A Constrained CA Model for Planning Simulation Incorporating Institutional Constraints

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Abstract In recent years, it is prevailing to simulate urban growth by means of cellular automata (CA in short) modeling, which is based on self-organizing theories and different from the system dynamic modeling. Since the urban system is definitely complex, the CA models applied in urban growth simulation should take into consideration not only the neighborhood influence, but also other factors influencing urban development. We bring forward the term of complex constrained CA (CC-CA in short) model, which integrates the constrained conditions of neighborhood, macro socio-economy, space and institution. Particularly, the constrained construction zoning, as one institutional constraint, is considered in the CC-CA modeling. In the paper, the conceptual CC-CA model is introduced together with the transition rules. Based on the CC-CA model for Beijing, we discuss the complex constraints to the urban development of , and we show how to set institutional constraints in planning scenario to control the urban growth pattern of Beijing.

Keywords urban model; constrained condition; non-construction area; cellular automata; spatio-temporal complex; urban planning; Beijing

1. Introduction

With the development of GIS and complex adaptive systems, urban models based on artificial life or discrete dynamics have become an important area of academic research. In recent years, this approach has been used to simulate urban growth by means of cellular automata (CA) modeling which is based on self-organizing theories that are different from the traditional system dynamic approaches.

Unlike the pure CA models, the CA models used to simulate urban growth should take into consideration not only the influence of neighborhoods, but also other factors that represent the complexity of urban system development. Generally, these transition rules are defined as constrained conditions (White, 1997). A number of researchers have used constrained conditions on a CA model to simulate urban growth (see, for example, Clark and Gaydos, 1998; White et al 1997; Engelen et al 1997; Wu 1998; Ward et al 1999 and 2000; Li and Yeh, 2000; Yeh and Li, 2001; David et al 2000; White et al 2004; Alkheder and Shan 2005; Guan et al 2005; Zhao and Murayama 2007; Liu et al 2007).

The constrained conditions introduced in CA urban models can be classified into three types: macro socio-economic constraints, spatial constraints, and institutional constraints. The macro socio-economic constraints represent the macro-level factors such as economic development and population control which constrain the amount of construction land in the simulation. The spatial constraints represent local conditions such as accessibility of high density residential area or public facilities. The institutional constraints represent government policies such as urban development plans, zoning controls, and natural area protection regulations. The CA urban models rarely consider all the three types of constraints simultaneously. In particular, the existing CA models generally pay less attention to institutional constraints, and these constraints are often simply defined if they are included. The role of institutional conditions in past urban growth is also not identified, making the models an overly subjective process that does not adequately represent the historical trends. Furthermore, specific institutions and policies cannot be simulated in detail because they are either ignored or represented by overly simplified modeling constraints.

This paper introduces the concept of complex constrained CA (CC-CA) modeling, which integrates the macro socio-economic, spatial and institutional constraints into a CA model, in particular with land-use planning and zoning as institutional constraints. Planning is represented by 110 construction constraint factors (CCFs) related to natural resources protection and hazard prevention that constrain urban development (Long et al, 2006). If these 110 CCFs are not considered in the process of managing urban growth, protected natural areas will be encroached upon to some degree and environmental hazards will be encountered. However, in a CC-CA model, the role of these factors constraining urban growth in different historical phases can be identified and compared, allowing urban growth to be simulated under the influence of different constraints.

In section 2 of this paper, a conceptual CC-CA model is introduced along with its transition rules. In section 3, the CC-CA model for Beijing is developed and the complex constraints are discussed. Section 4 describes the process of using the institutional constraints to control the urban growth of Beijing. The paper is summarized in the final section along with a discussion on further research on the CC-CA modeling.

2. Research approach

2.1 Conceptual Model

Hedonic price models assume that commodity prices are determined by the total utility of their various properties, and the price variation reflects the composition of commodity properties (Lancaster, 1966). For example, Butler (1982) holds that housing prices are affected by three types of factors – location, building and neighborhood – and the price reflects the total preferences of consumers. Similarly, urban development is an index of real estate prices, as perceived by the developer of a particular parcel or block. Recognizing this, the following spatial variables are used in the CC-CA model:

(1) LOCATION as a spatial constrained condition: the minimum distance to urban or town centers of different administrative hierarchy (for Central City, *d_tam*, namely Tiananmen square; for important new cities, *d_vcity*; for other new cities, *d_city*; for important towns, *d_vtown*; for other towns, *d_town*), to wetlands (*d_river*), to regional roads (*d_road*), to township divisions (*d_bdtown*), and to the attractions of Greater Beijing (*f_rgn*);

(2) NEIGHBOR as a spatial constrained condition: the development intensity in the neighborhood, that is the number of urban built-up cells divided by total neighbor cells (*neighbor*);

(3) GOVERNMENT as an institutional constrained condition: the urban planning condition (*planning*), the cultivation suitability (*landresource*), the constrained construction zoning (*con_f*).

