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Spatiotemporal changes of landscape pattern in response to urbanization

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Abstract

The combined method of urban gradient analysis and landscape metrics in analyzing the changes of landscape pattern has been widely applied since its introduction by Luck and Wu (2002). In order to address the temporal dynamics of landscape change, this study integrated transect analysis with temporal trend analysis and specifically discussed how changes of residential pattern are related to forms of urban growth. Using Dane County, Wisconsin, USA as an example, a 60 km transect passing through the City of Madison was set up to represent a continuum of rural-urban-rural landscapes. Changes of landscape pattern from 1968 to 2000 were analyzed by FRAGSTATS with four metrics—percentage of landscape (PLAND), Shannon's evenness index (SHEI), patch density (PD), and mean patch size (MPS). Findings from metric analyses revealed that the degree of land-use diversity and landscape fragmentation is positively related to the degree of urbanization.

Specifically, at the class-level, residential land-use type shows the strongest positive relationship to the degree of urbanization in all of the class-level metrics adopted. Changes in residential land-use pattern were further analyzed with the number of housing units. The analyses revealed that there are different patterns of residential development along the transect in the study area—with the core urban area expanding outward in a contiguous manner while the rural areas have scattered development. This study demonstrated the additional insights into landscape change by integrating the spatial and the temporal perspectives and by targeting the forms of residential developments.

Keywords: Gradient analysis; Landscape pattern; Landscape metrics; Urbanization; Madison, Wisconsin

1. Introduction

Urban areas account for only two percent of the Earth's land surface but over half of the world's population now resides in cities (United Nations, 2001). High population density in urban areas has resulted in a large-scale modification of the environment. Urbanization is a complex process of converting rural land uses to urban land uses and has caused various impacts on ecosystem structure, function, and dynamics (McDonnell et al., 1997; Antrop and Van Eetvelde, 2000; Pickett et al., 2001; Luck and Wu, 2002). As a city grows, the increasing concentration of population and economic activities demands more lands to be developed for public infrastructure (e.g. roads, water facilities, and utilities), housing, and industrial and commercial uses. Land transformations associated with the process of urbanization can affect ecosystem properties such as biodiversity (Sukopp et al., 1990; Gilbert, 1991; Jim, 1993; Savard et al., 2000), biogeochemical cycles (McDonnell and Pickett, 1990; Wear et al., 1998; Bennett, 2003), and climate conditions (White et al., 2002; Zhou et al., 2004; Zhang et al., 2005).

One systematically effective approach to analyze the effects of urbanization on ecosystems is studying the changes of ecosystem patterns and processes along an urban-to-rural gradient (McDonnell and Pickett, 1990). Since the gradient parallels the intensity of urbanization, the changes of ecosystem characteristics can reflect the degree of human influences on the environment. The "gradient paradigm" of urban ecological research was first introduced by McDonnell and Pickett (1990). Based on this paradigm, variation in the degree of urbanization, in terms of land-use intensity and human intervention, is the "gradient". Similar to natural environmental gradients, "urbanization" is correlated to the spatial changes of ecosystem characteristics, such as species diversity (especially avifauna) (Blair, 1996; Natuhara and Imai, 1996; Blair and Launer,

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1997; Ishitani et al., 2003; Maestas et al., 2003; Crooks et al., 2004; Sparks et al., 2005), vegetation composition and structure (Medley et al., 1995; Moffatt et al., 2004; Borgmann and Rodewald, 2005; Williams et al., 2005), soil nutrients (Pouyat and McDonnell, 1991; Pouyat et al., 1995; Zhu and Carreiro, 1999; Bennett, 2003; Pouyat and Carreiro, 2003), and water quality (Wear et al., 1998; Snyder et al., 2003).

As the examples illustrate, studies of the influences of urbanization on ecosystem properties cover a wide spectrum of ecological research. However, most of the studies focus on individual ecosystem components rather than taking the whole landscape into account. Increasingly, studies from a landscape ecological perspective suggest how changes in landscape pattern would lead to consequent changes in ecological functions and processes (Turner et al., 2001). In an urban context, the two most studied topics of the influences of landscape pattern on ecosystems are the effects of habitat fragmentation on urban fauna and vegetation (Bastin and Thomas, 1999; Mortberg, 2001; Young and Jarvis, 2001; Olff and Ritchie, 2002) and the influences of land-use pattern on water quality (Wear et al., 1998; Fitzpatrick et al., 2004; Chen et al., 2005).

