Ecological Complexity 8 (2011) 1–8

Contents lists available at ScienceDirect

Ecological Complexity

journal homepage: www.elsevier.com/locate/ecocom

Quantifying spatiotemporal patterns of urbanization: The case of the two fastest growing metropolitan regions in the United States

Jianguo Wu [a,b,c,*], G. Darrel Jenerette [d], Alexander Buyantuyev [a,c], Charles L. Redman [b]

[a] School of Life Sciences, Arizona State University, Tempe, AZ 85287, USA
[b] School of Sustainability, Arizona State University, Tempe, AZ 85287, USA
[c] Sino-US Center for Conservation, Energy, and Sustainability Science (SUCCESS), Inner Mongolia University, Hohhot, China
[d] Department of Botany and Plant Sciences, University of California, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 3 March 2010
Received in revised form 10 March 2010
Accepted 10 March 2010
Available online 9 April 2010

Keywords:
Spatiotemporal patterns of urbanization
Land use change
Landscape metrics
Spatial pattern analysis
Scale
Phoenix
Las Vegas

ABSTRACT

Urbanization is the most drastic form of land use change affecting biodiversity and ecosystem functioning and services far beyond the limits of cities. To understand the process of urbanization itself as well as its ecological consequences, it is important to quantify the spatiotemporal patterns of urbanization. Based on historical land use data, we characterize the temporal patterns of Phoenix and Las Vegas – the two fastest growing metropolitan regions in the United States – using landscape pattern metrics at multiple spatial resolutions. Our results showed that the two urban landscapes exhibited strikingly similar temporal patterns of urbanization. During the past several decades, urbanization in the two desert cities resulted in an increasingly faster increase in the patch density, edge density, and structural complexity at both levels of urban land use and the entire landscape. That is, as urbanization continued to unfold, both landscapes became increasingly more diverse in land use, more fragmented in structure, and more complex in shape. The high degree of similarity between the two metropolitan regions may be attributable to their resemblance in the natural environment, the form of population growth, and the stage of urban development. While our results corroborated some theoretical predictions in the literature, they also showed spatiotemporal signatures of urbanization that were different from other cities. Resolving these differences can certainly further our understanding of urban dynamics. Finally, this study suggests that a small set of landscape metrics is able to capture the main spatiotemporal signatures of urbanization, and that the general patterns of urbanization do not seem to be significantly affected by changing grain sizes of land use maps when the spatial extent is fixed. This landscape pattern analysis approach is not only effective for quantifying urbanization patterns, but also for evaluating spatial urban models and investigating ecological effects of urbanization.

1. Introduction

Since the industrial revolution in the late 18th century, the world population has increased exponentially at an astonishing rate. The human population was only 5 million when primitive agriculture occurred more than 10,000 years ago, and crossed the first billion mark in 1830 (http://www.census.gov/ipc/www/idb/worldpopinfo.php). It reached 2 billion in 1930, 3 billion in 1960, 4 billion in 1975, 5 billion in 1987, and 6 billion in 1999, and now is approaching 7 billion (over 6.807 billion as of March 2010). In other words, it took more than 10,000 years for the world population to increase from 5 million to 1 billion, but only 100 years later did it reach 2 billion. Since then, the time for adding 1 billion people on the planet earth has been reduced to 30 years (from 2 to 3 billion), 15 years (from 3 to 4 billion), and 12 years (from 4 to 5 and from 5 to 6 billion). Importantly, the world urban population has increased much faster than the rural population, rising from 14% in 1900 to 29.1% in 1950, 47% in 2005, and will be about 61% by 2030. Furthermore, future population growth will occur primarily in urban areas. Now we are witnessing a historic turning point in human history as *Homo sapiens* transforms from a predominantly agrarian to a mostly urban species (Wu, 2008).

The United Nations (2004) projected that while the world population will most likely stabilize around 9.1 billion by 2100, the urban population will continue to increase. The increasing urban nature of humanity has a number of profound environmental and socioeconomic implications for the world's future (Grimm et al., 2000, 2008; McGranahan and Satterthwaite, 2003; Wu, 2008). Urbanization has affected biodiversity, ecosystem functioning and services, and these impacts go far beyond the city limits. Although urbanized areas cover only about 3% of the earth's land surface,

* Corresponding author at: School of Life Sciences, Arizona State University, 427 E. Tyler Mall, Tempe, AZ 85287, USA. Tel.: +1 480 965 1063; fax: +1 480 965 6899.
E-mail address: Jingle.Wu@asu.edu (J. Wu).

1476-945X/$ – see front matter
doi:10.1016/j.ecocom.2010.03.002

they account for more than 78% of carbon emissions, 60% of residential water use, and 76% of the wood used for industrial purposes (Brown, 2001). Cities in developed countries have historically contributed much more to the alteration of the atmospheric composition than those in developing countries. For example, the per person carbon dioxide emissions from Canberra, Chicago, Los Angeles and the like were 6–9 times the world's average, and the per capita emissions in the United States were 200–500 times those in developing nations in 1996 (McGranahan and Satterthwaite, 2003). In 1986, the developed countries used 100 times more chlorofluorocarbons and halons (chemicals responsible for the stratospheric ozone depletion) than the developing nations (McGranahan and Satterthwaite, 2003).

On the other hand, cities are the centers of scientific and technological innovations, economic development, and decision-making, and represent arguably the most important habitats for humans (Wu, 2008). Yet, cities are among the least understood ecosystems of all despite the fact that the study of "ecology in cities" may trace back several decades (Collins et al., 2000; Grimm et al., 2000; Wu, 2008). Urban ecological systems provide unique and important opportunities for studying the effects of human activities on ecosystem processes because urbanization exposes the entire ecosystem to severely altered climate and other environmental conditions, which allows for comparison with surrounding natural environment (McDonnell and Pickett, 1990; Zipperer et al., 2000; Carreiro and Tripler, 2005; Gagne and Fahrig, 2007; Roy et al., 2007). In addition, urban areas capture a wide variety of land use activities in a spatially heterogeneous mosaic of patches (e.g., various urban, residential, and agricultural cover types), providing a challenging yet necessary place to study the relationship between landscape pattern and ecosystem processes (Zipperer et al., 2000; Wu and David, 2002; Wu, 2008).

