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Modeling urban expansion scenarios by coupling cellular automata model and system dynamic model in Beijing, China

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Abstract

Spatially explicit urban expansion models that can trace urban development in the past and predict the expansion scenarios in the future are indispensable for examining urban planning policies. This paper demonstrates a new urban expansion scenario (UES) model by coupling one ''bottom-up'' cellular automata (CA)-based model and one ''top-down'' system dynamics (SD)-based model. By implementing the UES model in Beijing, the urban evolution from 1991 to 2004 was simulated and the UESs from 2004 to 2020 were predicted. The results suggest that a dilemma of urban expansion versus limited water resource and environment deterioration exists. Dealing with such a dilemma remains a challenge for the local government.

Keywords: Urban expansion; Cellular automata; System dynamic; Beijing

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Introduction

Urban expansion is a complicated process that is determined by the interactions of biophysical factors and human factors in space and time at different scales (Barredo, Kasanko, McCormick, & Lavalle, 2003; Lambin & Geist, 2001). Modeling is a valuable way to understand a process (Costanza & Ruth, 1998). There still lacks spatially explicit urban expansion models that can effectively trace the urban development in the past and predict possible expansion scenarios in the future so that related urban planning policies can be examined. Since land use models are useful tools to understand the land use process and support land use planning and policy making (Verburg, Veldkamp, de Koning, Kok, & Bouma, 1999), further development of urban land model to effectively describe the complicated process of urban expansion is still indispensable (Chen, Gong, He, Luo, & Tamural, 2002).

A variety of approaches have been used to model the spatial process of urban growth, including potential models (Weber & Puissant, 2003), Markov chains (López, Bocco, Mendoza, & Duhau, 2001) and spatial logistic regression (Cheng & Masser, 2003). Berling-Wolff and Wu (2004) have provided a review of models developed for urban dynamics in the last half century. Recently, there is growing literature on applications of cellular automata (CA) models in urban growth and land use change (Batty, Couclelis, & Eichen, 1997; Clarke, Hoppen, & Gaydos, 1997; White & Engelen, 1997; Wu & Webster, 1998). A CA model is a dynamic model with local interactions to reflect evolution of the system, where space and time are considered as discrete units and space is often represented as a regular lattice of two dimensions (White & Engelen, 1997). CA-based models have the strong ability to represent non-linear, spatial and stochastic processes (Batty et al., 1997). Many works have already demonstrated the CA model's capability to simulate spatial pattern and process of urban expansion in a very realistic way (Batty et al., 1997; Clarke et al., 1997; Sui & Zeng, 2001; White & Engelen, 1997; Wu & Webster, 1998; Xian & Crane, 2005). However, as a "bottom-up" model, CA cannot represent well macro-scale political, economic and cultural driving forces that influence urban expansion (Ward, Murray, & Phinn, 2000). Research is urgently needed on how to improve a CA model's ability to represent the complexity of urban expansion influenced by human and natural factors at different scales. Some considered the integration of the CA model and economic models (Barredo et al., 2003; White & Engelen, 2000). Theobald and Gross (1994) discussed the possibility to integrate the CA model, the SD model and Geographical Information System (GIS). Recently, Wu and Webster (1998) developed a hybrid model by combining a CA model and an economic model and obtained satisfactory results for urban expansion simulation. White and Engelen (2000) linked a CA model with a regional development model for urban development research. The CA-based hybrid models improve the CA's ability to reflect actual land use change and have drawn great interests in the research community.

A system dynamics (SD) model can not only arrange and describe the complicated connections among each element in different levels, but also deal with dynamic processes with feedback in a system. Moreover, it can predict the complex system change under different "what-if" scenarios, which is very useful in examining and recommending policy decisions in management and social systems (Mohapatra, Mandal, & Bora, 1994). Since the works on SD model reported by Forrester (1961), the method has been widely used in different fields of natural science, social science and engineering technology

(Clemson, Tang, Pyne, & Unal, 1993; Naill, Gelanger, Klinger, & Petersen, 1992). Recently, the powerful ability of the SD model to reflect the complexity of land use driving forces has also been studied (Guo et al., 2001; Li and Simonovic, 2002). For the complicated process of urban expansion, the SD model can be an appropriate approach to reflect the driving forces and analyze the implications of different policies. However, as a ‘‘top-down’’ model, SD model’s ability to represent the spatial process of land use is weak because it can not deal with spatial data well and can not effectively describe the detailed distribution and situations of the spatial factors in the land system (Guo et al., 2001; Zhang, 1997). Considering the strength and weakness of both the SD model and the CA model, this paper presents a loose-coupled urban expansion scenarios (UES) model that integrates these two models and demonstrates its application in Beijing, China.

As the host of the 2008 Olympic Games, Beijing, the capital city of China, is one of the oldest and most densely populated cities in the world (Li, Wang, Paulussen, & Liu, 2005). Since China implemented the reform and open policy and began her transition from a centrally-planned, rural-based economy to a market-oriented, urban-based economy in 1978 (Gu & Shen, 2003), Beijing has been experiencing fast economic development and an unprecedented process of urbanization. The population and the Gross Domestic Product (GDP) of the city increased from 8.72 million and 10.88 billion RMB yuan in 1978 respectively to 14.93 million and 428.33 billion RMB yuan in 2004 (BMSB, 2005). Such changes improve the livelihood of the residents and give sound support to the city’s efforts to transform itself into a global city (Wei & Yu, 2005). However, like other metropolitan area in developing countries, Beijing also faces many problems including air pollution, large floating population from rural areas, lost of the high-yield agricultural land, destruction of historic urban fabric and increased disaster risk (Chen, Ganesan, & Jia, 2005; Gaubatz, 1999; Sit, 1996). Many studies on Beijing’s fast urbanization and urban land use can be found in the literature, including urban land change detection (Dai, Ma, & Ou, 2005; Ma & Bagan, 2005), urban pattern and process understanding (Deng & Huang, 2004; Gu & Shen, 2003), driving force investigation (Wu & Webber, 2004), urban growth prediction (Chen et al., 2002; Liu & Zhou, 2005), and environmental and ecological problems analysis (Chen, H et al., 2005; Chen, T et al., 2005; Yang, McBride, Zhou, & Sun, 2005). Recently, the continuous city expansion to form a ‘‘big pancake’’ by encroaching good cultivated land and green space in the urban/rural fringe area becomes a focus of discussion. This aimless expansion can easily result in traffic jams, excessive sprawl, lack of green space, increased ‘‘heat island’’ effect and air pollution (Chen, H et al., 2005; Jim & Chen, 2003; Li et al., 2005; Wang, Chi, & Ouyang, 2001). In addition, after the unprecedented process of urbanization for over 20 years, water shortage has become the most important constraint to Beijing’s future development (Chen, H et al., 2005; Varis & Vakkilainen, 2001). Beijing’s usable water resources per capita are only 19.2% of the national average and 3.5% of the world average (Chen, H et al., 2005). Aggravated water shortage is due to the combined effects of the scare water resource, the hectic growth of demand and the inefficient wastewater treatment. Diverse measures have been adopted by the government, such as implementing the project to divert water from the Yangtze River and encouraging more efficient water use by increasing the price. However, the risk of a water crisis is more severe than ever (Chen, H et al., 2005). Therefore, the dilemma of the continuous urban expansion versus natural resource restriction and environment deterioration is becoming one of the main challenges confronting Beijing. Planning of a safe and secure city and region is seriously concerned and urged (Okada et al., 2005).

Our UES model is developed as a planning decision-support tool to deal with the dilemma of the continuous urban expansion versus limited natural resource and environment deterioration in Beijing. This new model differs from the existing models since it can not only reflect the complicated factors influencing urban expansion at the macroscopic scale but also possess the ability to spatially and explicitly represent land use evolution at the local scale. In addition, with its strong ability to simulate "what-if" scenarios of urban expansion, the complicated process of urban expansion with the restriction of water resource in Beijing can be understood and the related urban land planning polices can be effectively examined.