Changes of landscape pattern can be detected and described by landscape metrics which quantify and categorize complex landscapes into identifiable patterns and reveal some ecosystem properties that are not directly observable (Antrop and Van Eetvelde, 2000; Turner et al., 2001). Studies of landscape pattern change along an urban-to-rural gradient focus on the identification of urban texture—whether urban landscapes have unique "spatial signatures" that are distinguishable from other types of landscapes. Luck and Wu (2002) first integrated the gradient paradigm and metric analysis to study the characteristics of landscape pattern along an urban-to-rural transect in the Phoenix metropolitan region, Arizona, USA. By tracing the variation of landscape metric outputs along the urban-to-rural transect, their study nicely demonstrates how landscape patterns (e.g. patch type, patch density, and patch size) change in relation to different degrees of urbanization.

However, urban landscapes are dynamic and continuously changing as a city grows. Therefore, analyzing the spatial change of landscape patterns at one single point of time cannot capture the full dynamics of landscape change. In order to trace the temporal trend, landscape metrics can also be applied to measure the spatial characteristics of landscape pattern through time as Herold et al. (2003) and Dietzel et al. (2005) demonstrate in their studies. By focusing on the temporal changes, nevertheless, these studies take the whole landscape as a single unit without addressing the local, intra-city level variation in terms of the differential effects of urbanization on landscape change.

Therefore, by focusing either on the spatial transect or on the temporal trend alone, studies would fail to address the *spatiotemporal* dynamics of landscape change in response to urbanization. On the one hand, focusing only on the spatial dimension would overlook the fact that the area experiencing the most intense urbanization does not always concentrate on the central city, but would shift its location as the city grows. On the other hand, focusing only on the temporal dimension would overlook the fact that urbanization has differential effects on different sections along the urban-to-rural gradient. In order to address these gaps in the previous studies and to better capture the dynamics of landscape change in response to urbanization, this study integrates the spatial and temporal aspects together and analyzes landscape pattern changes *along the transect and through time*.

The second modification made by this study is the isolation of residential land use from other urban land-use types. Finding ways to manage the form of urban growth in order to curtail the negative environmental impacts of sprawl is one of the main challenges in contemporary urban and regional planning (particularly in the United States) (Carruthers, 2002; Burchell and Mukherji, 2003; Irwin and Bockstael, 2004; Daniels and Lapping, 2005). One proposal is to densify the development in existing urbanized areas and at the same time to regulate development in the outlying rural areas (Danielsen et al., 1999; Daniels and Lapping, 2005). Since residential development contributes to a large proportion of urban expansion, this study aims to analyze how different residential development density influences landscape patterns. Therefore, results from residential land-use pattern analysis are further correlated with the number of housing units in order to address whether high-density housing would contribute to a compact form of development in contrast to sprawl.

In short, the gradient paradigm in urban ecology is adopted as the framework for this study, and the application of metrics in landscape ecology serves as the method for quantifying landscape patterns. Using the City of Madison, Wisconsin, USA as an example, this study aims to examine the spatiotemporal changes of landscape pattern in response to urbanization and to address three research questions:

1. How do landscape patterns change along the urban-to-rural gradient and through time and whether urbanized landscapes have spatial characteristics that are distinguishable from those of rural landscapes?
2. How does the integrated method of both spatial and temporal analysis reveal more of the dynamics of landscape change than focusing on one dimension alone?
3. How do residential land-use patterns change as urbanization proceeds and how are these changes related to the form of urban growth?

Overall, this study attempts to enhance our understanding of the effects of urbanization on landscape patterns, which can serve as the basic information for identifying their potential ecological impacts and as the guidance for land-use planning as well.

2. Methods

2.1. Study area and sampling design

The City of Madison is the central city of Dane County, Wisconsin, USA. Land-use intensity (defined as the percentage of developed land per unit area) in Dane County diminishes from the city to peripheral rural areas (Fig. 1). The Madison area has experienced a rapid rate of urbanization in the second half of