center (Figures 4e and 4f).

The configurational landscape metrics such as contagion and fractal dimension did not show consistent trends along the transect (results not shown here). While contagion was highly variable and erratic, the result of the double-log fractal dimension was discarded because of the insufficient number of patches to calculate the measure and because of its erratic behavior.

Discussion and conclusions

Our study has demonstrated that the center and spatial pattern of urbanization can be quantified using a combination of landscape metrics and gradient analysis. The results from our study can adequately address the four research questions we defined earlier in Introduction: How do different land use types change with distance away from the urban center? Do different land use types have their own unique spatial signatures? Can urbanization gradients be detected using landscape pattern analysis? How do the urban gradients differ among landscape metrics? While the answer to all these questions is generally affirmative, more details are discussed below.

The different land use types exhibited distinctive, but not necessarily unique, spatial signatures that were dependent on specific landscape metrics. For example, for patch type percent coverage, patch density, patch size coefficient of variation, landscape shape index, and area-weighted mean patch shape index, residential and urban land use types displayed similar patterns along the transect from west to the urban center–a largely monotonic gradient with its peak at the urban core. Desert showed a similar pattern for patch density, patch size coefficient of variation, landscape shape index, and area-weighted mean patch shape index, but a rather different pattern for patch type percent coverage and mean patch size (Figures 3a and 3c). For all the six measures, agriculture displayed a very different, yet unique, multiple-peaked pattern. Therefore, different land use types may indeed show distinctive 'spatial signatures' as distance-based 'landscape pattern profiles' which may be used to compare urban developmental patterns between cities and dynamics of the same city over time. Such comparisons may help understand different underlying processes that are responsible for various forms of urban morphology. Because of the variability inherent in land use data and introduced by analysis, using multiple landscape metrics, as in this study, seems necessary to increase the robustness of the results. However, it became clear from this study (and other studies such as Frohn (1998) and Wu (2000)) that some commonly used measures (e.g., fractal dimension and contagion) were neither effective nor reliable for detecting changes in landscape structure.

It was clear, though not surprising, from this study that the degree of human impact on the Phoenix landscape depended on the distance from the urban center. An urbanization center was clearly identifiable with the six landscape metrics when plotted along a transect. Specifically, all the landscape metrics indicated dramatic changes in landscape pattern at 75 km and 155 km, marking the urbanizing front of the Phoenix metropolitan area in the west-east direction. While the landscape-level metrics were able to characterize the center of urbanization as having the smallest mean patch size and the highest patch richness, patch density, patch size coefficient of variation, landscape shape index, and area-weighted mean shape index, the class-level indices provided more detailed information on the relative contributions of individual land use types. The high degrees of fragmentation and spatial complexity of the urbanization center, while not new findings of the sort, were able to be quantified in relation to distance and individual land use types. Processes and factors responsible for urbanization such as socioeconomic activities and land ownership resulted in the heterogeneous arrangement of land uses in the Phoenix metropolitan area. Although the distance-dependent trends of land use as represented by different landscape metrics were not exactly linear or symmetrical, some general patterns did emerge. It should be noted that, while the dramatic increase in spatial complexity within the intensely urbanized area indicated by the shape indices (landscape shape index and area-weighted mean patch shape index) were undeniable, the magnitude might be affected by the resolution of the data or the scale of analysis (Hunsaker et al. 1994; Jelinski and Wu 1996; Wu 2000; Wu et al. 2000). For example, for the residential land use type, connecting neighborhoods, instead of individual houses or blocks, were represented, and the former definitely had more spatially complex shapes than the latter. For the extremely large desert patches that might have complex boundaries, the relatively small size of the moving window imposed an artificial regular shape on them, yielding low values of shape metrics. Thus, the interpretation of such landscape pattern analysis must consider the possible effects of scale.

Although this study was not designed to test the existing theories of urban development, such as those mentioned in Introduction, the results of this young and rapidly growing metropolitan Phoenix may provide some interesting perspectives on urban morphology. First of all, a 165 km long and 15 km wide transect in this study provided an excellent opportunity for characterizing broad-scale landscape pattern change along a urban-rural-natural environment gradient. It may be difficult to find such large transects in Europe or even in the older metropolitan areas in the United States. Second, both the human population and urbanized area in the Phoenix metropolitan region have been growing exponentially, and their growth rates are highly correlated. This may be indicative of a young and fast growing city, or urban development in a desert environment, or more likely both. Third, none of the classic theories–concentric zone theory, sector theory, and multiple nuclei theory–seems to be able to adequately account for the land use pattern of Phoenix. This is at least partly because theses theories were developed based primarily on studies of old and well-established cities (i.e., Chicago, San Francisco, and Boston). At a first glance, the urbanization gradient revealed by the transect analysis seemed to suggest that different land use zones were distinguishable: urban-residential-agricultural-native desert (see Figure 3a). However, a closer examination of Figures 3 and 4 reveals that urban and residential land uses were not separable, and that agriculture did not form a single zone. Furthermore, it is evident from visually inspecting Figure 1 that this transect pattern was not isotropic–the different land uses did not form rings. Although neither transportation corridors nor multi-nucleus structures seemed to dictate the land use pattern of the Phoenix area, the distributions of roads, rivers, Native American reservations, and satellite cities must have played a rule in shaping the urban morphology. Thus, a self-organizing, cellular automata model with various top-down constraints seems more appropriate for understanding the urban morphology of Phoenix (Wu and David 2002 (in press)).

The changes in landscape pattern along the transect as revealed by our analysis may have important ecological implications. For example, the elimination of large desert patches, increased habitat fragmentation, and substantially high patch density of human land use types may significantly affect the biogeochemical cycling and biota of this area (e.g., McIntyre et al. (2001) and Baker et al. (2001)). The effects of the urbanization pattern on ecological conditions and processes are the focus of a series of current studies at the Central Arizona-Phoenix Long-Term Ecological Research site. Applications of landscape ecological approaches to the study of urbanization can help understand the relationship between the landscape pattern and urban ecological processes (Hobbs 1988; Cook 1991; Foresman et al. 1997; Pickett et al. 1997; Antrop and Van Eetvelde 2000; Zipperer et al. 2000). In particular, combining gradient analysis with landscape metrics, as illustrated here, can help to quantitatively identify and characterize the gradients and complex spatial pattern of urbanization, which can subsequently be related to ecological and socioeconomic processes. This study was only a first step towards understanding the structure and functioning of the Phoenix urban landscape. The extension of this study to understanding the mechanisms involved in urban landscape pattern formation necessitates a more comprehensive framework that explicitly incorporates geographical, ecological, socioeconomic, and political considerations (e.g., Luck et al. (2001)).

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