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Monitoring and modeling urban expansion—A spatially explicit and multi-scale perspective

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ABSTRACT

In the context of promoting new urbanization in China, urban expansion has been the subject of a consolidated line of research in the past two decades. In this study, we integrate remote sensing, a geographical information system, and spatial analysis techniques to monitor and model urban expansion with a spatially explicit and multi-scale perspective in Wuhan, the megacity in central China. We first extract urban built-up land from medium to high resolution images from 1995 to 2010 and analyze the expansion dynamics at the parcel level. For the exploration of the driving mechanisms underlying urban expansion, 20 explanatory variables are then categorized into three groups: characteristics, density, and proximity. A kernel window is then utilized to filter the extracted urban built-up land map at multiple scales. Moran's I is later used to test the spatial autocorrelation in the percentage of urban built-up land area and the residuals. Finally, a spatial lag model and a spatial error model are applied to explore the causal factors of urban built-up land. It is revealed that the area of transportation land in Wuhan has increased tremendously, and urban built-up land is less scattered at the micro-scales. Regardless of the scale or model, housing density and gross domestic product (GDP) are positively correlated with the urban built-up land area, whereas the influence of other factors is shown to vary along with the scale or model. The results also confirm the superiority of the spatial regression models, and better fitting is produced with the increase in the scale. In the future, it is anticipated that the interpretation of remote sensing images and spatial analysis techniques will be optimized for better manifestation of intra-urban spatial interaction. In this process, the scale effect is an issue that should not be neglected in future studies of urban expansion.

Introduction

China issued its "New Urbanization Planning" in 2014 to promote sustainable, human-oriented, and efficient urbanization. Furthermore, municipalities all over the country have started to formulate new urban planning to optimize the spatial form and improve people's living conditions (Fang & Ma, 2013; Shan & Huang, 2013). In this context, urban expansion, a long-standing phenomenon, has aroused great concern among researchers and government officials (Ma & Xu, 2010; Wu, Xu, & Yeh, 2007). As a matter of fact, the expanded urban areas have changed the natural and socio-economic landscape in China both positively and negatively. In addition, the emergence of various development zones has stimulated socio-economic development to a great extent (Wong & Tang, 2005; Yeh & Wu, 1996). The reshaping of the urban form also means housing rehabilitation, suburbanization of the population and industries, as well as extensive infrastructure construction (Tian & Ma, 2009; Xie, Fang, Lin, Gong, & Qiao, 2007). However, the encroachment of fertile arable land in rural areas has given rise to a food security problem and other environmental and ecological problems (Deng, Wang, Hong, & Qi, 2009; Kong, 2014; Li, Feng, & Hao, 2009). In recent years, the sprawling urban areas have also resulted in social segregation and inequality problems (Gu & Shen, 2003; Li, 2008).

For a better insight into the characterization and cost of urban expansion, the past decades have seen a proliferation of research into urban landscape change, in which satellite remote sensing and spatial modeling offer tremendous opportunities to monitor the dynamics of land-use change and identify the major drivers of urban expansion (Jat, Garg, & Khare, 2008; Xiao et al., 2006;

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Zeng, Liu, Liu, & Qiu, 2014). Globally, Angel, Parent, Civco, Blei, and Potere (2011) and Seto, Güneralp, and Hutyra (2012) have mapped and projected urban expansion worldwide, and China has been identified as having a high probability of a high rate of urban expansion. From 1981 to 2011, China's built-up area increased nearly fivefold, from $7.44 * 103\ km^2$ to $4.36 * 104\ km^2$, whereas an obvious spatial gradient can be seen in the urbanization ratio running from the east coast to the west inland (Liu, Zhang, & Hu, 2012; Ministry of Housing & Urban-Rural Development PRC, 2012). The Pearl River Delta and the Yangtze River Delta are two of the most populated and developed regions of China, and the spatial and temporal dynamic patterns of urban expansion in these areas have been widely investigated in the past few decades (Seto & Fragkias, 2005; Tian, Jiang, Yang, & Zhang, 2011). However, as the Chinese government attempts to implement its overall strategy of promoting a coordinated development of different regions, the "Rise of Central China Plan" (RCCP) was initiated in 2004, and capital cities in central China, such as Wuhan, have been considered as a priority. Massive infrastructure construction projects have been conducted, various development zones have been established or expanded, and natural resources such as rivers and lakes have been expropriated to a great extent (Zeng, Liu, Stein, & Jiao, 2015). In this context, monitoring and modeling urban expansion in Wuhan is beneficial for the investigation of urban development in central China.