Description of UES model

Basic concept of UES model

As discussed by Ward et al. (2000) and Barredo et al. (2003), urban expansion should be considered as a complex process that is self-organizing at a local level but constrained and modified by broad-scale factors, such as environmental and natural resource constraints, socio-economic and political systems, and urban and regional planning policies. The UES model is made up of two parts. The first part is an urban land demand scenario (LDS) module that aims at modeling different "what-ifs" of land demands at the national/regional scale by using a SD model. Broad-scale factors of natural resource constraints, land policy, population, economy, etc. are considered in this step. The second part is an urban land allocation module that will spatially and explicitly allocate urban land expansion scenarios at the local scale by using a CA model. The allocation considers land use suitability, the inherited attribute and neighborhood effect by using a CA model to keep the balance between urban land demand and supply. The general structure of the UES is shown in Fig. 1.

Components and function of the UES model

The urban LDS module based on a SD model

Regarding urban expansion as a complicated process that takes place in a relatively independent region, the urban LDS module will simulate the urban land demands in different restrictive conditions of water resource. Firstly, based upon the trends analysis and estimates of water resource in the region, the scenarios of water resource restriction are set and the maximum carrying capacity of population and industry in the region can be obtained. Specifically, the maximum population carrying capacity of water resource N_p can be calculated as follows:

$$N_p = \frac{w_1 Q_1}{L}, \tag{1}$$

where Q_1 is the available water resource in the region, w_i is the percentage of the water usage by total population of the region and L is the minimum per capita water consumption in the region (Long, 2004).

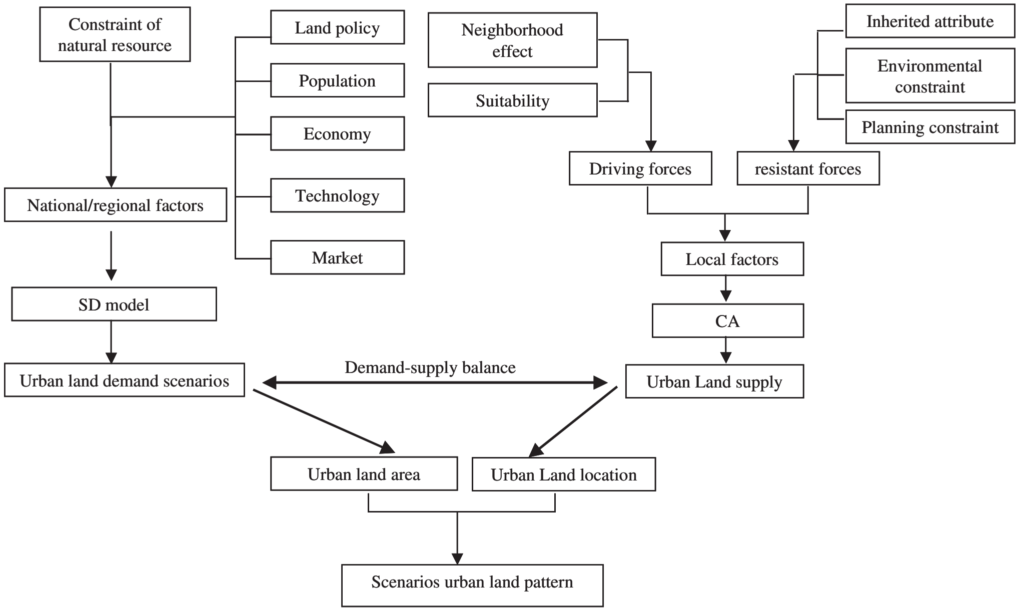

Fig. 1. The general structure of the UES model.

The maximum available water resource for industry in region C is generally expressed as follows:

$$C = \frac{w_2 Q_1 (1-b)}{(1-a)}, \tag{2}$$

where Q_1 is the available water resource in the region, w_2 is the percentage of the water usage by industry, a is the recycling rate of industry water usage and b is the consuming rate of industry water use (Liu, Chen, Huang, & Liu, 2003).

Then, simultaneously restricted by the maximum carrying capacity of population and industry of the region and driven by such economic and social factors as population increase, economic development, and technology advancement, the urban expansion process is simulated. Finally, the urban land demands are obtained based on the estimates of land demand for living, production and public service (for example, traffic system and green space) within the urban expansion process. The framework of the module is shown in Fig. 2.

The land use allocation (LUA) module based on a CA model

The land use allocation (LUA) module is developed on a CA model in order to spatially and explicitly model the urban expansion patterns of the different LDSs produced by the LDS module as described above. The goal of the LUA module is to keep the balance between urban land demand and supply.

As discussed by Barredo et al. (2003), the process of urban land expansion can be practically defined as an iterative probabilistic system. The probability ${}^tP_{K,x,y}$ that cell (x,y) with land use type K is occupied by urban expansion at time t, is a function of the driving forces ${}^tD_{x,y}$, the resistant forces ${}^tR_{x,y}$ and a stochastic perturbation ${}^tV_{x,y}$. It can be

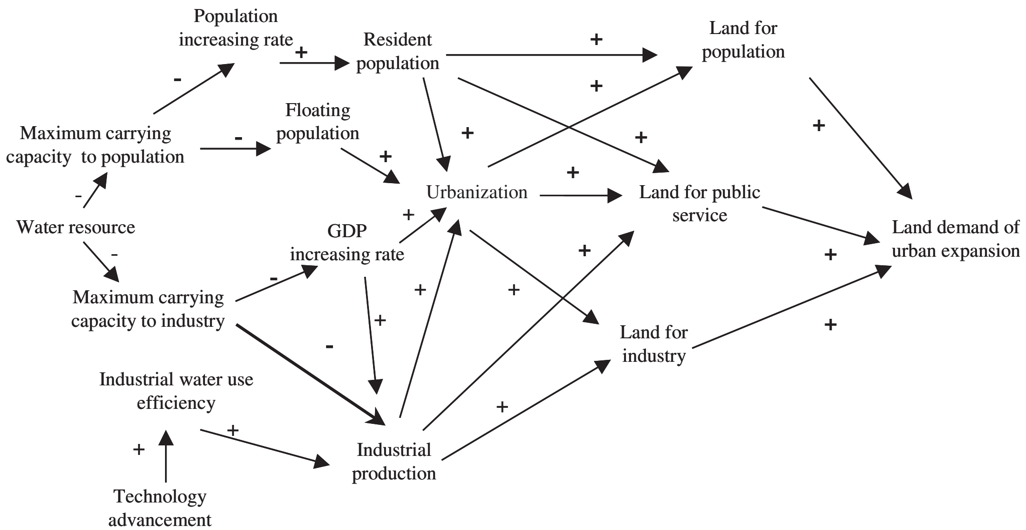

Fig. 2. The framework of urban land demand scenario module based on a SD model.

expressed as

$$^{t}P_{K,x,y} = f(^{t}D_{x,y}, {}^{t}R_{x,y}, {}^{t}V_{x,y}). \tag{3}$$

The driving forces of urban expansion $^{t}D_{x,y}$ can be expressed as

$$^{t}D_{x,y} = f(^{t}S_{x,y}, {}^{t}N_{x,y}), \tag{4}$$

where $^{t}S_{x,y}$ is the suitability of cell (x,y) to urban expansion at a time t, $^{t}N_{x,y}$ is the effect of neighborhood space that causes cell (x,y) be occupied by urban expansion at time t.

The resistant forces of urban expansion $^{t}R_{x,y}$ can be expressed as

$$^{t}R_{x,y} = f(^{t}I_{K,x,y}, {}^{t}EC_{x,y}, {}^{t}PC_{x,y}), \tag{5}$$

where $^{t}I_{K,x,y}$ is the inherited attribute of cell (x,y) to keep its current land use state K at time t, $^{t}EC_{x,y}$ is the environmental and ecological constraints that cause cell (x,y) not be occupied by urban expansion at time t and $^{t}PC_{x,y}$ is the land planning and land use policy constraints that cause cell (x,y) not be occupied by urban expansion at time t.

$^{t}V_{x,y}$ is the scalable random perturbation term of cell (x,y) at time t, it is defined as

$$^{t}V_{x,y} = 1 + [-\ln(rand)]^{a}, \tag{6}$$

where $rand$ $(0 < rand < 1)$ is a uniform random variable, and a is a parameter that allows the size of the perturbation to be adjusted.

