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Research Paper

The influence of physiography on historical and future land development changes: A case study of central Arkansas (USA), 1857–2030

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HIGHLIGHTS

- We developed an equation to measure development relative to physiography.
- We used a historical approach to reveal complex interrelationships in urban systems.
- Past and future urbanization in central Arkansas is dictated by local physiography.

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ABSTRACT

The intricate interrelationships between environment and society result in unique landscapes, each with its own development patterns and rates. While many studies have focused on how development impacts the environment; this study quantifies the influence of the environment, relative to human historical factors, on long-term (1857–2030) and large-scale (10,000 km^2) development patterns in a region with diverse physiography. A major component of this paper is the development of a Magnitude of Relative Change (MRC) equation to empirically measure long-term development trends and rates at regional scale in relation to multiple physiographic factors. We simulated past urban development trends and forecasted future patterns for the central Arkansas (USA) region using a modified SLEUTH-3r urban growth model. In doing this, we investigated the relationships and feedbacks between physiographic settings of the study area and past and future development patterns. Another vital component of this research is the adoption of an environmental historical approach to examine and evaluate development dynamics within and among ecoregions. Our analytical approach emphasizes the potential of environmental forces to influence land development transitions and at the same time appreciates the role of human advancements on shaping those dynamics.

1. Introduction

Landscapes are the result of intricate relationships and co-evolution between human development and surrounding environments (Aretano, Petrosillo, Zaccarelli, Semeraro, & Zurlini, 2013; Barau & Ludin, 2012; Lovell & Johnston, 2009). In an effort to understand these interrelationships, studies have begun to assess long-term land cover timelines in the context of environmental datasets (Bakker & Veldkamp, 2012; Julian, Thomas, Moursi, Hoagland, & Tarhule, 2012; Walker & Solecki, 2004). Further efforts have been made to simulate historical land cover changes and model future development by using a suite of geospatial data (Goldewijk & Verburg, 2013; Jantz, Goetz, Donato, & Claggett, 2010; Oguz, Klein, & Srinivasan, 2007; Verburg et al., 2002). Indeed, these sophisticated and spatially explicit models are beneficial for exploring the interwoven influence of socioeconomic and biophysical forces on urban growth patterns (Verburg, Schot, Dijst, & Veldkamp, 2004). While physiography is used as a template for urban growth studies, it is not typically considered as a main driver or constraint on urban growth.

Urban growth models were initially economically oriented in which cities were only dealt with as economic zones (Chen et al., 2002). With the geospatial revolution in the 1970s (Clarke, McLafferty, & Tempalski, 1996), there was a need for more realistic

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models that could use multiple sources of spatial data and view urban areas as dynamic environments in order to capture complex processes imbedded within urban systems especially at regional levels. First introduced in the 1980s by Batty, Longley, & Fotheringham (1989), cellular automata (CA) models have been the most popular in this regard. CA models avoid many shortcomings of traditional urban growth models because their organizational structure of cell, state, neighborhood, and transition rules matches land cover/use data structure (Oguz et al., 2007; Suarez-Rubio, Lookingbill, & Wainger, 2012). Even more importantly, CA models take into account temporal dynamics by using initial land use as a principle for possible change through decision rules.

After three decades of experience and technological advances, CA models represent the state-of-the-art for modeling urban growth at regional scales (Jantz et al., 2010; Rafiee, Mahiny, Khorasani, & Darvishsefat, 2009), particularly for their ability to simulate interactions among biophysical and socioeconomic drivers of land change (White & Engelen, 1997). The SLEUTH model (slope, land cover, exclusion, urban, transportation, and hillshade) is one of these CA models that uses physiography to guide urban growth, and has been widely used on account of its public-domain software with extensive documentation, adoption by many leading land change scientists, and transferability to any region of any size (Clarke, Hoppen, & Gaydos, 1997). In SLEUTH, some of the socioeconomic and biophysical factors are accounted for within an exclusion layer, which guides urban growth based on user-defined exclusions such as water and protected lands (Jantz et al., 2010). Mahiny and Clarke (2012) made a new enhancement to the SLEUTH model by incorporating multi-criteria evaluation (MCE). This urban suitability layer along with the exclusion layer helps to simulate more realistic development patterns given ecological and socioeconomic factors. While useful, SLEUTH and similar models have yet to fully exploit the inherent linkage between pattern and process to explore the empirical relationships between physiography and land development.

While numerous studies have widely utilized SLEUTH to simulate and predict American urban dynamics for many eastern and western cities (Clarke et al., 1997; Herold, Goldstein, & Clarke, 2003; Yang & Lo, 2003), urban areas in the South Central region of the US, which represents the frontier of eastern urban development, were largely neglected. We are only aware of one study in the South, which was carried out by Oguz et al. (2007) to characterize urban dynamics around the Houston Metropolitan area. The main goals of this and other traditional studies, however, were to mitigate urban dynamics and assess the anthropogenic and socioeconomic impacts of urban growth within metropolitan counties. No study has yet used the SLEUTH model as a platform to relate urban development patterns and trends to physiography.

In this study, we examine physiography's influence on urban and agricultural development by using two perspectives: ecoregion perspective (*sensu* Omernik, 1987; Level III Ecoregions) and cellular perspective (60-m square cells). The ecoregion perspective provides information on growth patterns within regions that are relatively homogenous in terms of topography, climate, potential natural vegetation, and soils. Ecoregions not only correspond well to spatiotemporal landscape patterns and composition, but they also help extrapolate relationships among natural and anthropogenic factors across broad scales (Griffith, Stephen, & Loveland, 2003; Omernik, 1987; Ramsey, Falconer, & Jensen, 1995). Omernik ecoregions were delineated at different hierarchical levels based on the variability of environmental characteristics within regions at the national and state level. While Level I provides the least variability at the national level, Level III provides better environmental details of subregions at state level (Gallant, Whittier, Larsen, Omernik, & Hughes, 1989). The cellular perspective, on the other hand, provides information on local interactions (i.e., cell-to-cell) between human development and the environment, which may help to explain human decisions based on physiographic constraints. For example, is a parcel of land near a river more likely to be developed than a parcel near a wetland? When combined, these two perspectives allow us to connect landscape pattern at multiple spatial scale and land-use change decision processes.

Here, land cover change patterns and processes were examined across a 10,000-km^2 area in central Arkansas, USA. We selected this region for several reasons. First, central Arkansas has a heterogeneous physiography, lying at the intersection of four vastly different ecoregions. Second, central Arkansas captures a diversity of land cover: large areas of forest, grassland, agriculture, wetlands, open water, and a variety of urban environments with different growth patterns. Finally, there are compatible medium-resolution (60 m) land cover maps readily available for this study area that date back to 1857 (via Jawarneh & Julian, 2012), which allow us to observe the beginning of land development in the region. The objective of this study was thus to analyze the role of physiography in spatiotemporal patterns of land cover change. While we focus on physiographic variables, we also discuss the influence of broad-scale socioeconomic variables on land development and address how these two factors interact.

2. Data and methods

2.1. Study area

2.1.1. Physiographic setting of central Arkansas

The 10,000-km^2 study area is centered on Little Rock, the capital city of Arkansas, USA (Fig. 1). In combination with the region's vast urban network, the heterogeneous physiographic setting of central Arkansas provides an ideal platform to study the environmental influences on past and present urban growth patterns. The temperate climate of central Arkansas is characterized by high rainfall (130 cm annual average), hot summers, and mild winters (Woods et al., 2004). The topography is defined by the fall line that separates the Gulf Coastal Plain to the southeast from the Interior Highlands to the northwest. The fertile, loamy soil of the coastal plain provides for large-scale rice, cotton, and soybean plantations. In the highlands, the soil is less fertile and more suitable for plantation forestry, poultry operations, and livestock grazing (Brister, 1977; Hanson & Moneyhon, 1989). These topographic regions are dissected by the Arkansas River, a major tributary to the Mississippi River that provides many valuable resources to the region, including navigation, recreation, flood control, hydropower, and water supply for agriculture, industry, and municipalities.

The study area stretches across four diverse ecoregions. The South Central Plains ecoregion to the south of the metropolitan area is composed of irregular forested plains broken by numerous hardwood bottomlands and small fragmented cultivated areas on the floodplain. The Ouachita Mountains ecoregion to the west is mostly forested with steep slopes along east–west trending ridges. Commercial logging is the major land use in these two ecoregions (Hanson & Moneyhon, 1989; Woods et al., 2004). The Arkansas Valley ecoregion, north of Little Rock, is characterized by broad floodplains bounded by scattered hills and mountains with fragmented pastures. The Mississippi Alluvial Plain to the east is composed of relatively broad flat plains with river terraces that historically were covered by forested and herbaceous wetlands, but are now agriculturally dominated with small scattered rural communities.

2.1.2. Settlement history

Central Arkansas has been inhabited for thousands of years by such cultures as the Folsom, Mississippian, Caddo, and Quapaw