An important first step to understanding the effects of urbanization on ecological processes is to quantify the spatial and temporal patterns of urbanization itself. In the past few decades, with the rapid development of landscape ecology, geographic information science, and related fields, a number of quantitative methods have emerged for quantifying the spatial pattern and its dynamics of urban landscapes (Wu et al., 2000; Jenerette and Wu, 2001; Luck and Wu, 2002; Alberti, 2005). In particular, landscape pattern metrics have been increasingly used to quantify the spatial gradients of an urban area along a transect, to compare different urban landscapes, and to describe the temporal dynamics of the same urban landscapes (Wu et al., 2000; Jenerette and Wu, 2001; Luck and Wu, 2002; Berling-Wolff and Wu, 2004; Wu, 2004; Seto and Fragkias, 2005; Zhu et al., 2006; Weng, 2007). The main purpose of this study was to quantify the historical land use change of the two fastest growing cities in the United States – Phoenix and Las Vegas, using a selected set of landscape metrics. Specifically, we compare the spatial and temporal patterns of urbanization in the Phoenix (1912–1995) and Las Vegas (1907–1995) metropolitan regions, test some of the theories and hypotheses on urbanization patterns, and conclude the paper with a discussion on several key issues of urban ecological research.

2. Study areas

Our study areas are Phoenix of the state of Arizona and Las Vegas of the state of Nevada, the two fastest growing metropolitan regions in the United States (Fig. 1). Phoenix is located in the southwestern USA, and is home to the Central Arizona-Phoenix Long-term Ecological Research (CAP-LTER) project on urban ecology (Grimm and Redman, 2004). Situated in the northern part of the Sonoran desert, this region is characterized by a hot and dry climate. The average summer temperature is 30.8 °C, the average winter temperature is 11.3 °C, and the annual precipitation is about 180 mm. Native vegetation is characterized by desert scrub communities dominated by creosote bush (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), and several other shrub species, including the magnificent cactus, saguaro (*Carnegiea gigantea*) – a widely recognized symbol of the Sonoran desert landscape.

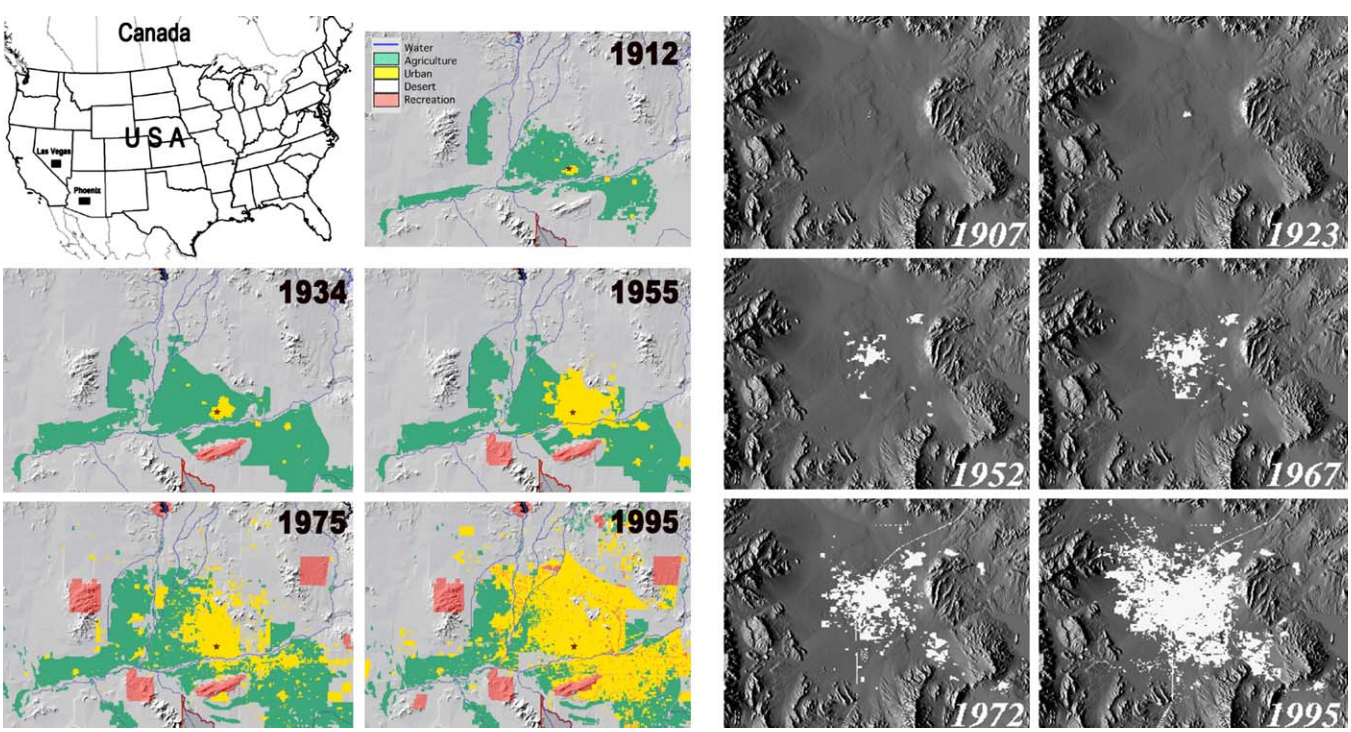

Fig. 1. Historical land use change in the Phoenix (a) and Las Vegas (b) metropolitan regions of USA (data for Phoenix from Knowles-Yanez et al., 1999; and data for Las Vegas from Acevedo et al., 2003).

Historically, this valley was the cradle of the Hohokam civilization beginning in 500–700 AD, and then largely abandoned by 1400 (Knowles-Yanez et al., 1999). Little settlement was established until the late 1800s when agricultural activities became prominent between 1870 and 1920 (Knowles-Yanez et al., 1999). Since 1880, the population in the Phoenix area has been increasing exponentially (Jenerette and Wu, 2001). As the sixth largest city in the country, Phoenix is one of the two fastest growing cities in the USA. Our previous simulation modeling work projected that the population in the Phoenix metropolitan region will likely continue to increase up to 7–8 million by 2030 (Berling-Wolff and Wu, 2004).

Located in the Mojave desert, Las Vegas is about 480 km to the northwest of Phoenix. The climate of this desert region is also characterized by hot summers, mild winters, and little rainfall mostly during the winter. Major native vegetation includes communities dominated by creosote bush (*L. tridentata*) and other desert shrub species. Las Vegas has a more recent history of human settlement than Phoenix. In 1855 Mormons first settled in the Las Vegas area, and the first major population growth did not occur until the 1930s (Acevedo et al., 2003). Gaming, entertainment and tourism industries began to bloom, and people continued to move in at an accelerating rate. Since the 1900s, the population of Las Vegas has been increasing exponentially, jumping from 25,000 in 1950 to more than 1 million in 1995 (Acevedo et al., 2003). Known as the ‘‘Entertainment Capital of the World’’, Las Vegas continues to grow at the fastest rate among all metropolitan regions in the United States.

Table 1
Generalized land use types and their constituents (from Knowles-Yanez et al., 1999).

Urban	Large lot residential
	Small lot residential
	Medium density residential
	High density residential
	Rural residential
	Neighborhood retail centers
	Community retail centers
	Regional retail centers
	Hotels, motels, and resorts
	Warehouse/distribution centers
	Industrial
	Business park
	Office
	Educational
	Institutional
	Public facilities
	Large assembly areas
	Transportation
	Airports
	Vacant
Desert	Vacant
	Dedicated or non-developable open space
Agricultural	Agriculture
	Rural residential
Recreation	Recreational open space

3. Data and methods

The historical land use dataset for Phoenix, including five time periods (1912, 1934, 1955, 1975, 1995), was obtained from CAP-LTER (Knowles-Yanez et al., 1999). Four general land use types were classified: urban, agricultural, recreation, and desert, and more detailed land use categories within each type are listed in Table 1. The historical land use data for Las Vegas, including six time periods (1907, 1923, 1952, 1967, 1972, 1995) were from Acevedo et al. (2003). Because the purpose of this dataset was primarily to depict the spatial and temporal pattern of urbanization, only three land use types were identified: urban, desert, and water.

Before spatial pattern analysis was conducted, the land use maps were rasterized at four spatial resolutions: 30 m $\times$ 30 m, 100 m $\times$ 100 m, 500 m $\times$ 500 m, and 1000 m $\times$ 1000 m, using ArcView Spatial Analyst. The reason for rasterizing the maps at four pixel sizes was to examine the effects of spatial resolution on spatial pattern analysis, which have been reported in a number of previous studies (Turner et al., 1989; Wu et al., 2000, 2002). The software package for landscape pattern analysis, FRAGSTATS (McGarigal and Marks, 1995), was used to quantify the landscape patterns of urbanization of the two study areas. Based on our previous studies (Wu et al., 2000, 2002; Berling-Wolff and Wu, 2004; Wu, 2004), we selected six pattern metrics (PD, MPS, SHDI, AWMFD, LSI, CONT) to characterize landscape-level changes and six class-level metrics (Urban%, MPS, ED, AWMFD, LSI and SqP) to focus on the spatiotemporal dynamics of urban land use (see Table 2 for details). Note that LSI and SqP are numerically related to each other (LSI = $(1 - \mathrm{SqP})^{-1}$) (Wu et al., 2002; Wu, 2004), and we used them both here to examine which one is more appropriate to describe the spatial dynamics of urbanization given that they contain redundant information.

Data quality and accuracy assessment represent an important and difficult problem in landscape analysis (Masek et al., 2000; Li and Wu, 2006; Iverson, 2007; Shao and Wu, 2008), and this is especially true when using historical land use change data that date back far before remotely sensed data were available. The historical land use data used in this study, like any other historical records, must contain errors induced by using different sources of information with different sampling and reporting protocols, techniques, and formats (Iverson, 2007; Rhemtulla and Mladenoff,

Table 2
Landscape metrics used in the study, all of which, except SqP, were based on McGarigal and Marks (1995). The mathematical formulations can be found in McGarigal and Marks (1995), Wu et al. (2002) and Wu (2004).

Landscape metric	Abbreviation	Description
1. Area-weighted Mean Patch Fractal Dimension	AWMFD	The patch fractal dimension weighted by relative patch area which measures the average shape complexity of individual patches for the whole landscape or a specific patch type.
2. Contagion	CONT	An information theory-based index that measures the extent to which patches are spatially aggregated in a landscape.
3. Edge Density	ED	The total length of all edge segments per hectare for the class or landscape of consideration (unit: m/ha).
4. Landscape Shape Index	LSI	A modified perimeter-area ratio of the form that measures the shape complexity of the whole landscape or a specific patch type.
5. Mean Patch Size	MPS	The average area of all patches in the landscape (unit: ha).
6. Patch density	PD	The number of patches per square kilometer (i.e., 100 ha).
7. Percent Class Area	%Class	Relative area of a specific patch type in a landscape (unit: %).
8. Shannon's Diversity Index	SHDI	A measure of the diversity of patch types in a landscape that is determined by both the number of different patch types and the proportional distribution of area among patch types.
9. Square Pixel	SqP	A normalized perimeter-area ratio of the form that measures the shape complexity of the whole landscape or a specific patch type.

2007). Given the complex nature of this problem, an accuracy assessment on these land use maps was not possible. These errors can affect the accuracy of landscape metrics, especially if high-resolution and detailed classification schemes are 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 can be significantly relaxed (Li and Wu, 2006; Buyantuyev and Wu, 2007; Shao and Wu, 2008). Therefore, the significance of our analysis did not reside in the individual values of landscape metrics at a given time, but rather the general spatiotemporal patterns of these metrics over several decades. The consistency of these urbanization patterns for two similar metropolitan regions demonstrates the robustness of the methods that we used.

4. Results

In this section, we first describe the changing landscape pattern during urbanization at the whole landscape level and then for a specific land use type – the urban land use.

4.1. Changes in the spatial pattern of the whole landscape during urbanization

With accelerating urbanization in the Phoenix and Las Vegas metropolitan areas, patch density has increased exponentially, and this trend was consistent at the four different spatial resolutions (Fig. 2). An explosive increase in patch density occurred around 1955 in Phoenix and the late 1960s in Las Vegas, indicating dramatic increase in the degree of landscape fragmentation. In contrast, the Mean Patch Size decreased rapidly during urbanization, especially after 1934 in Phoenix and 1925 in Las Vegas (Fig. 2). Shanon's Diversity increased with urbanization due largely to the increasing uneven areal distribution of the land use types (evidenced by the behavior of Shanon's Evenness Index not shown here). That is, as urbanization unfolded, the two metropolitan landscapes became more fragmented and more evenly distributed among land use types.

How did the shape complexity of individual patches and the entire landscape change during urbanization, and how was this structural complexity related at the two scales? For Phoenix, Area-Weighted Mean Fractal Dimension remained relatively unchanged up to 1955 and then increased steadily (similar pattern shown by Mean Patch Shape Index and Mean Patch Fractal Dimension which are not shown here to avoid redundancy). For Las Vegas, Area-Weighted Mean Fractal Dimension showed a similar pattern, but the increase after 1923 was much more rapid, especially between 1952 and 1967 (Fig. 2). For both cities, Landscape Shape Index, a form of patch perimeter-area ratio at the landscape level, also remained relatively unchanged in the early urbanization stage, and then increased exponentially. This pattern suggested that the shape of the landscape as a patch mosaic became more irregular with urbanization. Contagion, measuring the degree of clumping of patches that pertains to both the compositional and configurational aspects of landscape pattern, continued to decline during urbanization for both cities (Fig. 2). In general, the temporal patterns of these landscape indices indicate that the landscape shape complexity and the degree of fragmentation increased considerably during urbanization in both Phoenix and Las Vegas over the past several decades.

