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Embedding ecological sensitivity analysis and new satellite town construction in an agent-based model to simulate urban expansion in the beijing metropolitan region, China

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ABSTRACT

As the national center for politics and culture, Beijing's urbanization level is very high. Many policies within the proposed Beijing–Tianjin–Hebei region coordinated development plan affect the expansion of urban land. Therefore, it is very important to predict urban land use changes in Beijing for planning and management purposes. In this paper, we integrated of MAS (multi-agent system) and CA (cellular automata) to simulate new satellite towns construction and ecological sensitivity impact on land use change. Physical and social driving factors were used in the combined model. The MAS involved the actions of three types of agent: regional authorities, property developers, and residents. The study used the CA model to simulate the neighborhood effects of urban land use, and the MAS model to simulate agents' decisions. The new satellite towns and an ecological sensitivity analysis were embedded in the model to simulate the impact of decision making by the Beijing government on urban land expansion. Based on the land use data of 2005, the urban land area in 2010, 2015, 2020, and 2025 was predicted using the CA-MAS model. Urban expansion occurred faster during 2015–2025 than during the previous 10 years. Three land use types, i.e., cropland, woodland, and rural residential land, were the major sources of urban expansion. With respect to government decision making, the satellite towns were the priority areas of urban development, and urban development was restricted in ecologically sensitive areas. The New Districts of Urban Development were projected to become the main areas of future urban expansion in Beijing. The area designated for urban expansion around the ecologically sensitive areas was small. The results demonstrate that satellite towns and ecological sensitivity have large impacts on urban expansion. The results of this study will help to protect ecologically sensitive land, while enabling harmonious expansion of the city.

1. Introduction

Land use and land cover change (LUCC) is the basis of research on global change and sustainable development (Li, 1996; Rindfuss et al., 2004). The effects of land use changes and urbanization on ecosystems and sustainable land use have attracted increasing interest among researchers (Vitousek et al., 1997; Scarborough et al., 2012; Bihamta et al., 2015).

In order to enhance the functions of the capital and promote its world service capabilities, the national principal function regional planning had identified Beijing as the national optimum development region and has taken the lead in exploring and implementing district and county functional positioning (Beijing Municipal Government and China., 2005). The Ecological Preservation Development Districts (EPDD) was proposed firstly according to the "Guidance on the County's Functional Orientation and Evaluation Indices Construction". The establishment of EPDD is a priority since it played an important role in ecological construction and land use protection(Liu et al., 2015).With the rapid progress of urbanization, increasing amounts of cropland and rural residential land have been converted to urban land. The pattern of urban expansion is changing the Earth's surface temperature and affecting the global climate (Kalnay and Cai, 2003), leading to land degradation (Riley and Matson, 2000), increased sea levels, and other global environmental problems. The process of urbanization is reflected not only in growing urban populations and associated economic growth but also in changes in urban land use types and area. Simulations of the impact of urban planning on land use changes are important for the sustainable development of urban areas (Yao

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et al., 2016). Urban sprawl is influenced by environmental and human factors, and its mechanism of operation is very complicated. In the past, land use change prediction models were based on traditional city models, which commonly included a system dynamics (SD) model and a mathematical model. These models typically used mathematical statistics or empirical equations to express the dynamic time variation in a "top-down" analysis process (Zhang et al., 2008). However, in this type of model, the expression of spatial information is incomplete, and the spatial and temporal differences in urban expansion can be ignored, which does not reflect the complexity of the urban system's evolution (Tian and Wu, 2008). With the development of geographical information system (GIS) technology, especially the development of raster data, the cellular automata (CA) model has been widely used to simulate urban growth and future land use changes (Berling-Wolff and Wu, 2004; Santé et al., 2010; Wu and Webster, 1998). Unlike traditional urban models, this dynamic model uses a "bottom-up" simulation process; furthermore, it can be integrated with other models (Clarke et al., 1997). With the development of complexity science and artificial intelligence, the multi-agent system (MAS) has been widely used to simulate the spatiotemporal dynamics of complex land use systems (Chen et al., 2010). This model has been applied to agricultural economics, social science, decision science, financial markets, energy systems, and tourism management (Ansari et al., 2016; Cai et al., 2016; Deadman and Gimblett, 1994), as well as in transportation, resource management, and ecological systems (Grimm et al., 2005). The behavior of regional authorities, property developers, and residents were defined in the multi-agent system (MAS). This model has been widely used in the simulation of land use changes (Ralha et al., 2013; Buil et al., 2016). It can accurately simulate the complexities of land use changes in a multi-scale, multi-angle, and multi-level manner, and thus better reflect the dynamic relationship between urban land expansion and the natural environment (Bai et al., 2015). The CA model can be combined with a multi-agent system (MAS), and the combined model has been widely used in dynamic land use simulations. In the simulation of a dynamic city, Batty and Xie (1994) Batty et al. (1999) used an urban land structure with different life cycles, distances, directions, density thresholds, and conversion probabilities to establish an urban dynamic evolution model. White and Engelen (2000) White et al. (1997) used population, economy, and policy factors to simulate Dutch urban land use characteristics. Clark et al. (1997) used terrain, roads, and residential data to simulate and predict urban development in the San Francisco Bay area. To simulate dynamic changes in land use, Liu and Chen (2006) used a MAS model to simulate the urban residents, real estate developers, regional authorities, and other multi-intelligent bodies, as well as the environment between interactions that led to the evolution of urban spatial structure. The present study used physical factors (digital elevation model (DEM), rivers, lakes, etc.) and social factors (railways, main roads, economic development, government policies, etc.) to simulate and predict the impact of new satellite towns and ecological sensitivity on land use changes in the Beijing region. By simulating the decisions and behavior of residential, real estate development, and regional authority agents, the mechanisms of expansion and factors influencing urban land expansion were identified.