On the other hand, the quantification of the driving factors' contributory roles in changing the land-use patterns has been examined in a number of cities at different stages. Multivariate regression, logistic regression, spatial regression, and hybrid geospatial approaches integrating CA (cellular automata), Markov, or multi-agent models have been widely used to establish the relationship between urban expansion and its causative factors (Cheng & Masser, 2003; Jat et al., 2008; Kaya & Curran, 2006). Physical conditions, public service accessibility, neighborhood interaction, economic opportunities, the land market, population growth, the political situation, plans and policies, etc., have all been identified as major drivers in a number of studies (Antrop, 2005; Schneeberger, Burgi, Hersperger, & Ewald, 2007; Verburg, Ritsema van Eck, de Nijs, Schot, & Dijst, 2004; Yin et al., 2011). Recently, Jiang, Deng, and Seto (2012) used multi-level modeling to reveal that urban land rent and urban wages contribute to the total cultivated land conversion at the county level, whereas urban wages and foreign direct investment both positively contribute to cultivated land conversion at the provincial level in China. Zhang, Su, Xiao, Jiang, and Wu (2013) employed landscape metrics and spatial autocorrelation regression to discover that the distances to national and provincial roads, as well as the slope factor, are the most influential factors behind the urban landscape change in Hangzhou Bay at two block scales (4 km and 7 km).

However, we cannot deny that we still know relatively little about the finer-scale variations in urban form, and a spatially explicit analysis of urban patterns requires data on land use at a sufficiently disaggregated scale (Irwin, Bockstael, & Cho, 2006). Firstly, previous studies have highlighted the importance of scale when describing the evolution of the urban form, and cell units have been found to be the best vehicle to reveal the scale effect, in modeling in particular. Secondly, attempts have been made with cell units to characterize urban expansion, but further multi-scale exploration of the driving mechanisms has not yet been undertaken (Huang, Zhang, & Wu, 2009; Millward, 2006). Thirdly, although a series of spatial determinants have been examined to establish a causal relationship with urban expansion, newly developed or characteristic geospatial factors still lack recognition (Jokar Arsanjani, Helbich, Kainz, & Darvishi Boloorani, 2013). In fact, apart from the widely identified railways, highways, and central business centers, the locations of provincial/municipal buildings, hospitals, communication hotspots, and bridges are all potential drivers requiring further investigation (Zhang et al., 2013). Finally, urban expansion, in its nature, is the extending of anthropogenic activities, which can be best reflected at the parcel level as it is the finest scale that can be used to implement normative planning and policies. However, there have been very few studies that have characterized urban expansion at the parcel level. Long and Liu (2013) undertook automatic parcel identification using points of interest (POIs) in Chinese cities, and parcel-based characterization of urban expansion has been found to be an optimal choice to manifest urban form in an operational fashion, and it is also practical for the authorities when devising policy responses to the problems associated with expansion (Bhatta, Saraswati, & Bandyopadhyay, 2010; Zhou & Ma, 2000). As a result, the exploration of a finer-scale or multi-scale analysis would not only benefit researchers and allow a better manifestation of intra-urban structures and processes, but also the end users, since normative planning or policies such as mitigating the expansion or the encouragement of infilling development are performed at micro-scales, such as on parcels (Long & Liu, 2013).

In our study, we propose an integrated method to characterize the urban expansion of Wuhan, a typical metropolitan area in central China, from 1995 to 2010, at multiple scales. The purpose of our approach is: (1) to characterize urban expansion at a parcel level from 1995 to 2010; (2) to implement a spatial regression at multiple scales and compare the results for 2010; and (3) to illustrate the intra-urban characterization and modeling of urban expansion for policy makers.

Materials and methodology

Study area and materials

Geographical location

Wuhan, one of the top 10 largest cities in China, as ranked by the output of gross national product (no. 9 in 2011), the road area (no. 8 in 2011), and total fixed-asset investment (no. 9 in 2011), is strategically located in the central region between 29°58′N–31°22′N and 113°41′E–115°05′E. Currently, there are seven districts in the city center, as illustrated in Fig. 1. For a long time, the city has been a major hub for trade and transportation (Ali & Zhao, 2008). As the capital city of Hubei province, Wuhan is situated at the confluence of the Yangtze River and Han River. The administrative area of the central city is $864\ km^2$. From west to east, it binds the upper and lower stretches of the Yangtze together, serving as the intermediary for goods passing between the Sichuan Basin—western China's industrial powerhouse—and the Yangtze River Delta. From north to south, it anchors the Beijing–Guangzhou railway, a 2324-km-long (1444-mile-long) trunk line that gives China's traditional political core, the North China Plain, direct access to the prosperous but historically restive Guangdong province. Just as important as these national-level axes are the numerous interprovincial infrastructure linkages that converge on Wuhan. These roads, waterways, and highways bring goods and people from inland provincial capitals such as Xian, Changsha, Kunming, and Zhengzhou down to Wuhan's ports and, from there, on to Shanghai. The city serves to integrate China's disparate geographic and economic macro-regions into one coherent economic system, and helps enable the central government to enforce political control and social management over these regions (Han & Wu, 2004).

Urban development

With regard to Wuhan's development, we attempt to seek its trajectories with respect to the Chinese political context. Before