4.2. Changes in the spatial pattern of urban land use

To further examine how the spatial pattern of urbanization changed over the past several decades in the two desert cities, we used five landscape metrics to quantify the temporal dynamics of the urbanized area, a key patch type in understanding urban morphology. Here, we only show the patterns of the selected

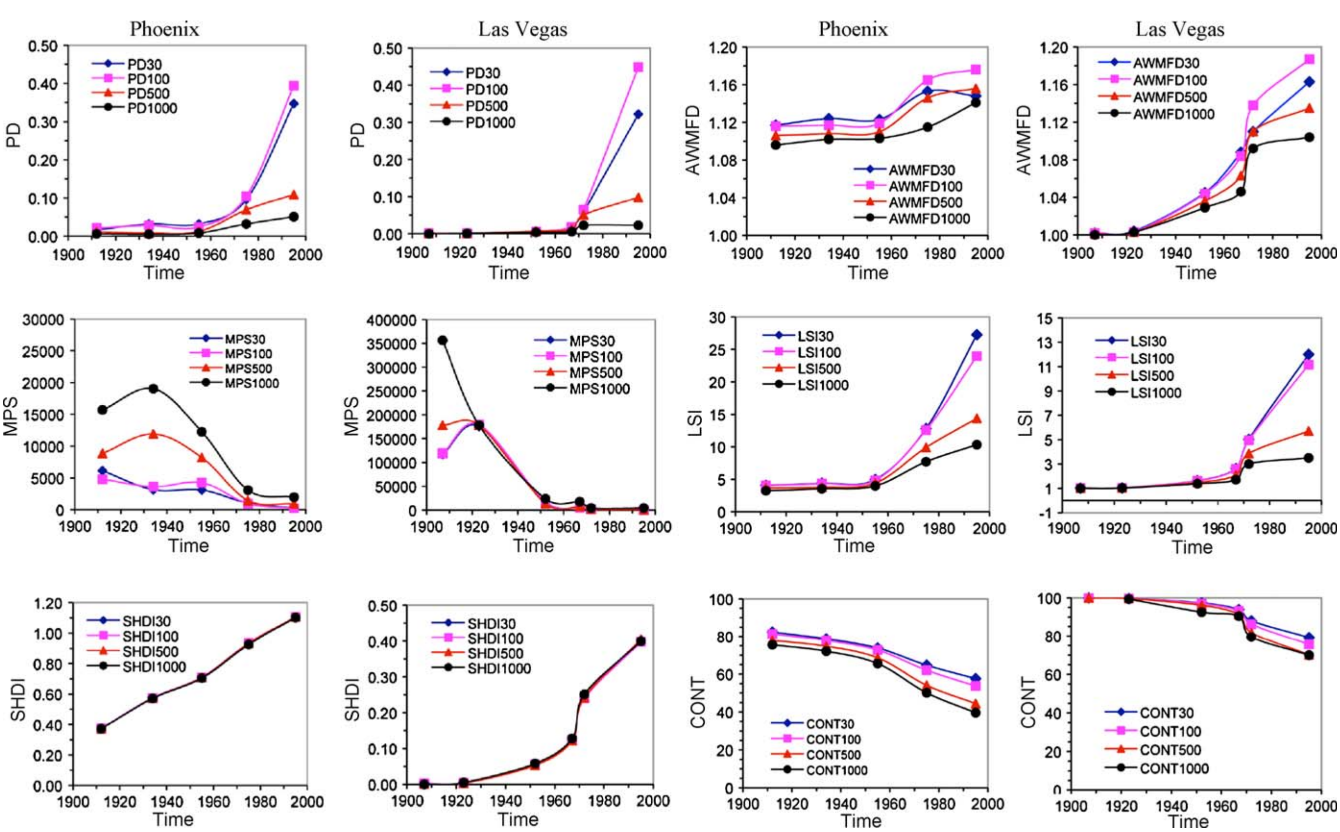

Fig. 2. Spatiotemporal patterns of urbanization in Phoenix and Las Vegas as described by six landscape-level pattern metrics at four spatial resolutions.

landscape metrics at the finest spatial resolution (30 m × 30 m), which offers the most detailed spatial information for this particular purpose. Each of the six indices showed quite a similar pattern between Phoenix and Las Vegas.

The values of the percent area of the urban land (%Class Area in FRAGSTATS), edge density, and Landscape Shape Index increased exponentially during urbanization in both metropolitan regions (Fig. 3). In Phoenix, a significant portion of urbanization took place in previous agricultural land (evidenced by the class area of desert and agriculture not shown here). The rapid increase in the density of patches and edges of the urban land were indicative of the increasing degree of fragmentation of urban land uses. Mean Patch Size of urban land exhibited a roughly bell-shaped pattern, indicating that the average urban patch reached its largest size sometime during the course of urbanization (Fig. 3). This pattern was more prominent in Phoenix than Las Vegas. Area-weighted Mean Patch Fractal Dimension increased steadily. In contrast with Landscape Shape Index, Square Pixel, a normalized patch perimeter-area ratio (Wu, 2004), showed an S-shaped pattern.

4.3. Effects of changing the spatial resolution of land use data

We computed landscape-level metrics at four different spatial resolutions (or grain sizes: 30 m × 30 m, 100 m × 100 m, 500 m × 500 m, and 1000 m × 1000 m). The percent areas of patch types changed little with changing spatial resolution. However, if the coarser-resolution maps had been created by progressively aggregating finer-resolution maps, which was not the case here (see Section 3), larger resolution effects on class area would have been greater (e.g., Wu et al., 2002; Wu, 2004). Shanon's Diversity Index also did not vary appreciably with changing spatial resolution in this particular case. Patch density, edge density, Area-Weighted Mean Fractal Dimension, Landscape Shape Index, and Contagion all showed a similar temporal pattern at the four grain sizes, but the between-grain size differences tended to increase as urbanization intensified (Fig. 2). Mean Patch Size, on the other hand, exhibited larger between-grain size discrepancies at the early stage of urbanization (Fig. 2).