2. Materials and methods

2.1. Study area

The city of Beijing is the capital of the People's Republic of China. It is located in the northern region of the North China Plain, backed by the Yan Mountains, between 115.7°–117.4°E and 41.6°–39.4°N (Fig. 1). The city is about 176 km long from north to south, and 160 km wide from west to east. It is the national center for politics, culture, international exchange, and technological innovation, and is also famous worldwide for its ancient history. At the end of 2014, the residential population was 21.5 million people living within an area of 16,410.54 km^2 (Beijing Statistics Bureau, 2015). The northern, northeastern, and western areas of the city are mountainous, accounting for about 62% of the total area, while the central and southeast parts of the city are plain areas, accounting for about 38% of the total area. Beijing has a typical northern temperate semi-humid continental monsoon climate; due to the mountainous terrain surrounding the city, the climate is complex and changeable. The weather is hot and rainy in summer and cold and dry in winter, and the spring and autumn seasons are short. The annual mean temperature is 10–12 °C,with mean temperatures of −7 to −4 °C in January and 25–26 °C in July.The extreme minimum temperature is −27.4 °C, and the extreme high temperature is 42 °C.

2.2. Data procurement and pretreatment

Three types of data were used in this study: social economic data, spatial data, and urban planning policy data. The social economic data were collected from Beijing Statistical Yearbook (Beijing Statistics Bureau, 2015). The social economic data included the total population and gross domestic product (GDP) (Fig. 2). The spatial data were Landsat TM/ETM+ images, DEM data, and digital city data. Landsat TM/ETM+ images were obtained free of charge from the United States Geological Survey (USGS) and USA (2016). The urban land use data were interpretations of remote sensing data from 2005 and 2008, which identified six land use types: cropland, forest land, grassland, water body, building land (urban land, rural residential land, and other construction land), and unused land (Liu et al., 2002) (Fig. 3). The accuracy of land use data obtained by this method in 1995 was 92.9% (Liu et al., 2005). DEM data had a resolution of 30 m. The data set was provided by the Geospatial Data Cloud site of the Computer Network Information Center, Chinese Academy of Sciences (Geospatial Data Cloud and China, 2016). DEM data were used to obtain altitude, slope, and aspect using the ArcGIS10.2 toolbox. Digital city data were obtained from the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences. The digital city data included traffic data, river data, educational resources, medical and health resources, leisure facilities, and food markets. Traffic data included railways and different types of roads. Educational resources included primary schools, secondary schools, universities, and colleges. Medical and health resources included medical health service establishments, pharmacies, clinics, and hospitals. Leisure facilities included the city square, parks, and sports centers. Food markets included supermarkets and shopping plazas. The digital city data were used to acquire thematic information. Urban planning policy data were available from the Beijing Municipal Commission of Urban Planning (Beijing Municipal Commission of Urban Planning, 2005a,b,c).

In this study, land use and factors driving changes were determined at a spatial resolution of 100 × 100 m. The distance variables affecting land use change included natural driving factors (DEM, slope, aspect, distance to rivers, and distance to parks) and social driving factors (distance to government offices, to hospitals, to schools, and to roads). According to the spatial analyst in ArcGIS10.2, the "Euclidean distance" tool was used to obtain these data (Fig. 4). We overlaid the DEM, slope, aspect, and distance data according to their coordinates.

3. The CA-MAS model of urban land use change

3.1. The systematic framework of the model

The Beijing urban expansion model consisted of three components: GIS, CA, and MAS. The role of the GIS was to provide spatial information and basic spatial data pre-processing. The CA component was used to include the impacts of environmental driving factors on urban land expansion. The MAS sub-model reflected the different agents that influence urban land conversion. Its systematic framework is shown in Fig. 5. To describe the agent system, Rao and Georgeff (1998) proposed the Beliefs–Desires–Intentions (BDI) model structure. Beliefs represent