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Exploring zoning scenario impacts upon urban growth simulations using a dynamic spatial model

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ABSTRACT

Dynamic spatial models are being increasingly used to explore urban changes and evaluate the social and environmental consequences of urban growth. However, inadequate representation of spatial complexity, regional differentiation, and growth management policies can result in urban models with a high overall prediction accuracy but low pixel-matching precision. Correspondingly, improving urban growth prediction accuracy and reliability has become an important area of research in geographic information science and applied urban studies. This work focuses on exploring the potential impacts of zoning on urban growth simulations. Although the coding of land-use types into distinct zones is an important growth management strategy, it has not been adequately addressed in urban modeling practices. In this study, we developed a number of zoning schemes and examined their impacts on urban growth predictions using a cellular automaton-based dynamic spatial model. Using the city of Jinan, a fast-growing large metropolis in China, as the study site, five zoning scenarios were designed: no zoning (S0), zoning based on land-use type (S1), zoning based on urbanized suitability (S2), zoning based on administrative division (S3), and zoning based on development planning subdivision (S4). Under these scenarios, growth was simulated and the respective prediction accuracies and projected patterns were evaluated against observed urban patterns derived from remote sensing. It was found that zoning can affect prediction accuracy and projected urbanized patterns, with the zoning scenarios taking spatial differentiation of planning policies into account (i.e., S2–4) generating better predictions of newly urbanized pixels, better representing urban clustered development, and boosting the level of spatial matching relative to zoning by land-use type (S1). The novelty of this work lies in its design of specific zoning scenarios based on spatial differentiation and growth management policies and in its insight into the impacts of various zoning scenarios on urban growth simulation. These findings indicate opportunities for the more accurate projection of urban pattern growth through the use of dynamic models with appropriately designed zoning scenarios.

1. Introduction

The past few decades have witnessed a rapid growth in both the world's urban population and the amount of built-up land, particularly in a number of developing countries. This has led to significant changes in Earth's land surface that threaten the integrity of global ecosystems (Rafiee, Mahiny, & Khorasanic, 2009). For example, although the proportion of people living in cities in China more than tripled between 1978 and 2015, the urban built-up land coverage increased by nearly seven times over the same period (*The Yearbook of China's Cities*, 2015). Rapid urban land expansion has become the primary form of land-use change in China and has prompted concerns over loss of large areas of high-quality farmland and primary forest, inadvertent climate repercussions, and degradation in the overall quality of life (Ma et al., 2014; Song, Pijanowski, & Tayyebi, 2015).

Urban growth is a complex, dynamic process that is driven by multiple biophysical and socio-economic factors (Akın, Clarke, & Berberoglu, 2014; Irwin, Jayaprakash, & Munroe, 2009; Maimaitijiang, Ghulam, Sandoval, & Maimaitiyiming, 2015; Shafizadeh-Moghadam & Helbich, 2015). Land-use change models can be used to explore urban growth and land-use change dynamics to aid planners and resources managers in understanding land-use changes and their potential socio-ecological consequences under different constraints (Liu, Li, & Shi, 2008; Yang & Lo, 2003). Over the years, various land-use change

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models have been developed, a number of which are suitable for urban growth simulation. These include statistical models (e.g., Hu & Lo, 2007), artificial neural network models (e.g., Liu & Seto, 2008), cellular automaton (CA) models (e.g., Aburas, Ho, Ramli, & Ash'aari, 2016; Arsanjani, Helbich, Kainz, & Boloorani, 2013; Chowdhury & Maithani, 2014; Clarke, Hoppen, & Gaydos, 1997; Ku, 2016), and agent-based models (e.g., Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Valbuena, Verburg, Bregt, & Ligtenberg, 2010). Whereas statistically-based models are generally static in nature and more appropriate for diagnostic or prescriptive applications, cellular automaton- and agent-based models are dynamic and can be used for exploring future urban development under different constraints (Torrens, 2011).

In this paper, we look primarily at urban cellular automaton models based on their capability for exploring urban dynamics and on their general popularity (Torrens, 2011). Cellular automation models simulate land cover or land use change using a set of rules which regulate cell (pixel) conversions depending on their location, spatial relationships with other cells and various landscape constraints. A well-known example of an urban cellular automata model is the Slope, Land-use, Exclusion, Urban extent, Transportation, and Hillshade (SLEUTH) model, which has been widely applied in urban growth prediction and forecasting (e.g., Al-shalabi, Billa, & Pradhan, 2012; Berling-Wolff & Wu, 2004; Clarke et al., 1997; Clarke & Gaydos, 1998; Herold, Goldstein, & Clarke, 2003; Jantz, Goetz, & Donato, 2010; Jantz, Goetz, & Shelley, 2003; Onsted & Chowdhury, 2014; Silva & Clarke, 2002; Yang & Lo, 2003). At the same time, despite their successful track record of application and high overall accuracy, cellular automaton models can suffer from low pixel-matching precision (i.e., low local-scale precision) (Jantz et al., 2003). Thus, improving urban growth prediction accuracy and reliability has become an important area of research in geographic information science and applied urban studies (Brown et al., 2013; Liu & Yang, 2015; Torrens, 2011). Although much progress has been made in developing more technologically sophisticated urban cellular automaton models, there have been some persistent challenges to the applicability of these models in reproducing patterns resembling real cities, driven primarily by limitations on the availability of spatial data at required resolutions and difficulties in representing spatial complexity, regional differentiation, and growth management policies (see Liu & Yang, 2015; Torrens, 2011; Yang & Lo, 2003).