5. Discussion

5.1. General urbanization patterns of Phoenix and Las Vegas

In this study, we selected six landscape-level metrics (PD, MPS, SHDI, AWMFD, LSI, CONT) and five class-level metrics (Urban%, MPS, ED, AWMFD, and SqP) to quantify the spatial signatures of historical land use change in the two most rapidly growing metropolitan regions in the United States – Phoenix and Las Vegas. Overall, the two metropolitan regions showed strikingly similar temporal patterns of urbanization. During the past several decades, urbanization in the two desert cities resulted in an increasingly faster increase in patch density, edge density, and structural complexity at both levels of the urban land use and the entire landscape, suggesting increasing landscape fragmentation and decreasing landscape connectivity.

Landscape dynamics can be depicted in a 3-dimensional space constructed with three landscape metrics (O'Neill et al., 1996). For urbanizing landscapes, we suggest to use Shannon's Diversity,

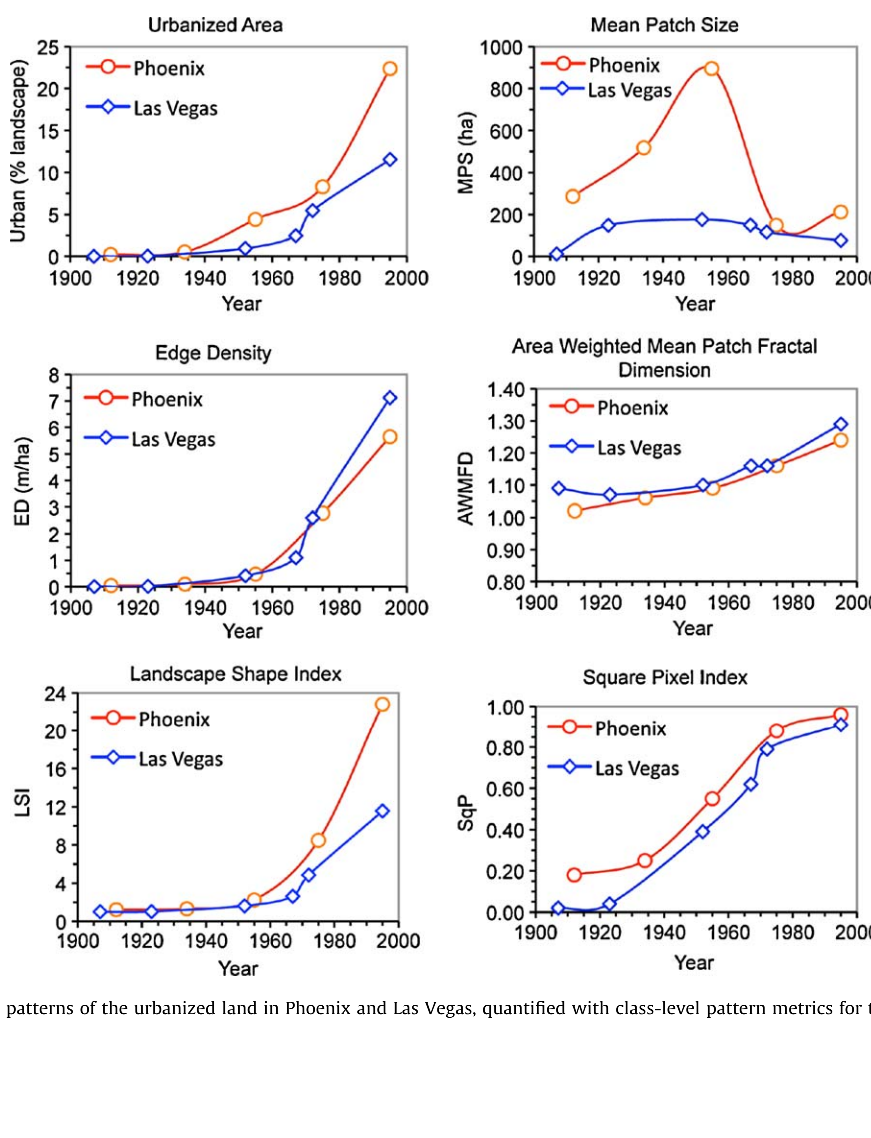

Fig. 3. Spatiotemporal patterns of the urbanized land in Phoenix and Las Vegas, quantified with class-level pattern metrics for the urban land use type.

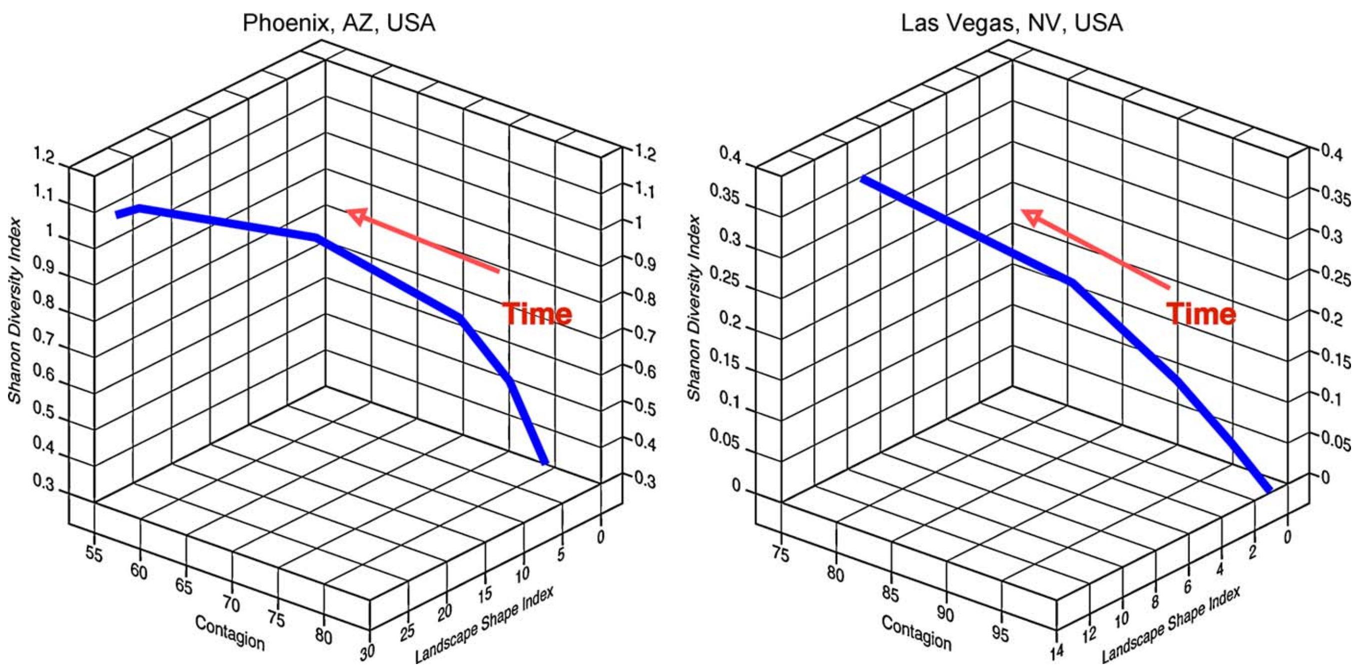

Fig. 4. A three-dimensional representation of the urbanization trajectory of Phoenix and Las Vegas.

