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Modeling the dynamics of urban and ecological binary space for regional coordination: A case of Fuzhou coastal areas in Southeast China

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ABSTRACT

The linkage of urban planning and the dynamics of regional ecosystem services value (ESV) allows sustainable aims more accessible, which is increasingly interested by researchers. This paper combines urban expansion and eco-compensation to construct the urban-ecological coordinated development model (UECDM) which aims to find a new urban expansion mode basing on the balance of regional ESV. UECDM is composed of three modules: prediction of urban expansion, eco-compensation and spatial simulation. With this model, the urban expansion and eco-compensation of Fuzhou areas was simulated. The result shows: urban land has expanded 12,805 ha, with a total ESV loss of 688 million yuan. In order to obtain the balance of regional ESV, 1,142 ha of cultivated land and 3,316 ha of other land should be converted into forestland; 2,588 ha of cultivated land into tidal flats; 2,027 ha of other land into water areas. This model could produce quantitative results for decision makers during the rapid urbanization for sustainable development.

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1. Introduction

Radical land-use changes driven by urbanization have caused a series of ecological problems such as the greenhouse effect and species decrease. (Kucukmehmetoglu & Geymen, 2016; Sawut, Eziz, & Tiyip, 2013). The coordinated development between urban expansion and ecological protection plays a crucial role in regional sustainable development. (Churkina, 2008). Studies on urban expansion from an ecological aspect have become a major research field. Many scholars have done a lot of research on this issue from four aspects: Firstly, the ecological theory was applied to urban and regional planning to solve ecological problems in the process of urban expansion (Fabos, 1979; Forman, 1995). Secondly, the concept of ecological security pattern was put forward to control urban sprawl (Yu, 1999). It set rigid space limitations for urban expansion and established the development strategy of "ecology first" (Gong, Liu, Xia, & Zhao, 2009; Su et al., 2016; Yin et al., 2016). Thirdly, the relationship between urban expansion and the ecological environment was quantitatively analyzed. Costanza, d'Arge, and De Groot (1997) established a "unit value"-based paradigm for evaluating the ESV. Many researchers (Chuai et al., 2016; Long, Liu, Hou, Li, & Li, 2014; Wan et al., 2015) used this method to evaluate the loss of ESV caused by urbanization. Besides, Zhang, Hu, Xu, and Yin (2011), Wang (2014) analysed the coordination degree between urban expansion and regional environment. Lastly, owing to the advancement of computer and spatial information technology, the simulation analysis has become an important research hotspot. Various models are widely used to simulate urban-ecological process to help researchers and decision makers (Agarwal, Green, Grove, Evans, & Schweik, 2002; Al-Ahmadi, See, Heppenstall, & Hogg, 2009; Verburg, Schot, Dijst, & Veldkamp, 2004).

The simulation models can be divided into the macro-kinetic model, the micro-kinetic model and the integration model from the perspective of model creation. The macro-kinetic model simulates urban expansion by such macro-variables as society and economy (Almeida, 2003, pp. 23–30; Forrester, 1969; Frank & Jens, 1998). It better reflects the overall dynamic characteristics of urban development, but it can't reflect the micro-features and individual

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behavior of city while the micro-mechanism is considered as the cause of the complexity of city system.

Currently, the micro-kinetic model has become the main aspect of studies. Cellular automata (CA) model is the most widely used. It can simulate the complex evolution of geographical time-space via the state changes of micro-individuals, which has attracted the interest of many researchers (Batty, 1992; Birkin, 1990; Clarke & Hoppen, 1997; Kuang et al., 2011; Landis, 1994; Ma & Ai, 2015; Silva & Clarke, 2002; Tobler, 1970; White & Engelen, 1997). However, the CA model is faced with "rule" dilemma, since the formalization of "rule" has separated it from the essential process of urban growth. The multi-agent model, a newly developed micro-kinetics model, reveals the urban growth process through analyzing the behaviors of individual decision-makers such as residents, enterprises and governments (Jokar Arsanjani, Helbich, & de Noronha Vaz, 2013; Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Zheng, Shen, Wang, & Hong, 2015). Though the multi-agent model stands for the frontier field of artificial intelligence, the application of it is restrained by the complexity of individual behavior and the difficulty of data obtaining. Besides, the minimum cumulative resistance (MCR) model was first applied to the research of species spreading process and was later introduced into urban expansion simulation (Huang & Chen, 2015; Kaaapen & Scheffer, 1992). MCR has certain advantages in simulating urban expansion since it is open and it can combine qualitative analysis with quantitative analysis. The micro-kinetic models mainly simulate the expansion of individual city for research on the structure and form of urban space while seldom simulate the urban-regional compound system.