Further, to simplify the calculation, the probability ${}^{t}P_{K,x,y}$ that cell (x,y) with the land use type K is occupied by urban expansion at time t can be expressed as

$$ {}^{t}P_{K,x,y} = \left(\sum_{i=1}^{m-2} {}^{t}W_i {}^{t}S_{i,x,y} + W_{m-1} {}^{t}N_{x,y} - W_m {}^{t}I_{K,x,y} \right) \times \prod_{r=1} {}^{t}EC_{r,x,y} \prod_{l=1} {}^{t}PC_{l,x,y} {}^{t}V_{x,y}, \tag{7} $$

where $\sum_{i=1}^{m-2} {}^{t}W_{i,x,y} {}^{t}S_{i,x,y}$ is the inherent suitability of cell (x,y) to be occupied by urban expansion at time t, in which ${}^{t}S_{i,x,y}$ is a standardized suitable score [0,100] of factor $i(1, \ldots, m-2)$ of cell (x,y) to urban expansion at time t, such as traffic accessibility and topography, and W_i is the weight of this factor. ${}^{t}N_{x,y}$ is the effect of neighborhood space that causes cell (x,y) be occupied by urban expansion at time t and W_{m-1} is its weight. ${}^{t}I_{K,x,y}$ is the inherited attribute of cell (x,y) to keep its current land use state K at time t and W_m is its weight. The weights (W_1, W_2, …, W_{m-2}, W_{m-1}, W_m) reflect different degree of contribution of the above factors to drive or resist urban expansion. $\Pi_{r=1} {}^{t}EC_{r,x,y}$ is the product of some binary variables representing environmental and ecological constraints to urban expansion. If ${}^{t}EC_{r,x,y} = 0$, cell (x,y) may be constrained by environmental and ecological requirement, such as areas subjective for flooding and protected area for water source, which is hypothesized not to be occupied by urban expansion in the simulation. Otherwise, ${}^{t}EC_{r,x,y} = 1$. $\Pi_{l=1} {}^{t}PC_{l,x,y}$ is the product of some binary variables representing the land planning and land use policy constraints to urban expansion. If ${}^{t}PC_{l,x,y} = 0$, cell (x,y) may be constrained by the land planning and land use policy requirement, such as historic urban area, high-yield farmland protection area, high risk area of geological disaster, and planned green belt exclusive of urban land use. Otherwise, ${}^{t}PC_{l,x,y} = 1$. ${}^{t}V_{x,y}$ is the same as in Eq. (3).

The effect of neighborhood space ${}^{t}N_{x,y}$ that causes cell (x,y) be occupied by urban expansion at time t can be further calculated as

$$ {}^{t}N_{x,y} = A \sum_{c} {}^{t}W_c {}^{t}G_c = A \sum_{c} \frac{{}^{t}G_c}{C^K}, \tag{8} $$

where, ${}^{t}W_C$ is the weighting parameter expressing the strength of the interaction between cell (x,y) and an urban cell at a distance C in the neighborhood space at time t (Barredo et al., 2003). The stronger the interaction, the larger the weighing parameter. According to the first law of geography that near things are more related than distant things (Tobler, 1970), the ${}^{t}W_C$ can be calculated as $1/C^K (k = 1, 2, 3, \ldots)$. ${}^{t}G_C$ is a binary variable. If the cell at a distance C in the neighborhood space at time t is urban land, ${}^{t}G_c = 1$; otherwise ${}^{t}G_{c,l} = 0$. A is a scalar to standardize ${}^{t}N_{x,y}$ into the range of [0,100].

The inherited attribute of the cell (x, y) to continue functioning as land use K at time t ${}^{t}I_{K,x,y}$ is defined as a constant in the range of [0,100] according to the ability of the land use K to keep its original status in the model. The stronger the inherited attribute of the land use K to keep its original condition, the larger the constant.

After the probability of cell (x, y) to be converted to urban is obtained, it is possible to simulate the urban expansion patterns of different LDSs. First, with one simulation period defined as one year, the urban LDSs at the national/regional scale of each simulated period is obtained. Then, each cell's ${}^{t}P_{K,x,y}$ is calculated and the non-urban cells are converted to urban according to probability (highest probability is converted first) until the urban land demand in the simulation period is satisfied.

Implementation of the UES model for Beijing

Study area and data

To effectively understand the dilemma of continuous urban expansion versus water resource restriction and to examine the related land planning policy, the whole administrative area governed by Beijing Municipality is used as the study area with a total land area of 16,808 km^2.

Located on the northern edge of the North China Plain, the administrative area of Beijing Municipality (longitudes 115°25′–117°30′ E, latitudes 39°28′–41°25′ N) is composed of four city districts (Xuanwu, Xicheng, Chongwen, and Dongcheng), four suburban districts (Haidian, Shijingshan, Fengtai and Chaoyang), eight outer suburban districts (Mengtougou, Fangshan, Daxing, Tongxian, Shunyi, Changping, Pinggu, Huairou), as well as two rural counties (Yangqing, Miyun). Traditionally, the four city districts plus the four suburban districts are viewed as the central city with about 300 km^2 in area (Fig. 3). Beijing is in the temperate climatic zone with a mean annual temperature of 12 °C and an average annual precipitation of 640 mm (Li et al., 2005). A great degree of topographic variation is found in the region. The mountains are located in the northwest, which account for 62% of the surface area with an average elevation about 1000 m above sea level. The so-called Beijing Plain is in the southeast where the elevation is below 100 m

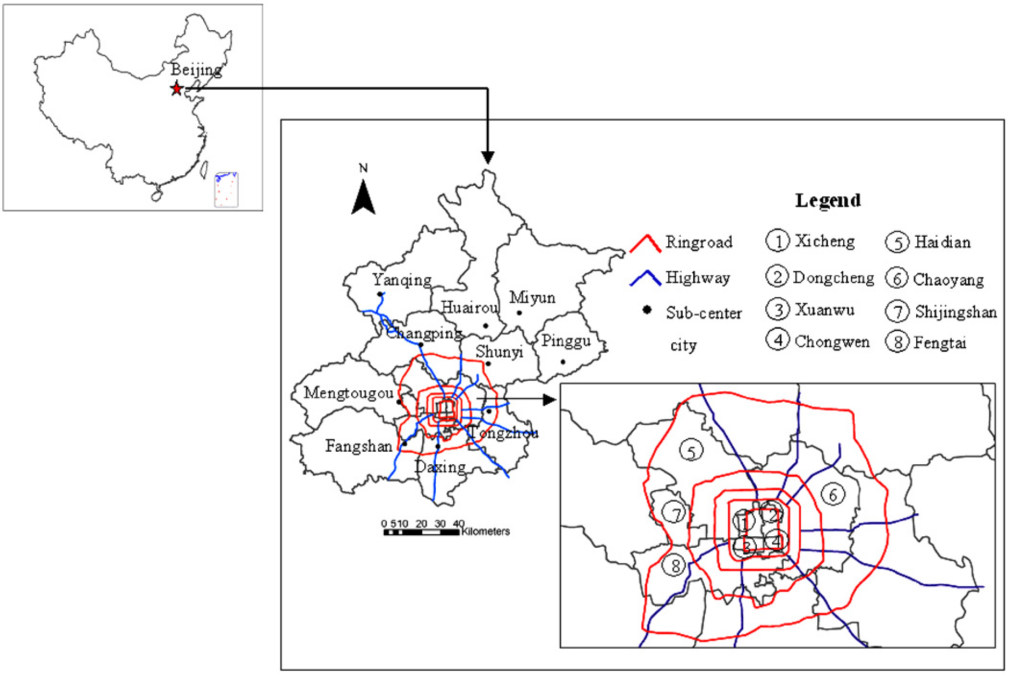

Fig. 3. The study area.

above sea level. As the most intensively developed area of Beijing, the plain covers 38% of the administrative area, and is the main focus of urban expansion (Li et al., 2005).

Beijing's road system can be briefly described as a network, with ring roads and radial roads as its arteries. The road around the Forbidden City is named the First Ring Road, and the ring roads beyond are the Second, Third, Fourth, Fifth and the Sixth Ring Roads in the order of the radial distance from the center of the city (Fig. 3). Before 1949, Beijing's development was confined within the old city, now marked by the Second Ring Road. The implementation of Reform and Open Policy since 1978 brought a phase of rapid urbanization and further encroachment into the surrounding countryside (Li et al., 2005).

Three Landsat-5 Thematic Mapper (TM) images acquired on May 6, 1991, May 16, 1997 and April 1, 2004 and one Landsat-7 Enhanced Thematic Mapper (ETM+) image acquired on April 30, 2000 were collected for the case study. In addition, essential ancillary data including 1: 100,000 topographic map and transportation map were also obtained from the local government. All the data layers were registered to the same Universal Transverse Mercator (UTM) coordinate system and sampled to the same pixel resolution of 180 m, which is large enough to capture spatial details and small enough to reduce computation time.