Contagion, and Landscape Shape Index to describe the spatio-temporal trajectory of urbanization. Such diagrams may be used for both monitoring urban dynamics and comparing different urban regions. In the case of Phoenix and Las Vegas, the 3-dimensional trajectory diagram (Fig. 4) clearly shows that both landscapes became increasingly more diverse in land use, more fragmented in structure, and more complex in shape. When such diagrams are used, however, caution must be exercised. First, the choice of landscape metrics should be relevant to the research questions or the objective of the study. Ideally, the metrics should be orthogonal (Riitters et al., 1995). Second, the spatial resolution and extent of the maps used to compute landscape metrics for the same landscape at different times and for comparing different landscapes must be commensurate because of the well-known effects from changing the scale of analysis (Wu, 2004).

The high degree of similarity between the two metropolitan regions may be attributed to their resemblance in the natural environment, the form of population growth, and the stage of urban development. Specific socioeconomic drivers, however, were quite different in these two regions: they were gaming and other entertainment-related activities in Las Vegas, but high-tech-related job opportunities, retirement relocations, and tourism in Phoenix. This implies that different socioeconomic processes may result in similar urban landscape patterns. These case studies of Phoenix and Las Vegas are exceptional in their rates of urbanization within the United States and globally. By examining cities on the extreme, we hope to learn more generally about the trajectories of urban landscape modification. A recent synthesis of urban growth among 25 cities throughout the world suggests many cities in Asia and South America are transforming their landscapes similarly as Phoenix and Las Vegas with extensive urban expansion both within the urban core and on the fringes (Schneider and Woodcock, 2008).

5.2. Testing hypotheses on urbanization patterns

Are there any general spatiotemporal patterns or developmental regularities of urbanization? Such general patterns can not only facilitate our understanding of urban systems, but also guide our practices in urban planning, design, and management. Most theories of urbanization patterns are based on the idea of periodicity in the form of waves or growth phases, and the spatiotemporal patterns predicted or prescribed by these theories have not been adequately tested (Dietzel et al., 2005). Combining remotely sensed data, landscape pattern analysis and geographic information systems provides a powerful approach to testing urban morphological theories (Luck and Wu, 2002; Dietzel et al., 2005; Xie et al., 2006; Zhu et al., 2006).

Integrating the idea of development waves and growth phases, Dietzel et al. (2005) hypothesized that "urban growth can be characterized as having two distinct processes, diffusion and coalescence, with each process following a harmonic pattern." In other words, urbanization exhibits cyclic patterns in time and space driven by two alternating processes: diffusion that spreads urban growth from existing centers to new development areas and coalescence that is characterized by outward expansion and gap infilling of existing urban areas (Dietzel et al., 2005). These authors further translated their hypothesis into testable temporal patterns of landscape pattern metrics: during a full diffusion-coalescence cycle of urbanization, urban land area increases monotonically; urban patch density, edge density, and mean nearest neighbor distance all increase first, then each peak at different times, and finally decrease, exhibiting a unimodal shape; contagion is highest at the beginning of the diffusion process and the end of coalescence process and reaches its lowest value in between, thus exhibiting a somewhat mirror image of urban patch density (Dietzel et al., 2005). Based on an analysis of the urban development of several cities in the Central Valley of California, USA, Dietzel et al. (2005) concluded that the urbanization patterns of spatial metrics were confirmed.

The monotonic increase in urban land area during urbanization is self-evident, and should hold in most cases unless a city is being abandoned or undergoes some sort of reversed urbanization. Our results, however, also showed a monotonic decrease in landscape contagion and a monotonic increase in urban patch density, edge density, and other fragmentation-related metrics over a period of more than 80 years in both Phoenix and Las Vegas. The only landscape metric in our study that showed a unimodal pattern is Mean Patch Size for urban land use. Although Dietzel et al. (2005) did not explicitly discuss this metric, their hypothesis should predict that Mean Patch Size increases during an urbanization cycle as the dominant process shifts from diffusion to coalescence. Another example of this theory was illustrated by Xu et al. (2007).

These discrepancies may be attributable to a few factors. First, although the historical data for Phoenix and Las Vegas in our study covered a period of more than 80 years – close to the 100-year period used in Dietzel et al. (2005), the urbanization process of these two metropolitan regions may still be in its early stage (i.e., dominated by diffusion). Second, differences in the spatial extent of the study landscapes often lead to differences in metric values, and the spatiotemporal patterns of urbanization may differ between such small cities as those in Dietzel et al. (2005) and large metropolitan regions like Phoenix and Las Vegas. Third, the land use data used in Dietzel et al. (2005) to test their hypothesis were actually compiled from three different sources: historical records, remote sensing imagery, and simulation modeling, together covering a period of 100 years (1940–2040). The accuracy of their simulated "data" was not possible to validate empirically.

Forman and Godron (1986) postulated that, along a landscape modification gradient: (1) patch density increases exponentially; (2) the regularity of patch shape increases; and (3) landscape connectivity decreases. These patterns have been repeatedly supported for urbanizing landscapes throughout the world (Luck and Wu, 2002; Weng, 2007; Schneider and Woodcock, 2008). The time series of the historical land use data in Phoenix and Las Vegas can be thought of as representing a natural-to-urban spatial gradient (a time-for-space perspective). Thus, our results may be used to examine whether these general patterns of urbanization hold. As shown in previous sections, during urbanization in Phoenix and Las Vegas: (1) patch density increased exponentially; (2) the shape complexity of both urban land and the entire landscape also increased dramatically, suggesting a decrease in the regularity of patch shape; and (3) landscape connectivity decreased in an accelerating manner, assuming that landscape connectivity is positively related to Contagion and negatively to patch density and edge density. Thus, our results supported the two hypotheses on patch density and connectivity, but not the one on shape regularity.

