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Urban dynamics, landscape ecological security, and policy implications: A case study from the Wuhan area of central China

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ABSTRACT

Monitoring of urban growth and the characterization of its patterns in the Wuhan area of central China from 1988 to 2013 was performed using an integrated approach of remote sensing (RS) and geographic information system (GIS) techniques and statistical methods. We also undertook a qualitative analysis of the impact of urban growth on landscape ecological security. The results showed that the Wuhan area was in a rapid process of urbanization between 2000 and 2011, with an average urban growth rate of 10.666 km^2/a and 2.969 km^2/a in the surrounding region and city proper, respectively. An aggregated pattern was the primary growth type in the whole study area, while linear and leapfrog patterns mainly occurred in the surrounding region. Rapid urban growth has aggravated the landscape fragmentation and has led to considerable declines in ecosystem services. A Pearson correlation analysis was used to qualitatively explore the relationships between the urban growth patterns and the factors associated with ecological security. It was found that the ecosystem fragmentation and ecosystem services were correlated with the urban growth rate, the three types of urban growth, and the compactness of the urban form. Of the three growth types, the leapfrog growth pattern destroys the integrity of water bodies, thereby preventing the connection of lakes to the main surface water network, and thus results in increase fragmentation and reduction of ecosystem services. Although the land-use policies implemented in Wuhan during the study period have promoted the development of the local economy, they have failed to protect the ecosystem. Urban growth speed should be effectively controlled because natural resource protection is as important as, and even more important, to some extent, than encouraging extensive economic development. This research has highlighted the importance of the joint application of urban growth quantification and the monitoring of the changes in the factors associated with ecological security in landscape planning.

Introduction

As the world population has continuously grown and become concentrated in town and city dwellings, urban areas have witnessed an enormous increase in the past 30 years, and this is particularly apparent in developing countries such as China and India (Seto, Fragkias, Güneralp, & Reilly, 2011). Urbanization is a spatial and social process that is related to the transformation of rural areas into urban lands, the movement of people from rural to urban areas as well as the changes in their life styles. Urban growth is a spatial process which refers to the increased area of towns and cities as the population is concentrated in these areas (Bhatta, Saraswati, & Bandyopadhyay, 2010). Although urbanization can promote socioeconomic development and improve the quality of life, the irreversible transformation from semi-natural and natural ecosystems into impervious surfaces has resulted in considerable environmental and ecological problems worldwide (Bhatta et al., 2010; Habibi & Asadi, 2011; Su, Jiang, Zhang, & Zhang, 2011). Therefore, understanding the effects of urban growth on the ecosystem and quantifying the relationships between urban dynamics and landscape ecological security is crucial for effective urban planning and environmental protection policy making, in order to support sustainable development.

A considerable number of academic studies from all around the world have focused on the driving forces of urban expansion (Li, Zhou, & Ouyang, 2013; Lu, Wu, Shen, & Wang, 2013; Thapa & Murayama, 2010; Wu & Zhang, 2012), and there has been increasing interest in characterizing and quantifying the temporal

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dynamics of the spatial patterns of urban growth (Aguilera, Valenzuela, & Botequilha Leitão, 2011; Bhatta et al., 2010; Herold, Scepan, & Clarke, 2002; Ji, Ma, Twibell, & Underhill, 2006; Seto & Fragkias, 2005). However, to date, less attention has been paid to the impact of urban growth on the ecological security of a region. The environmental and ecological problems of the landscape changes resulting from urbanization are significant (Carlson & Traci Arthur, 2000; Wu, Ye, Qi, & Zhang, 2012). It is, however, especially difficult to characterize the relationships between urban growth patterns, changes in ecosystem values, and the consequent loss of ecological capacity in a human-dominated ecosystem (Wu et al., 2012). Rapid urban growth, as the most obvious land transformation, has resulted in significant changes in the structure and functioning of ecosystems (Liu, Li, & Zhang, 2012; Yang, Li, Wang, & Hu, 2011). The study of Su, Xiao, Jiang, and Zhang (2012) reported that landscape fragmentation, configuration, and diversity could significantly impair the provision of ecosystem services. To date, however, to the best of our knowledge, there has not been a study of the influence of different urban growth patterns on the changes in ecosystem structure and ecosystem services. Moreover, as the spatial characteristic of the urban form, and the result of urban growth, urban compactness has been the subject of many discussions (Capello & Camagni, 2000; Liu, Song, & Arp, 2012; Schneider & Woodcock, 2008). Nevertheless, few studies have examined the relationship between urban compactness and landscape structure and ecosystem services. Therefore, there is a need for long-term monitoring of the urbanization process, to evaluate the ecological consequences of urban growth at a landscape scale. For this study, we selected the Wuhan area to examine the different types of urban growth patterns and to monitor the long-term ecosystem changes.

The goals of this study were four-fold. Firstly, we attempted to quantify the urban growth in Wuhan and to characterize the patterns of development. Secondly, we aimed to determine the changes in ecosystem structure and ecosystem services, which are fundamental indicators of landscape ecological security, between 1988 and 2013. Thirdly, we attempted to discover the correlations between urban growth and the factors associated with landscape ecological security. Finally, we related the results to changes in land-use policy.

Method

Study area and data

The city of Wuhan, which is the capital of Hubei Province as well as the largest city in central China (Fig. 1), lies in the middle reaches of the Yangtze River. It covers a total area of 8549 km^2, of which 39.27% consists of plains and 18.17% is hilly and mountainous regions. The Wuhan area has witnessed rapid urbanization and has experienced significant economic growth. In 2012, it had an urban population of 5.55 million, which was over 67.54% of the total population. Meanwhile, the gross domestic product (GDP) increased almost seven-fold, from 120.7 billion yuan in 2000 to 800.4 billion yuan in 2012 (Wuhan Municipal Bureau of Statistics, 2012). Currently, the municipal territory consists of 13 administrative units, in which seven districts constitute Wuhan city proper, and the other six districts are in the surrounding region.

In this study, a multi-spectral Landsat TM/ETM + imagery time series dataset covering six years was downloaded from the US Geological Survey (USGS) and was employed to produce land-use/cover maps of the Wuhan area. In addition to this, two land-use data maps of 1996 and 2006 were obtained from the Wuhan Land Resources and Planning Bureau and were used as ancillary data for the accuracy assessment of the imagery classification.

Mapping urban dynamics from remote sensing imagery

A post-classification comparison method was used to quantify the urban growth extent of 1988, 1995, 2000, 2005, 2011, and 2013 (for a similar case, see Wu & Zhang, 2012). Prior to classification, atmospheric correction was performed. The RS images and the GIS data were then geometrically rectified to a common UTM coordinate system. The 2013 images were first corrected based on 90 ground control points (GCPs) that were evenly distributed in the study area. An image-to-image registration based on the 2013 images was then undertaken to ensure that all the images had the same projection. The root-mean-square error (RMSE) was limited to within 0.5 pixels (15 m). The supervised maximum likelihood classifier (Canty, 2006) in ENVI and a visual interpretation method were employed to classify the images. A classification scheme of five land-use/cover types was used to implement the classification, namely built-up land, forest, cropland, water, and bare land (Were, Dick, & Singh, 2013). The overall accuracies and the Kappa coefficient were greater than 80% and 0.7, respectively, which indicates that the classifications accurately represent the real landscape (Janssen & Van der Wel, 1994; Landis & Koch, 1977). All the aforementioned processing steps were performed in the ENVI 4.8 software environment.

Quantifying and characterizing urban growth

Urban growth rate and intensity

The urban growth rate (UGR) and intensity (UGI) indexes can be used to represent changes in the quantity of an urban area per unit time, and they are key indicators for evaluating the extent and rate of change of urban expansion (Ma & Xu, 2010; Xu & Min, 2013):

$$UGR_i = \frac{ULA_{i,t+n} - ULA_{i,t}}{ULA_{i,t}} \times \frac{1}{n} \times 100\% \tag{1}$$

$$UGI_i = \frac{ULA_{i,t+n} - ULA_{i,t}}{n \times TLA_{i,t}} \times 100\% \tag{2}$$

where UGR_i is the urban growth rate; UGI_i is the urban growth intensity for unit i; $ULA_{i,t+n}$ and $ULA_{i,t}$ are the percentage of urban land area in unit i at time $t + n$ and time t, respectively; TLA_i is the total land area of unit i; and n is the time interval between time t and time $t + n$. The UGR index calculates the growth of an urban area as a percentage of the total growth of the urban areas in the study period. The UGI index denotes the growth of an urban area as a percentage of the total area of the land units in the study period.

Urban growth types

Three types of urban growth patterns were identified in the Wuhan area: an aggregated pattern, a linear pattern, and a leapfrog pattern. The aggregated pattern corresponds to the clustering of patches to form patches of a larger size (Fig. 2). The linear pattern is related to the elongation process of patches increasing along with road networks. The leapfrog pattern involves an increase in the dispersed or isolated patches distributed in a region. To identify the three growth categories, the urban land-use maps were first converted to polygon maps in the ArcGIS software platform. An individual urban land-use map was then overlaid with its adjacent-year urban map to distinguish the newly developed urban patches. Finally, the distance from the new urban patches to the existing urban patches (d_1) and the road networks (d_2) of the previous year were determined by the Near tool in ArcGIS 9.3. If the d_1 of a new urban patch was equal to 0, we considered it as an aggregated pattern; if the d_2 of a new urban patch was within 1 km, it was labeled as a linear pattern; otherwise, the patch did not belong to either of the two aforementioned categories, and it was