Model validation and urban growth simulation from 1991 to 2004

It is necessary to validate the UES model before using the model to predict future land use patterns since the simulated urban patterns are not only determined by the urban land demands at the broad-scale but also influenced by the factors and their weighting parameters associated with driving forces and resistant forces at the local scale (Silva & Clarke, 2002). Such validation is only possible when the urban land use distribution is known for two points in history with a considerable number of years in between (Verburg, Veldkamp, & Bouma, 1999).

Remotely sensed data, including satellite images and aerial photographs, provide reliable information for studying historical land use change (Veldkamp & Fresco, 1996). In this study, Landsat TM/ETM+ data were used to produce land use/cover maps of Beijing for the years of 1991, 1997, 2000 and 2004 (Fig. 4). Then the land use/cover maps of 1997, 2000 and 2004 were used to validate the UES model with the 1991 map as the beginning of the simulation. Ten factors closely associated with the driving forces and the resistant forces of urban expansion were selected and incorporated in the transition potential calculation. These factors were: distance to central city, distance to subcenter cities (Changping, Shunyi, Tongxian, Daxing, Mengtougou, Fangshan, Pinggu, Miyun, Huairou, Yanqing), distance to expressway, distance to airport, distance to highway, distance to Ring Roads, distance to railway, slope, neighborhood effect and the inherited attribute of the occupied land. Since the above 10 factors were measured in different units, they were all transformed into a normalized scale (that is, 100 = maximum contribution to expansion, 0 = minimum contribution to expansion) with the support of a Geographic Information System (GIS) before inputting into the UES model (Chen et al., 2002). Then, an adaptive Monto-Carlo approach introduced by Chen et al. (2002) was used to calibrate the weights of these factors based on the historical urban land use changes obtained from remotely sensed data. This approach not only avoids subjectively determination of the weights, but also supports the analysis of the effect of the driving and resistant factors on realistic urban growth. The basic idea of the approach is to try to find the optimal

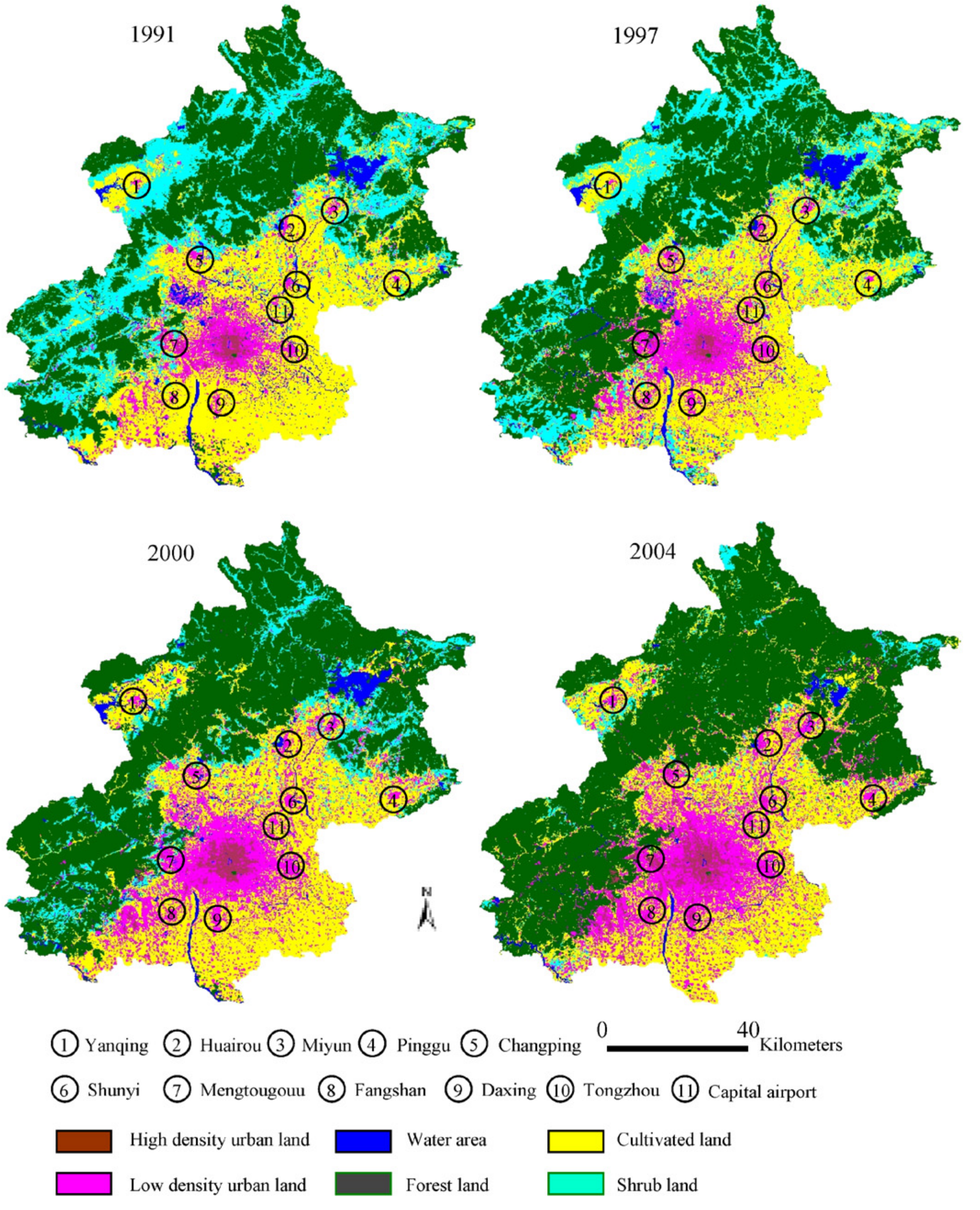

Fig. 4. Land use/cover change in Beijing from 1991 to 2004.

combinations of weights that can make the simulated urban growth as close as the realistic urban growth (Chen et al., 2002). The urban growth during the periods of 1991–1997, 1997–2000, 2000–2004 was simulated, respectively, about 500 times according to 500 different sets of weights with the hypothesis that 500 iterations can obtain the reliable weights to represent the main features of urban expansion in the Monto-Carlo simulation (Chen et al., 2002).

For each simulation of one period, the simulation result was compared with the actual urban land in the ending year of the period, and the fitness index *kappa* was calculated to measure the overall performance of the simulation. The fitness index *kappa* is based on the error matrix approach and defined as follows:

$$kappa = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+}x_{+i})}{N^2 - \sum_{i=1}^{r}(x_{i+}x_{+i})}, \tag{9}$$

where x_{ii} represents the element in the main diagonal of the error matrix, that is, the case where the class label in the simulated image and actual image sets agree. x_{i+} is the row total, x_{+i} is the columns total, r is the number of classes and N is total number of the elements in the error matrix (Nishii & Tanaka, 1999). The *kappa* parameter is widely used to assess the accuracy of thematic land use/cover maps produced by remotely sensed data (Foody, 2002), which is considered capable of measuring the overall performance of the simulation.

Among all 500 simulations for each period, the highest fitness index was about 0.73 for the period of 1991–1997, 0.76 for 1991–1997 and 0.80 for 1997–2000, respectively. The best-fit simulations for 1991–1997, 1997–2000 and 2000–2004 are shown in Fig. 5. Furthermore, Table 1 shows the calibrated weights in the three periods corresponding to the best-fit simulations. It is evident that simulation results from UES model are generally very similar to the actual urban patterns, though the scattered and small-scale urbanization phenomenon in the region was not fully captured by the simulation.

As shown in Fig. 5, the dominant pattern of urban development in Beijing from 1991 to 2004 was the rapid and continuous expansion of the center city to form a "big pancake" by encroaching good cultivated land and green space in the urban–rural fringe area.