The focus of this paper is the sensitivity of urban growth to development planning policies, which are important in urban growth management but have not been adequately addressed in urban modeling practices (e.g., Berling-Wolff & Wu, 2004; Clarke et al., 1997; Lahti, 2008; Silva & Clarke, 2002; Wu, Hu, & He, 2009) due to difficulties in incorporating such development policies into the conversion rules used by cellular automaton-based urban models (see Torrens, 2002). One way to address this issue is to use an exclusion layer to indirectly integrate various development policies into the simulation process (e.g., Akın et al., 2014; Jantz et al., 2003; Silva, Ahern, & Wileden, 2008). However, this approach has had only limited success to date because other issues, including spatial complexity and regional differentiation, must be considered along with planning policies (e.g., Goldstein, Candau, & Clarke, 2004).

Urban planners often use zoning to differentiate land-use types as a method for controlling and guiding the growth and changes in urban land use (Onsted & Chowdhury, 2014). This top-down growth control and management approach has been widely adopted in the developed world and is now being applied in a number of developing countries, including China (Long, Gu, & Han, 2012; Tian & Shen, 2011). In China, all levels of government play very important roles in making urban development policies and in building urban public service facilities and infrastructures. A notable example of this is the establishment of several special economic zones by the central government in the early 1980s as part of the country's economic reforms and policy of opening to the world. These economic zones have profoundly affected urban growth patterns in the country and made it necessary to consider zoning in urban growth modeling.

Several studies have recognized the implications of zoning for urban expansion simulations and have noted how the appropriate use of zoning information can help improve simulation accuracy (Clarke et al., 1997; Onsted & Chowdhury, 2014). In this paper, "zone" is a term used to refer to any subdivision of the landscape and can categorize divisions by land-use type, administrative division, development planning subdivision, etc. Despite its advantages, zoning has rarely been incorporated in urban modeling practices because its ability to significantly affect the modeling outcomes has been generally disregarded or considered too difficult to demonstrate (Onsted & Chowdhury, 2014). For example, in a study by Lahti (2008) the SLEUTH model, a cellular automaton-based dynamic urban model, was successful in capturing bottom-up ecological processes but could not adequately reproduce top-down phenomena due to its difficulty in establishing a connection between bottom-up-oriented conversion rules and top-down urban development policies. In other studies, SLEUTH was found to be incapable of thoroughly capturing the characteristics of urban growth for various administrative divisions even when zoning was taken into account (e.g., Wu et al., 2009). It should be noted that in these previous studies zoning information was generally derived from either large administrative divisions (e.g., Wu et al., 2009) or land-use types (e.g., Berling-Wolff & Wu, 2004; Jantz et al., 2010; Rafiee et al., 2009).

The aim of this study was to explore the potential impacts of zoning on urban growth prediction and forecasting using the SLEUTH cellular automaton-based dynamic spatial model. SLEUTH was selected for the study because of its flexibility, openness, non-linearity, and adaptive ability (Clarke et al., 1997; Clarke & Gaydos, 1998). Using a set of urban growth rules, the SLEUTH model can simulate complex urban growth dynamics. The model can be calibrated using historical urban expansion data to obtain the best possible coefficient combinations. Detailed discussion on model design and implementation procedures can be found in previous studies (e.g., Clarke et al., 1997; Clarke & Gaydos, 1998; Herold et al., 2003; Silva & Clarke, 2002; Yang & Lo, 2003). Because of its rapid growth during the past several decades, the city of Jinan, Shandong Province, China was selected as the study site. Several distinct zoning scenarios based on land-use type, urbanization suitability, administrative division, and development planning subdivision were carefully designed and used to simulate urban growth. Based on the model results, the potential impacts of zoning were examined. Specifically, two questions were addressed: (1) Would zoning affect urban growth prediction accuracy and projected urbanized patterns? and (2) Which zoning scheme would allow the urban growth model to generate more accurate outcomes? The findings of this study provide a valuable reference for addressing zoning information in urban growth simulations and informing future urban planning and zoning policies.

2. Study area

The study area represents a portion of Jinan, the capital city of Shandong Province in China. Jinan lies between Taishan Mountain to the south and the Yellow River to the north (Fig. 1a, b). The metropolitan area covers 8117 km^2 and comprises seven districts—Shizhong, Tianqiao, Lixia, Huaiyin, Licheng, Changqing, and Zhangqiu—and three counties—Pingyin, Jiyang, and Shanghe (Fig. 1c). Jinan has experienced rapid growth in its urban population along with an expansion of built-up land from 80.4 km^2 in 1949 to 383.3 km^2 in 2015 (*Statistical Year Book of Jinan*, 2015). By the end of 2015, the total population of Jinan was 7.13 million, of whom 4.84 million were urban residents. The city of Jinan formulated a primarily top-down regional planning strategy for 1996–2020 with the goal of promoting development toward the east, west, and north but restricting development toward the south due to the presence of Taishan Mountain. More specific urban development plans were formulated in 2003, including development of a new district, old town renovation, and urban expansion