The integration models created based on various modeling techniques are probably best tools to interpret spatial processes. CLUE-S is a widely used integration model which copes with the competitive relations between different land uses with system theory to synchronously simulate the changes of different land use (Verburg & Overmars, 2007, pp. 321–337; Verburg et al., 2002). It is commonly used to simulate the land changes while seldom applied to the simulation of urban expansion. Alberti and Waddell (2000) created an integration model of urban development and ecological dynamics by combining economy model, ecological model and land change model, aiming to interpret the complex process of urban growth. The Economy-Society-Ecology models were studied to seek the balance between economy development and ecology protection for sustainable development (Capello & Faggian, 2002; Liu, Xu, & Luo, 2014; Yang, 2004; Zhan, Zhang, Ma, & Chen, 2012). These models focus on interpreting the complex urban process from system theory, but they don't offer a space simulation program. Since complete data are needed as support, it is difficult to apply the models to practice.

From the existing research results, the current research on the micro-kinetic model focuses on prediction the expansion of individual city while seldom relates to the dynamic balance of the ESV. Although most of researchers consider ecological constraints as the condition of urban expansion, the dynamic balance of regional ESV can't be obtained through urban expansion separated from regional system. The integrated models try to build up the complex relationship between society, economy and ecology from the perspective of Systems Theory, but they lack a clear, quantitative expression method for the sustainable development goal. There are few research results of the ESV into the simulation model published to improve the shortcomings of the model.

As such, this paper aims to develop a new urban-ecological coordinated development model (UECDM) to explore a new urban expansion mode, which can maintain the dynamic balance of regional ESV. It is expected to combine urban expansion and regional eco-compensation to maintain the balance of the ESV, based on ANN (artificial neural network) model, GM (grey model) and MCR. The results of this research may shed some light on the human habitat environment in the rapid urbanization area, and provide a new perspective for sustainable development.

2. Model description: UECDM

2.1. The concept and structure of the model

Based on research on the capitalization of ESV, the regional ESV loss caused by urbanization could be compensated via corresponding measures (such as returning farmland to forest and returning farmland to tidal flats) (Costanza et al., 1997; Shao, 2011; Wu, Liu, & He, 2009; Xie et al., 2003; Zheng, 2008). From this perspective, the urban-ecological coordinated development model (UECDM) was created to simulate urban expansion and the corresponding eco-compensation. It is an effective tool to find a new urban expansion mode, which can maintain the dynamic balance of ESV.

The UECDM includes three modules: First is the module of urban expansion prediction. It computes the increment of urban land through BP neural network model to build the relationship between the driving factors (population, economy and investment) and urban space. Second is the regional eco-compensation module. Based on the gray linear programming model (GM), it compensates for the ecological loss caused by urban expansion through regulating regional land use structure, thus achieving the ESV balance. Third is the spatial simulation module. Based on MCR model, it simulates the spatial scenarios of urban expansion and the eco-compensation. GIS database provides a series of map layers and attribute data, including the shape of the research area, location, land type, road and DEM data (Fig. 1).

2.2. The simulation method and process

2.2.1. The module of urban expansion prediction

A complex non-linear relationship exists between urban space and population, economy, investment and income, and the relationship among them can be established via BP neural network model (Liu, 2007) (Fig. 2). This paper selected urban population, GDP, urban fixed-asset investment and urban disposable income as independent variables and urban land as the dependent variable to formed BP neural network model with the data from 1990 to 2015 as a sample using Weka. According to the changes of the independent variables of 2020, the scale of urban land was predicted and delivered to the regional eco-compensation module.

2.2.2. The regional eco-compensation module

Urban expansion leads to land conversion and the ESV loss. The regional eco-compensation module aims to achieve the dynamic balance of regional ESV by optimization of regional land use structure. In order to achieve the above function, the GM, which is often used for land structure optimization, is introduced (Gao & Qiu, 1999). The expression is as follows:

$$\begin{aligned} &F(X) = C^T X \\ &\otimes (A) X \le b \\ &X \ge 0 \end{aligned} \tag{1}$$

In this expression: F(X) is the objective function, F(X)→max (or min); X represents the decision variable, $X = [X_1\ X_2\ X_3\ \ldots\ X_n]^T$; C represents the benefit coefficient, $C = [C_1\ C_2\ C_3\ \ldots\ C_n]^T$; A represents the constraint coefficient; and b represents the constraint, $b = [b_1\ b_2\ b_3\ \ldots\ b_n]^T$.

The steps for constructing the GM are as follows:

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