Apart from the unprecedented economic development and steady population increase since 1978, three factors, including the strong agglomeration effect of the central city, the Ring Roads-based traffic system, and the inefficient protection of the agricultural land and the greenbelt, have played important roles in such urban expansion in Beijing as suggested in Table 1. The calibrated weights reflect the different degrees of contribution of each factor to the urban expansion process. Compared with other factors, the neighborhood effect and the distance to central city reflect the agglomeration effect of the urban development and the attractive power of the central city. These factors dominated the urban growth process in Beijing from 1991 to 2004. The sum of the two factors' weights is about 0.67 in 1991–1997, 0.60 in 1997–2000 and 0.52 in 2000–2004, respectively, far greater than the total of other factors. The Ring Road was weighted the third highest. Its weight is a little greater than that of the sub-cities, about equal to the total of the expressway, railway and highway. The agricultural land and the greenbelt was not effectively protected since the weight of the inherited attribution of the occupied is only 0.04 in 1991–1997, 0.05 in 1997–2000 and 0.06 in 2000–2004, respectively, indicating a very minor influence. The reason of such inefficient protection of the agricultural land and the greenbelt mainly lies in the conflicts between real estate development, the undervaluation of the agricultural land and the greenbelt and the ignorance of their significant ecosystem services to the residents in the urban area (Costanza et al., 1997; Li et al., 2005). For instance, the financial compensation requested for building over green space within the Second Ring Road was

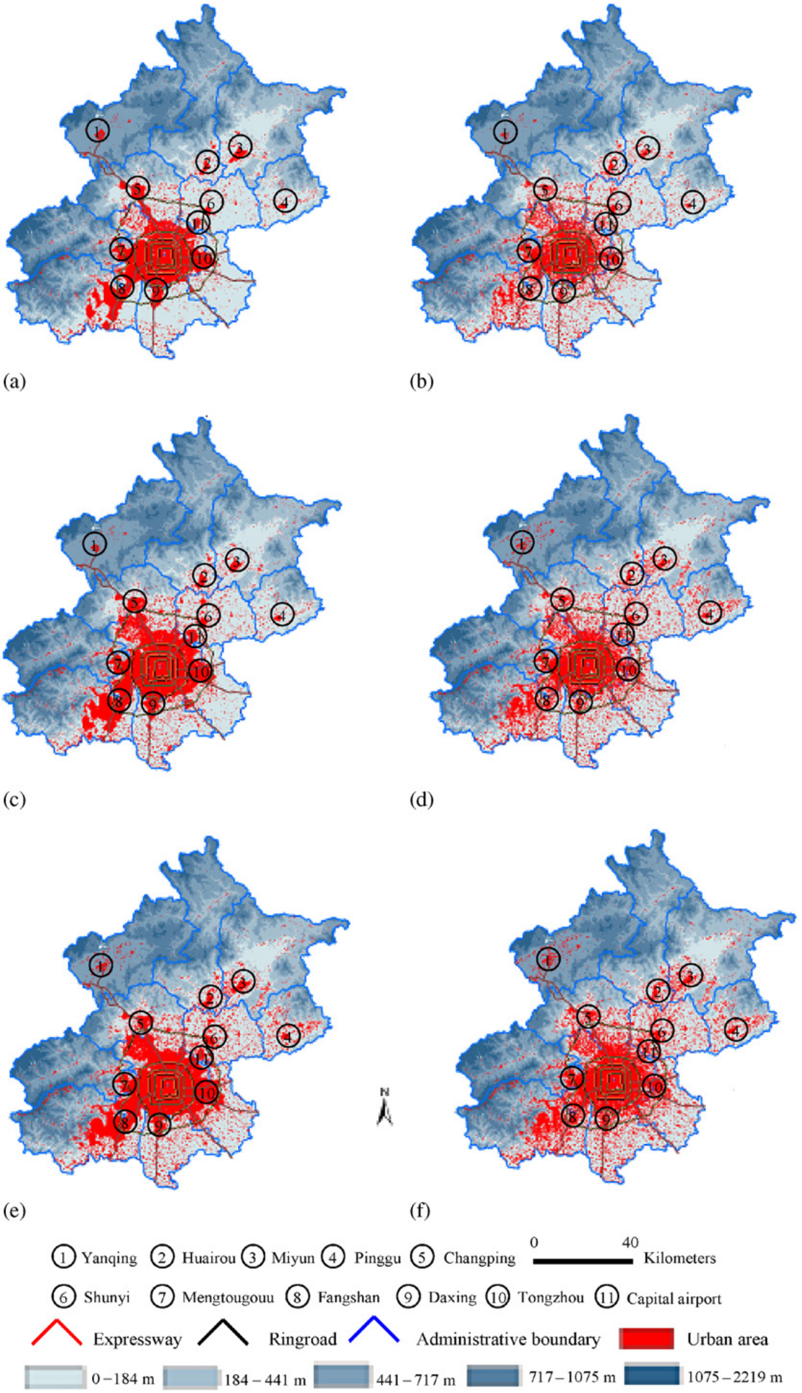

Fig. 5. Urban growth simulation in Beijing from 1991 to 2004. (a) Simulated urban pattern in 1997 (Kappa = 0.73); (b) actual urban pattern in 1997; (c) simulated urban pattern in 2000 (Kappa = 0.76); (d) actual urban pattern in 2000; (e) simulated urban pattern in 2004 (Kappa = 0.80); (f) actual urban pattern in 2004.

Table 1
Calibrated weights for the periods of 1991–1994, 1997–2000 and 2000–2007

Factors of driving forces/ resistant forces	Weights for 1991–1997 simulation	Weights for 1997–2000 simulation	Weights for 2000–2004 simulation
Distance to expressway	0.03	0.04	0.05
Distance to Ring Roads	0.09	0.12	0.13
Distance to railway	0.02	0.03	0.03
Distance to highway	0.03	0.03	0.03
Distance to airport	0.02	0.02	0.03
Distance to central city	0.17	0.14	0.13
Distance to sub-cities	0.06	0.08	0.09
Slope	0.02	0.03	0.05
Neighborhood effect	0.52	0.46	0.40
Inherited attribute of the occupied land	0.04	0.05	0.06

only 6000 Yuan RMB (723 US$/m^2), while the price of new residential floor space in this area is about 10,000 Yuan (Li et al., 2005).

As urged by many researchers (Chen, H et al., 2005; Chen et al., 2002; Li et al., 2005), such rapid and continuous city expansion to form a "big pancake" in the urban-rural fringe area already exerted great pressures on the existing supporting system of the city and did harm to Beijing's sustainable development.

Simulation of urban expansion patterns from 2004 to 2020

Dealing with the dilemma of continuous urban expansion versus limited water resource and environment deterioration in Beijing is a complicated issue and remains a challenge to both the academic community and the local government. In-depth and thorough discussion of the dilemma is beyond the scope of this paper. However, as a tool capable of implementing "what-if" scenario analysis to urban expansion, the UES model can spatially and explicitly simulate the urban expansion patterns in the near future. Examinations and analysis of these future scenarios will contribute to the endeavors to understand the dilemma of urban expansion in Beijing. Therefore, based on the results of model validation and urban growth simulation from 1991 to 2004, the simulation of urban expansion patterns from 2004 to 2020 was also implemented using the UES model.

Urban LDSs with the limitation of water resource till 2020

Since water shortage has already been recognized as the most important constraint to Beijing's future development, the extrapolation and estimation of the future water supply ability provides the basis for the analysis of future urban development scenarios in Beijing. Among the many current predictions of water supply in Beijing till 2020, the latest predictions were published by Ruan and Wei (2004) and Beijing Municipal Government (2005). These predictions were widely accepted due to their considerations of the latest factors related to Beijing's water supply, such as the diverted water from Yangtze River, technology advancement, and the implementation of water conservation measures (Table 2). Therefore, our study proposed three scenarios based on the above two water

Table 2
Predictions of water supply in Beijing till 2020

Year	Surface water (SW) ($10^8 m^3$)	Utilized rate of SW(%)	Available groundwater (AGW) ($10^8 m^3$)	Utilized rate of AGW (%)	Recycling utilized water ($10^8 m^3$)	Diverted water ($10^8 m^3$)	Available water supply ($10^8 m^3$)	Data source
2000	13.25	65.08	27.15	156.76	3.52	0.00	43.92	①
2020	15.26	75.00	18.32	105.77	5.10	11.07	49.75	①
2020	15.26	75.00	18.32	105.77	5.10	12.44	51.12	②
2020	15.26	75.00	18.32	105.77	5.10	16.32	55.00	②

Note: ① represents the data from Ruan and Wei (2004); ② represents the data from Beijing Municipal Government (2005).

Table 3
Historical urban land changes from 1991 to 2004 and the urban land demand scenarios under the different restrictions of water shortage in Beijing till 2020

Year	Scenario A (km^2)	Scenario B (km^2)	Scenario C (km^2)
1991	1206.47	1206.47	1206.47
1997	1870.79	1870.79	1870.79
2000	2331.88	2331.88	2331.88
2004	2726.66	2726.66	2726.66
2007	3073.84	2995.87	2874.74
2010	3452.34	3332.31	3207.10
2015	3659.88	3515.64	3284.53
2020	3895.01	3732.36	3380.82

Note: Historical urban land (including high density and low density urban land) data in Beijing from 1991 to 2004 are based on the remotely sensed data in Fig. 4.

supply predictions. They are scenario A, in which urban development is slightly limited by water resource with $55 \times 10^8\,m^3$ water capacity in 2020; scenario B, in which urban development is limited by water resource with $51.12 \times 10^8\,m^3$ water capacity in 2020; and scenario C, in which urban development is strongly limited with $49.75 \times 10^8\,m^3$ water capacity in 2020. Using the LDS module of the UES model, the urban LDS with the limitation of water resource till 2020 were obtained (Table 3). Obviously, different water supply can only support the different amount of development with the urban land demands ranging from $3895.01\,km^2$ in scenario A to $3732.36\,km^2$ in scenario B and $3380.82\,km^2$ in scenario C in 2020. This implies that (1) the future urban development should be strictly limited by the maximum carrying capacity of water resource and (2) the current measures that guarantee the water supply of the city should be effectively implemented to support the city's future development.

Urban expansion patterns from 2004 to 2020 with the related land use planning policies examined

In addition to the predictions of urban land demands under the different scenarios of water resource, the LUA module of the UES model can also spatially and explicitly provide the urban expansion patterns in the near future under the different "what-ifs" of urban land use planning policies. This implies that some urban land use planning polices can be examined and analyzed to help us to further understand the dilemma of urban expansion in Beijing. In this paper, the urban land development patterns of scenario B is further simulated with different "what-if" urban planning policies since scenario B represents the most probable future situation according to the latest Urban Master Plan of Beijing of 2004–2020 (BMG, 2005).

Fig. 6 shows the urban development patterns in Beijing from 2007 to 2020, if the city continues to expand on its trend from 1991 to 2004 without special planning policies checks. The results show that the "pancake" pattern would be strengthened in 2020. The precious green space and cultivated land between the Fifth Ring Road and the Sixth Ring Road would be obviously occupied by the unlimited expansion of the center city. The sub-cities of Changping, Shunyi, Tongzhou, Daxing, Fangshan, Mengtougou would be connected with the central city and became one part of it in 2020, developing much faster than sub-cities of Yangqing, Miyun, Huairou and Pinggu. Such a "pancake" urban pattern will greatly challenge the city's sustainable development.

If the cultivated land, especially the high-yield farmland protection area in the plain is effectively protected, what would happen to the city? Fig. 7 shows the urban development patterns in Beijing from 2007 to 2020, if the city's expansion were to be constrained by high-yield farmland protection policy. That is, the high-yield farmland protection area in the plain in 2004 was assumed not to be occupied by urban expansion till 2020. It can be seen that the trend of the big "pancake" expansion of the central city would be slowed down to some extent. Meanwhile, the small towns outside of the Sixth Ring Road would have the chance to develop faster to satisfy urban land demands. However, apart from the situation, the central city still keeps some expanding trend to form a big "pancake" (Fig. 7). The rationality of such protection in Beijing needs to be further researched and discussed because most of the high-yield farmland is located in the urban–rural fringe in the plain area. Conflict exists between the public interests of food security and ecological benefit of the high-yield farmland and the heavy agglomeration effect of the urban development driven by market forces.

Fig. 8 provided another urban development scenario in Beijing from 2007 to 2020, if strict urban planning policy were taken to stop the expansion of the central city. In the scenario, the land between the Fifth Ring Road and the Sixth Ring Road would be regarded as one special "green belt" of the central city. All the land in the "green belt" was forced to keep their status in 2004 without any changes until 2020. Under this policy, the trend of central city to form a big pancake would be stopped, while the sub-cities in the region would develop very fast with many small and medium "pancakes" forming outside of the Sixth Ring Road, such as Changping, Huairou, Miyun, Tongzhou, and Daxing. It seems encouraging to implement such a strict policy to stop the current expansion of the central city. However, the actual situation will be complicated. On the one hand, driven by the large urban land demands, the central city has the high potential to expand into the current urban-rural fringe area. Compulsively stopping such expansion seems uneconomical and impossible due to its enormous policy executive cost. On the other hand, the fast development of sub-cities in the region also implies the vast loss of the high-yield agricultural land around these sub-cities.

Fig. 9 shows the scenario of urban patterns in Beijing from 2007 to 2020, if the expansion were controlled simultaneously by policies that restrict development in the high-yield agricultural land and the "green belt". In the scenario, all the land in the "green belt"

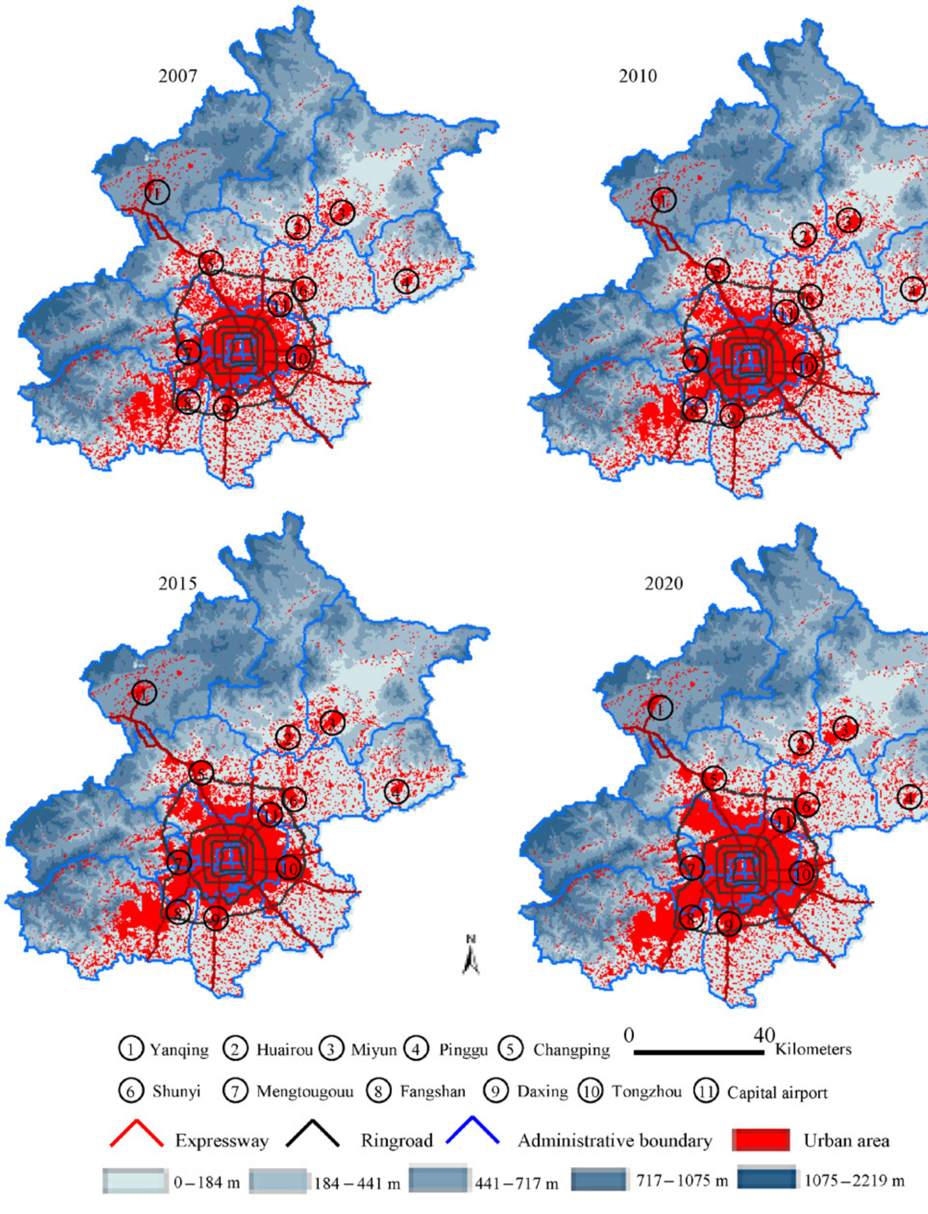

Fig. 6. Urban expansion scenario in Beijing from 2007 to 2020 without the restriction of urban planning policy.