Among the above spatial variables, LOCATION and NEIGHBOR are both spatial constrained conditions, and GOVERNMENT stands for institutional constrained conditions, in which *planning* indicates the land-use scheme in the city master plan, signifying the land-use and urban morphology control policies of the government. Landresource denotes the cultivation suitability and can imply the cropland protection policies of the government. *Con_f* stands for the construction constraints counteracting urban growth and reflects the natural resources protection and environmental hazard prevention policies of the government. Generally, the institutional constrained conditions including *planning, landresource and con_f* are and will be effective and efficient measures for the government to control the urban growth.

The macro socio-economic constrained conditions are also included in the conceptual CC-CA model. In respect that population control, economic development have great influence on urban growth speed, the later can be reflected by some macro parameters such as GDP, urban population, average urban salary, communication cost, cropland productivity, industrial land area, etc. And through adjusting the macro-level urban policies, it is possible to alter the urban growth speed to control the urban growth pattern.

Based on the above analysis, a conceptual model of CC-CA is established as shown in formula 1. Generally, the status of one cell is determined by the status of its own in the last iteration, neighbor cells, and macro socio-economic, spatial and institutional constrained conditions. In this CC-CA model, the transition from non urban construction land to urban construction land is simulated, while other transitions arenot considered.

$$V_{i,j}^{t+1}=f\{V_{i,j}^{t},Global,Local\}$$
$$=\{V_{i,j}^{t},LOCATION,GOVERNMENT,NEIGHBOR\}$$
$$=f\left\{\begin{array}{l} V_{i,j}^{t}, \\ d\_tam_{i,j}, d\_vcity_{i,j}, d\_city_{i,j}, d\_vtown_{i,j}, d\_town_{i,j}, \\ d\_river_{i,j}, d\_road_{i,j}, d\_bdtown_{i,j}, f\_rgn_{i,j}, \\ planning_{i,j}, con\_f_{i,j}, landresource_{i,j}, \\ neighbor^{t}_{i,j} \end{array}\right\} \quad (1)$$

$V_{i,j}^{t}$ is the cell status at ij of time t

$V_{i,j}^{t+1}$ is of the cell status at ij of time t+1

f is the transition rule

2.2 Complex constrained conditions in status transition rule

MCE is implemented here to establish the status transition rules of the CC-CA model. MCE formatted transition rules have the capability to transparently include both the positive and negative influencing factors of urban growth within one framework. We use the methods of WU (2002) and Clark and Gaydos (1998) to retrieve their weights in the transition rules shown in formula 2.

$$S_{ij}^{t}=\beta_{0}$$
$$+\beta_{1}*d\_tam_{ij}+\beta_{2}*d\_vcity_{ij}+\beta_{3}*d\_city_{ij}+\beta_{4}*d\_vtown_{ij}$$
$$+\beta_{5}*d\_town_{ij}+\beta_{6}*d\_river_{ij}+\beta_{7}*d\_road_{ij}+\beta_{8}*d\_bdtown_{ij}$$
$$+\beta_{9}*f\_rgn_{ij}+\beta_{10}*planning_{ij}+\beta_{11}*con\_f_{ij}+\beta_{12}*landresource_{ij}$$
$$+\beta_{13}*neighbor^{t}_{ij}$$

$$P_{g}^{t}=\frac{1}{1+e^{-S_{ij}^{t}}}$$

$$P_{g}^{t}=\exp\left[\alpha\left(\frac{P_{g}^{t}}{P_{g\,max}^{t}}-1\right)\right]$$

$$if\ p_{ij}^{t}>p_{threshold}\ then\ v_{ij}^{t+1}=1$$

S_{ij}^{t}, the development suitability
β, the coefficient in logistic regression
P_{g}^{t}, the initial transition probability
$P_{g\,max}^{t}$, the max value of P_{g}^{t} in iteration t
P_{ij}^{t}, the final transition probability
$P_{\text{threshold}}$, the urban growth threshold
α, the dispersion parameter ranging from 1 to 10, indicating the rigid level of development

In the CC-CA model, all the spatial variables, except *neighbor*, are included in the logistic regression, and the corresponding coefficients, namely weights w^{1-12} in MCE, can be obtained. After that, the weight for neighbor (wN^*) can be calibrated out, by using the sole parameter looping method (MonoLoop) instead of looping all parameters' weights like Clark and Gaydos (1998) did. Various wN values are calibrated to find wN^* with the best matching index while keeping obtained w^{1-12} as constant.

Then, wN^* retrieved accomplishing with w^{1-12} are input in the transition rules to simulate urban growth form. *Goodness-of-fit* (accuracy of point to point comparison, *GOF* in short) is selected to assess the matching degree between the simulated and the observed urban forms, and its maximum value in theory is 100%. On the one hand, the method combining logistic regression and MonoLoop can reduce the calibrating time greatly; and on the other hand, it is able to identify the actual trends of urban growth in the past (details regarding transition rules are available in Long et al, 2008).

3. Model application

3.1 Study area

Under the background of the booming domestic economy and Olympic economy in Beijing, it is in great need of identifying the future urban form of Beijing. