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Delimiting the urban growth boundaries with a modified ant colony optimization model

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ABSTRACT

Delimiting urban growth boundaries (UGBs) has been generally regarded as a regulatory measure for controlling chaotic urban expansion. There are increasing demands for delimiting urban growth boundaries in fast growing regions in China. However, existing methods for delimiting UGBs mainly focus on intrinsic dynamic processes of urban growth and ignore external planning interventions. Delimiting UGBs to restrain chaotic expansion and conserve ecological areas is actually a spatial optimization problem. This study aims to develop an optimization-based framework for delimiting optimal UGBs by incorporating dynamic processes and planning interventions into an ant colony optimization (ACO) algorithm. Local connectivity, total utility values and quantity assignment were integrated into the exchange mechanism to make ACO adaptive for the delimitation of UGBs. The core area of Changsha-Zhuzhou-Xiangtan urban agglomeration, a very fast growing area in Central China was selected as the case study area to validate the proposed model. UGBs under multi planning scenarios with given combinations of weights for urban suitability, high-quality farmland protection, and landscape compactness were efficiently derived from the ACO model. Hypothetic datasets were initially used to test the performance of ACO on global optimum and its ability to optimize complex landscape patterns. Compared with experts' planning scenario, the optimal UGBs delimited by ACO model is practical. Results indicate that spatial optimization methods are plausible for delimiting optimal UGBs.

1. Introduction

A large amount of non-urban land has been converted into urban land with the development of economy and society, and this trend is observable in fast urbanizing regions (Lambin & Meyfroidt, 2011). In China, urbanization levels rose dramatically in the past 30 years and have currently reached over 50%. However, most cities have shown pell-mell expansion patterns, which would cause a series of ecological and environmental problems, such as farmland erosion, forest degradation, and among others (Hoekstra & Wiedmann, 2014; Wei & Ye, 2014). In this case, it is an urgent problem to design a suitable spatial pattern for directing urban growth.

It has proven that smart urban growth can increase the density of urban services and protect surrounding natural ecosystems (Jun, 2004). The scope and pattern of urban-land allocation must initially be restrained in a certain areas, and the edge of it can be actually defined as the urban growth boundaries (UGBs) (Nelson & Moore, 1993). Establishing UGBs has been regarded as a regulatory measure for directing smart urban growth (Knaap & Hopkins, 2001). UGBs can be traced back to the concept of Great Britain's green belt in 1930s, but they were really used as an urban planning tool about in 1960s. In the United States, the typical UGBs were established in 1958 around Lexington, Kentucky, and particularly UGBs carried forward by Portland, Oregon has been taken as a classical reference for other cities (Nelson & Moore, 1993). Currently, UGBs have played an important role and become a cultural symbol in urban planning (Abbott & Margheim, 2008). America has taken UGBs as a significant tool to direct the smart growth and made them of legal qualification (Hepinstall, Coe, & Hutyra, 2013; Knaap & Hopkins, 2001). Many other countries such as Swiss and India have also managed to promote the efficiency of UGBs on urban planning. In China, delineation of UGBs has been given significant attention by government and researchers in recent years. Some big cities have been aware that it is important to delimit UGBs for restraining the pell-mell urban growth, and different similar policy such as basic ecological line in Shenzhen has been correspondingly put forward. A total of 14 cities such as Beijing, Shanghai, Guangzhou, Xiamen, and among others were selected as piloting areas to delimit UGBs in 2014, and this task was expected to be finished in 2015. Some

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researchers have also selected Beijing and Jinan as case study areas to discuss the implementation procedure of UGBs delineation (Gennaio, Hersperger, & Bürgi, 2009; Long, Han, Lai, & Mao, 2013; Venkataraman, 2014; Zheng & Lv, 2016). The application of UGBs as a significant tool to direct the smart growth is being carried forward by Chinese government.

The increasing popularity of UGBs for restraining pell-mell expansion requires efficient and feasible techniques to delimit those boundaries especially in China. A large number of methods have been applied in solving this problem. For example, UGBs could be delineated by planners with experiences. However, UGBs delimited by planners' artworks lack of quantitative analysis and the patterns delimited by different experts may show great difference (Long et al., 2013). Therefore, models have been developed to identify the probable boundaries quantitatively. Land use suitability evaluation models have been widely used to delimit UGBs (Bhatta, 2009). In those models, urban land use suitability is commonly evaluated from a series of spatial factors, e.g. topography and traffic conditions (Cerreta & De Toro, 2012). Although these evaluation methods are easy to implement, it is difficult to estimate the contribution of geographical factors to potential urban suitability in future (Kiran & Joshi, 2013). Moreover, in the view of urban-land allocation, not only suitability but also landscape patterns are the significant aspects (Cao, Huang, Wang, & Lin, 2012). Landscape characteristics are commonly ignored when delineating UGBs if only suitability evaluation models were considered (Santé, Crecente, & Miranda, 2008a).

As is well known, cities are dynamic systems influenced by both anthropogenic activities and natural processes (Washington-Ottombre et al., 2010). Urban growth pattern can be predicted from spatio-temporal variation trends of urban dynamics. Data mining algorithms such as spatial logistic regression (SLR) and artificial neural network (ANN) have been adopted to discover the urban growth probability (Tayyebi, Perry, & Tayyebi, 2014; Tayyebi, Pijanowski, & Tayyebi, 2011). Compared with land use suitability models, these models can identify the contribution of spatial driving factors from the selected training samples, but they generally ignore the local interaction among land use cells (Batty & Xie, 1999). Bottom-up based geo-simulation models such as cellular automata (CA), which integrate the spatial growth probability and local interaction, have been then applied to the prediction of land conversion in future (Li, 2011; Santé, García, Miranda, & Crecente, 2010). UGBs can thus be delimited from the simulation result of urban expansion (Long et al., 2013; Mitsova, Shuster, & Wang, 2011).

However, future urban growth does not strictly follow historical rules. For example, the government may regulate the growth direction in terms of socio-economic status and some special planning objectives such as ecological conservation (Long, Gu, & Han, 2012), and thus, the delimitation and prediction of UGBs based on historical rules is not always reasonable. Planning regulation and planning demands should be involved for the delineation of UGBs. Therefore, the balance among urban growth processes, planning regulations, and landscape characteristics appeals to the attention of UGBs delimitation (Gordon, Simondson, White, Moilanen, & Bekessy, 2009), which can be viewed as a land use spatial optimization problem (Ligmann-Zielinska, Church, & Jankowski, 2008). Simple GIS spatial analysis tools and process-based simulation models cannot obtain optimal results (Li, Chen, Liu, Li, & He, 2010). It is, therefore, essential to introduce spatial optimization models for delimiting UGBs.

Although UGBs are just designed as boundary lines, they can essentially be viewed as optimal patterns of urban-land allocation in the future. According to current researches, genetic algorithms (GA) (Brookes, 2001), simulated annealing (SA) (Santé, Boullón, Crecente, & Miranda, 2008b), particle swarm optimization (PSO) models (Liu, Wang, Ji, Liu, & Zhao, 2012a; Masoomi, Mesgari, & Hamrah, 2013), ant colony optimization (ACO) algorithms (Li, Lao, Liu, & Chen, 2011), etc. have proven to be effective in solving such land use optimization problem. In those models, ACO has proven to be the most efficient in solving area optimization problems such as zoning protected natural areas and multi-type land use allocation, which are involved with conflicts among multiple objectives, implemented on raster surfaces (Li et al., 2011; Liu, Li, Shi, Huang, & Liu, 2012b). Therefore, this study aims to develop an optimization-based framework in which a modified ACO has been devised for creating optimal UGBs, and a fast growing area of Changsha-Zhuzhou-Xiangtan urban agglomeration in Central China is selected as the case study area to validate the availability of the proposed model.

2. Problem statement and methodology

2.1. Defining the mathematical model for delimiting UGBs

The essence of UGBs delineation is to constrain urban growth within a given region, protect surrounding rural landscapes and explore optimized urban spatial patterns in the geo-space (Cho, Chen, Yen, & Eastwood, 2006), which can be expressed as the set of grid cells in a two-dimensional matrix with I rows and J columns. The land inside the UGBs is allowed for urban growth, whereas the land outside the UGBs is set aside for farming, forestry, and low-density residential development (Abbott & Margheim, 2008). Optimal UGBs are to assign urban land for the most probably connected cells, which is aim to balance the conflicts between urban growth and ecological conservation. The status of a cell in row $i(i=1,2,\cdots,I)$ and column $j(j=1,2,\cdots,J)$ can be represented as a binary variable x_{ij} and $x_{ij}\in\{0,1\}$, such that $x_{ij}=1$ if the cell is allowed for urban growth; otherwise, $x_{ij}=0$. Whether cell (i,j) is 1 or 0 is determined by the given objectives and constraints. Then, the urban growth boundaries can be derived from the edge of the patches labeled as 1. In this study, the objectives and constraints defined in the model are listed as follows.

2.1.1. Objectives

2.1.1.1. Maximum suitability for urban growth. Urban growth is mainly influenced by a series of spatial factors, and the suitability of a land cell for urban growth is often expressed as the status of location condition (e.g. transportation, topography, and surrounding environment) (Kiran & Joshi, 2013). Maximum suitability is calculated using the following equation:

$$Max \quad f_{suitu} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \times SuitU_{ij}}{\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij}} \tag{1}$$

where f_{suitu} is the average suitability of the growth pattern, $SuitU_{ij}$ is the suitability of cell (i, j) for allocating urban land.

2.1.1.2. Maximum preservation for high-quality farmlands. Encroaching on a number of farmlands is inevitable for urban growth. However, the immoderate occupation must be restrained for food security (Godfray et al., 2010). The quality of farmlands determines the quantity and location of those preserved, farmlands of the highest quality have the highest probability to be preserved. The value for measuring maximum farmland preservation is calculated as follows:

$$Max \quad f_{farmp} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \times (1 - Suit\,F_{ij})}{\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij}} \tag{2}$$

where f_{farmp} represents the average level of high-quality farmlands preserved. $SuitF_{ij}\in(0,1)$ is defined as the quality of farmland, which can be measured using the suitability evaluation of agricultural land use.