would keep their status in 2004 and the high-yield farmland protection area in the plain would not be occupied by urban expansion. The simulated results showed that the trend of central city to form a big "pancake" would be stopped. In addition, the expansion of the sub-cities, such as Shunyi, Changpin, Miyun and so on, would also be limited because they are surrounded by high-yield cultivated land. As a result, the urban land outside of the Sixth Ring Road would be forced to develop fast to satisfy the urban land demand, causing

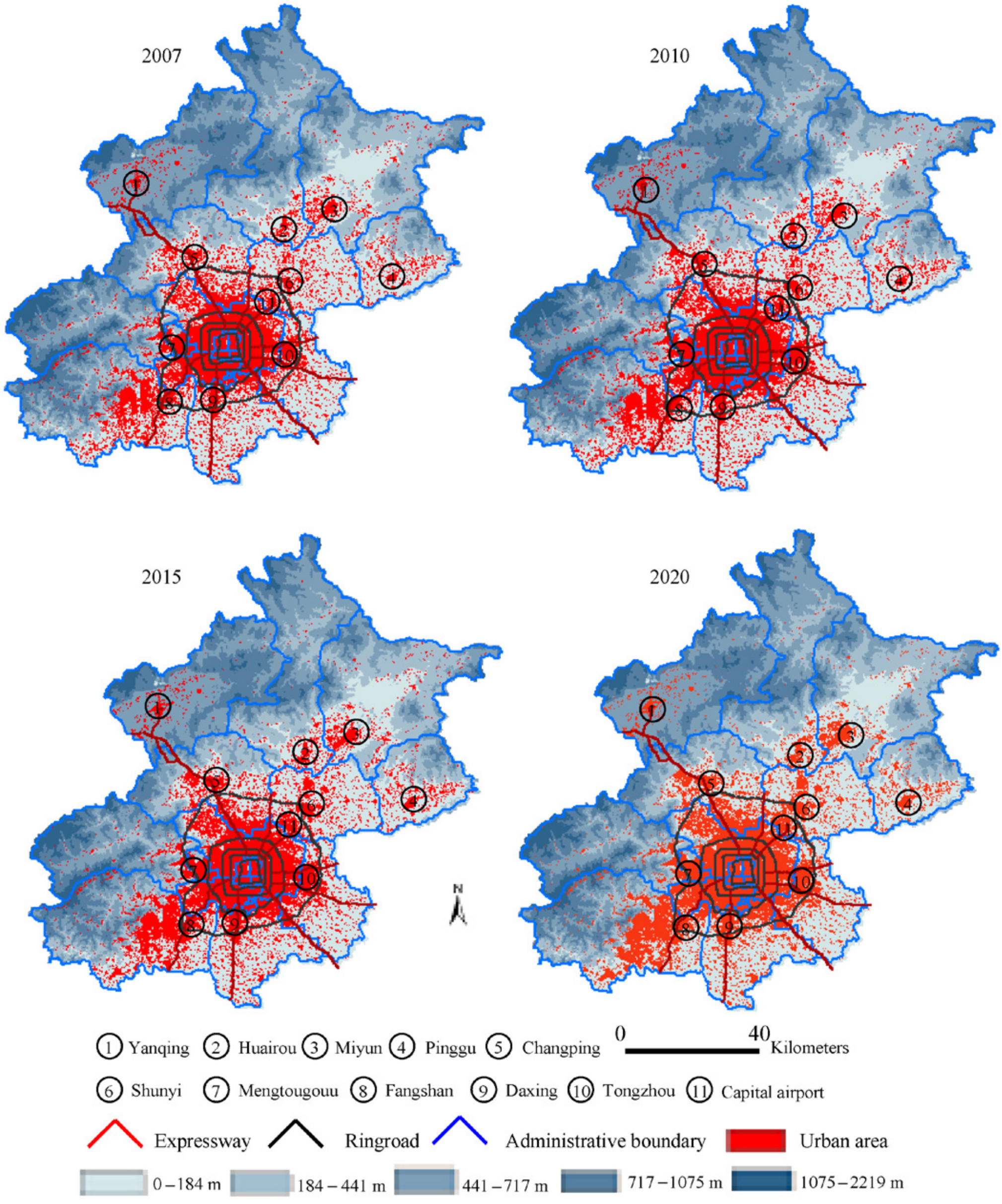

Fig. 7. Urban expansion scenario in Beijing from 2007 to 2020 under the restriction of high-yield farmland protection area.

many small "urban patches" to appear far away from central city, especially in the south edge of Beijing. Such urban expansion pattern also has its problems. Apart from its enormous policy executive cost, the development of many small towns far away from central city would be economically inefficient due to the ignorance of the agglomeration effect of the central city.

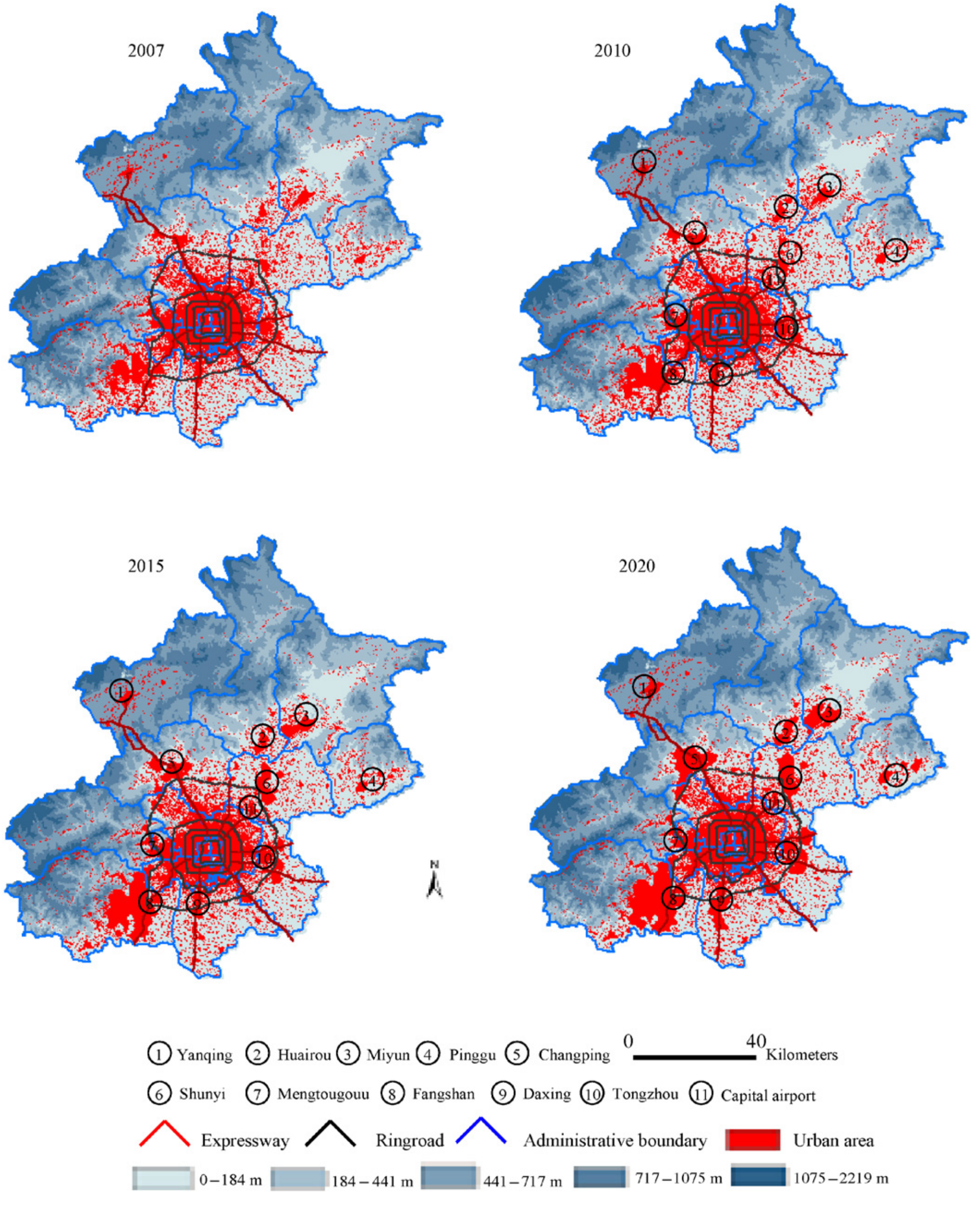

Fig. 8. Urban expansion scenario in Beijing from 2007 to 2020 under the restriction of the "green belt".

The simulating results provide planners the possibilities of urban expansion as driving by economic and social forces and restricted by planning policies. In summary, there exists a big dilemma of the continuous urban expansion versus limited water resource and environment deterioration in Beijing. Effective measures should be taken to deal with the dilemma so that Beijing's development can be sustainable. Under the heavy pressure from

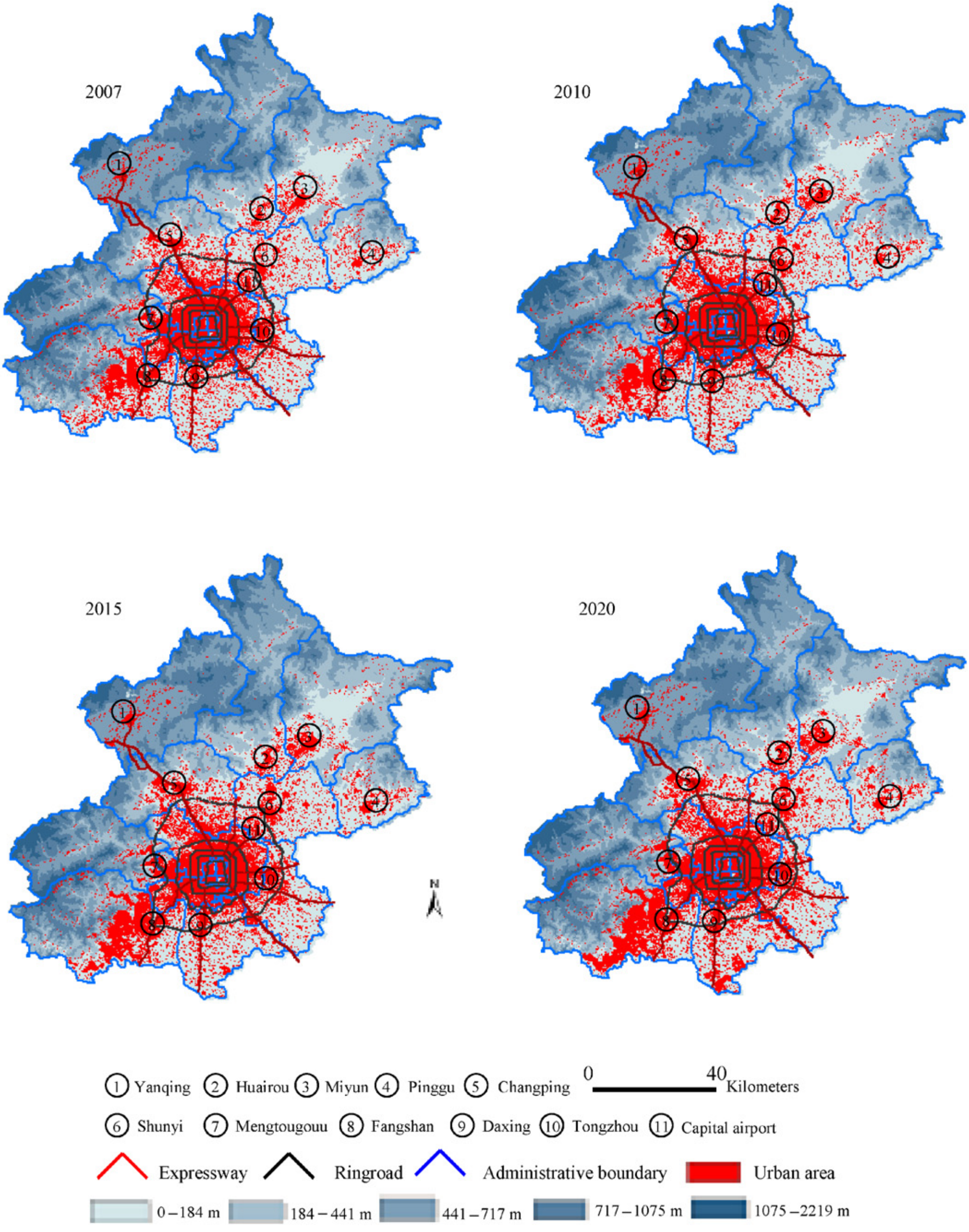

Fig. 9. Urban expansion scenario in Beijing from 2007 to 2020 under the restriction of both the "green belt" and high-yield farmland protection area.

the steady population increase and fast economic development, the possibility of continuous urban expansion into the urban–rural fringe to form one big "pancake" seems very high. Though thorough discussions of the policies to confront such dilemma is far beyond the scope of this paper, the UES model provided one convenient way to spatially and explicitly examine and analyze the related policies. Furthermore, many urban land planning policies that focus on the areas within the administrative boundary of Beijing is insufficient to deal with the dilemma since the supporting ability of the land and water resource in Beijing were almost exhausted after its fast development over the last two decades. Future policies may have to look beyond the administrative boundary.

Conclusion and Discussion

Land use models are useful tools to understand the land use process and support land use planning and policy making. Spatially explicit urban expansion models that can effectively trace the urban development in the past and predict the possible expansion scenarios in the future are still indispensable. This paper presented a newly developed UES model by coupling one "bottom-up" CA-based model and one "top-down" SD-based model. Within the UES model, the SD model is used to predict the urban LDSs, considering such broad-scale factors as water resource, population, and economic development; and the CA model is used to spatially and explicitly model the urban expansion patterns to keep the balance of the urban land demand and supply. The UES model differs from existing models in that it can not only reflect the complicated factors influencing urban expansion at the macroscopic scale but also possess strong ability to represent land use evolution at the local scale. In addition, as a tool that aims at implementing "what-if" scenario analysis of urban expansion, it is convenient for the UES model to simulate the many UESs in the near future. Therefore, the UES model contributes to the need for planning-based visualization and decision-support tools.

The current UES model has two loosely coupled modules: the LDS module built upon SD and the LUA module built on CA. It is worthwhile to further develop a tight-coupled model based on the same idea of integrating SD and CA models. It would be interesting to research the possibility of incorporating spatial models into SD so that it can deal with the locational aspect that is currently handled by the CA model. On the other hand, incorporating the land demand and supply module directly into CA also makes a promising future project.

According to the simulation of urban evolution in Beijing from 1994 to 2004 and the prediction of the urban expansion patterns from 2004 to 2020, there exists a big dilemma of the continuous urban expansion versus limited water resource and environment deterioration in Beijing. Water shortage is becoming a main constraint to Beijing's sustainable development. The possibility of the continuous urban expansion in the urban–rural fringe to form one big "pancake" is very high. Urban land planning policies that focus on only the areas within the administrative boundary of Beijing are limited in their capabilities. Dealing with such a dilemma in Beijing remains a big challenge for the local government. The possible way may be to reduce the discrepancy between Beijing and its neighboring cities, for example, Tianjin. It may be time for Beijing to transfer part of its economic responsibility to the neighbor cities according to the jointly regional development of the macroscopic region of Beijing, Tianjin and Hebei province.

However, urban expansion is a complicated issue that is determined by the interactions in space and time of biophysical factors and human factors at different scales. As pointed out by Verburg, Veldkamp, and Fresco (1999), the scenario-based results from the UES model should not be interpreted as forecasts of future events. Rather, they just indicate possible patterns of urban expansion under the different "what-if" scenarios. In fact, the exploration of possible urban expansion patterns and the identification of 'hot spots' can be seen as an instrument to support urban land planning policy. It can also be used as a tool for understanding the possible impacts of urban expansion on terrestrial ecosystem. In this respect, the UES model can be seen as an essential planning-based visualization and decision-support tool.

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