5.3. Relating urban spatial patterns to ecological processes

Urban systems are spatially extended systems in which physical, ecological, and socioeconomic processes interact with spatial patterns. Thus, relating pattern to process is essential to understanding urban ecosystems, and this cannot be effectively done without first quantifying the spatial pattern of the urbanized and urbanizing areas under consideration. While the spatiotemporal patterns of urbanization can be readily quantified with landscape pattern metrics, from an ecological perspective, however, an ultimate goal of studying landscape pattern is to understand its relationship with ecological properties and processes (Wu and Hobbs, 2002, 2007). Urbanization is the most extreme form of land transformation, and urban landscapes are characterized by dense clustering of high-rises, rampant transportation networks, and extensive impervious surfaces. An increasing number of studies have shown that urbanization not only results in direct loss and fragmentation of natural habitats, but also profoundly affects biodiversity and ecosystem processes through urban heat islands, air pollution, water contamination, and human-introduced exotic species (Pickett et al., 2001; Jenerette et al., 2006, 2007; Gagne and Fahrig, 2007; Roy et al., 2007; Carreiro et al., 2008; Grimm et al., 2008; Wu, 2008). The actual effects of urban landscape pattern on ecological processes, however, cannot be predicted reliably without directly examining the ecological processes themselves (Li and Wu, 2004, 2007).

Relating historical land use change to ecological processes is often difficult, or even impossible in some cases, because of the lack of historical data on ecological variables (Knowles-Yanez et al., 1999; Rhemtulla and Mladenoff, 2007). In the Phoenix metropolitan area, such ecological data have been accumulating since the establishment of the Central Arizona-Phoenix Long-Term Ecological Research project in 1997. As the project progresses, our research will focus increasingly on the coupling between landscape pattern and ecological processes (Grimm and Redman, 2004; Jenerette et al., 2006; Jenerette et al., 2007; Shen et al., 2008). An important grand challenge for urban ecology is to identify what spatial patterns of urban development are the most beneficial and sustainable for both the human and non-human residents. Clearly, the answer depends on stakeholder needs, and between different stakeholders there will be conflicting interests. These needs will again vary geographically – what is appropriate for Phoenix may not necessarily be appropriate for Las Vegas or other cities. A fundamental dichotomy exists between managing for compact or diffuse cities. More compact urbanization will lead to a smaller physical footprint of the city and less disruption of adjacent hinterlands. More diffuse urbanization may lead to networks of remaining native habitats that can support diverse species and provide ready access to greenspace throughout the city. The current state of the science does not allow us to provide all the answers, but progress in understanding the variability of current urban landscapes is essential for developing such recommendations.

6. Conclusion

Our results suggest that a small set of landscape metrics is able to capture the main spatiotemporal signatures of urbanization. However, LSI and SqP, although both increasing with urbanization, actually showed different temporal trends. The asymptotic pattern of SqP suggested that the shape complexity of urban land was approaching the maximum (unity), but this was not consistent with the pattern shown by LSI, PD, ED, and AWMFD. Thus, we conclude that LSI is more appropriate than SqP for quantifying the spatial dynamics of urbanization. Also, it is important to consider the effects of changing scale (both grain size and extent) on the results the analysis (Turner et al., 1989; Jelinski and Wu, 1996; Wu et al., 2000, 2002; Li and Wu, 2004, 2007; Wu, 2004). Our analysis showed that the between-grain size difference tended to increase with the degree of urbanization for most of the selected metrics. The general spatiotemporal patterns of urbanization, however, do not seem to be significantly affected by changing grain sizes of the land use maps when the spatial extent is fixed. In ecological studies, spatial pattern analysis usually is only the first step to achieving a deeper understanding of ecological dynamics. This is especially true in the study of the ecology of cities that are extraordinarily heterogeneous in space. Our ongoing studies in the Phoenix metropolitan region focus primarily on the ecological and environmental consequences of the dramatically dynamic landscape pattern due to urbanization through both empirical and simulation modeling approaches (Grimm et al., 2008; Shen et al., 2008; Wu, 2008).

Acknowledgments

This research has been supported by grants from the U.S. National Science Foundation (DEB 97-14833, CAP-LTER) and (BCS-0508002, Biocomplexity/CNH). We thank anonymous reviewers for their constructive suggestions on an earlier version of this paper.

References

Acevedo, W., Gaydos, L., Tilley, J., Mladinich, C., Buchanan, J., Blauer, S., Druger, K., Schubert, J., 2003. Urban Land Use Change in the Las Vegas Velley. , http://geochange.er.usgs.gov/sw/changes/anthropogenic/population/las_vegas/index.html.

Alberti, M., 2005. The effects of urban patterns on ecosystem function. Int. Reg. Sci. Rev. 28, 168–192.
Berling-Wolff, S., Wu, J., 2004. Modeling urban landscape dynamics: a case study in Phoenix, USA. Urban Ecosyst. 7, 215–240.
Brown, L.R., 2001. Eco-Economy: Building an Economy for the Earth. W. W. Norton, New York, 333 pp.
Buyantuyev, A., Wu, J., 2007. Effects of thematic resolution on landscape pattern analysis. Landscape Ecol. 22, 7–13.
Carreiro, M.M., Tripler, C.E., 2005. Forest remnants along urban–rural gradients: examining their potential for global change research. Ecosystems 8, 568–582.
Carreiro, M.M., Song, Y.C., Wu, J. (Eds.), 2008. Ecology, Planning and Management of Urban Forests: International Perspectives. Springer, New York, 467 pp.
Collins, J.P., Kinzig, A., Grimm, N.B., Fagan, W.F., Hope, D., Wu, J., Borer, E.T., 2000. A new urban ecology. Am. Sci. 88, 416–425.
Dietzel, C., Herold, M., Hemphill, J.J., Clarke, K.C., 2005. Spatio-temporal dynamics in California's Central Valley: empirical links to urban theory. Int. J. Geogr. Inf. Sci. 19, 175–195.
Forman, R.T.T., Godron, M., 1986. Landscape Ecology. Wiley, New York, 619 pp.
Gagne, S.A., Fahrig, L., 2007. Effect of landscape context on anuran communities in breeding ponds in the National Capital Region, Canada. Landscape Ecol. 22, 205–215.
Grimm, N.B., Grove, J.M., Pickett, S.T.A., Redman, C.L., 2000. Integrated approaches to long-term studies of urban ecological systems. BioScience 50, 571–584.
Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. Science 319, 756–760.
Grimm, N.B., Redman, C.L., 2004. Approaches to the study of urban ecosystems: the case of Central Arizona-Phoenix. Urban Ecosyst. 7, 199–213.
Iverson, L., 2007. Adequate data of known accuracy are critical to advancing the field of landscape ecology. In: Wu, J., Hobbs, R. (Eds.), Key Topics in Landscape Ecology. Cambridge University Press, Cambridge, UK, pp. 11–38.
Jelinski, D.E., Wu, J., 1996. The modifiable areal unit problem and implications for landscape ecology. Landscape Ecol. 11, 129–140.
Jenerette, G.D., Harlan, S.L., Brazel, A., Jones, N., Larsen, L., Stefanov, W.L., 2007. Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. Landscape Ecol. 22, 353–365.
Jenerette, G.D., Wu, J., 2001. Analysis and simulation of land use change in the central Arizona – Phoenix region. Landscape Ecol. 16, 611–626.
Jenerette, G.D., Wu, J., Grimm, N.B., Hope, D., 2006. Points, patches, and regions: scaling soil biogeochemical patterns in an urbanized arid ecosystem. Glob. Change Biol. 12, 1532–1544.
Knowles-Yanez, K., Moritz, C., Fry, J., Redman, C.L., Bucchin, M., McCartney, P.H., 1999. Historic Land Use: Phase I Report on Generalized Land Use. Central Arizona-Phoenix Long-Term Ecological Research (CAPLTER) Arizona State University, Tempe, 21 pp.
Li, H., Wu, J., 2004. Use and misuse of landscape indices. Landscape Ecol. 19, 389–399.
Li, H., Wu, J., 2006. Uncertainty analysis in ecological studies: an overview. In: Wu, J., Jones, K.B., Li, H., Loucks, O.L. (Eds.), Scaling and Uncertainty Analysis in Ecology: Methods and Applications. Springer, Dordrecht, pp. 45–66.
Li, H., Wu, J., 2007. Landscape pattern analysis: key issues and challenges. In: Wu, J., Hobbs, R. (Eds.), Key Topics in Landscape Ecology. Cambridge University Press, Cambridge, pp. 39–61.
Luck, M., Wu, J., 2002. A gradient analysis of urban landscape pattern: a case study from the Phoenix metropolitan region, Arizona, USA. Landscape Ecol. 17, 327–339.
Masek, J.G., Lindsay, F.E., Goward, S.N., 2000. Dynamics of urban growth in the Washington DC metropolitan area, 1973–1996, from Landsat observations. Int. J. Rem. Sens. 21, 3473–3486.
McDonnell, M.J., Pickett, S.T.A., 1990. Ecosystem structure and function along urban–rural gradients: an unexploited opportunity for ecology. Ecology 71, 1232–1237.
McGarigal, K., Marks, B.J., 1995. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. Gen. Tech. Rep. PNW-GTR-351. Pacific Northwest Research Station, USDA-Forest Service, Portland, 122 pp.
McGranahan, G., Satterthwaite, D., 2003. Urban centers: an assessment of sustainability. Ann. Rev. Environ. Res. 28, 243–274.
O'Neill, R.V., Hunsaker, C.T., Timmins, S.P., Timmins, B.L., Jackson, K.B., Jones, K.B., Riitters, K.H., Wickham, J.D., 1996. Scale problems in reporting landscape pattern at the regional scale. Landscape Ecol. 11, 169–180.
Pickett, S.T.A., Cadenasso, M.L., Grove, J.M., Nilon, C.H., Pouyat, R.V., Zipperer, W.C., Costanza, R., 2001. Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. Ann. Rev. Ecol. Syst. 32, 127–157.
Riitters, K.H., O'Neill, R.V., Hunsaker, C.T., Wickham, J.D., Yankee, D.H., Timmins, K.B.J., Jackson, B.L., 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecol. 10, 23–39.
Rhemtulla, J.M., Mladenoff, D.J., 2007. Why history matters in landscape ecology. Landscape Ecol. 22, 1–3.
Roy, A.H., Freeman, B.J., Freeman, M.C., 2007. Riparian influences on stream fish assemblage structure in urbanizing streams. Landscape Ecol. 22, 385–402.
Schneider, A., Woodcock, C.E., 2008. Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. Urban Stud. 45, 659–692.
Seto, K.C., Fragkias, M., 2005. Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landscape Ecol. 20, 871–888.
Shao, G.F., Wu, J., 2008. On the accuracy of landscape pattern analysis using remote sensing data. Landscape Ecol. 23, 505–511.
Shen, W., Wu, J., Grimm, N.B., Hope, D., 2008. Effects of urbanization-induced environmental changes on ecosystem functioning in the Phoenix metropolitan region, USA. Ecosystems 11, 138–155.
Turner, M.G., O'Neill, R.V., Gardner, R.H., Milne, B.T., 1989. Effects of changing spatial scale on the analysis of landscape pattern. Landscape Ecol. 3, 153–162.
United Nations, 2004. World Population to 2300. United Nations, New York, 240 pp.
Weng, Y.-C., 2007. Spatiotemporal changes of landscape pattern in response to urbanization. Landscape Urban Plan. 81, 341–353.
Wu, J., David, J.L., 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol. Model. 153, 7–26.
Wu, J., Hobbs, R., 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landscape Ecol. 17, 355–365.
Wu, J., Hobbs, R.J. (Eds.), 2007. Key Topics in Landscape Ecology. Cambridge University Press, Cambridge, 297 pp.
Wu, J., Jelinski, D.E., Luck, M., Tueller, P.T., 2000. Multiscale analysis of landscape heterogeneity: scale variance and pattern metrics. Geogr. Inf. Sci. 6, 6–19.
Wu, J.G., 2004. Effects of changing scale on landscape pattern analysis: scaling relations. Landscape Ecol. 19, 125–138.
Wu, J.G., 2008. Making the case for landscape ecology: an effective approach to urban sustainability. Landscape J. 27, 41–50.
Wu, J.G., Shen, W.J., Sun, W.Z., Tueller, P.T., 2002. Empirical patterns of the effects of changing scale on landscape metrics. Landscape Ecol. 17, 761–782.
Xie, Y.C., Yu, M., Bai, Y.F., Xing, X.R., 2006. Ecological analysis of an emerging urban landscape pattern-desakota: a case study in Suzhou, China. Landscape Ecol. 21, 1297–1309.
Xu, C., Liu, M.S., Zhang, C., An, S.Q., Yu, W., Chen, J.M., 2007. The spatiotemporal dynamics of rapid urban growth in the Nanjing metropolitan region of China. Landscape Ecol. 22, 925–937.
Zhu, M., Xu, J.G., Jiang, N., Li, J.L., Fan, Y.M., 2006. Impacts of road corridors on urban landscape pattern: a gradient analysis with changing grain size in Shanghai, China. Landscape Ecol. 21, 723–734.
Zipperer, W.C., Wu, J., Pouyat, R.V., Pickett, S.T.A., 2000. The application of ecological principles to urban and urbanizing landscapes. Ecol. Appl. 10, 685–688.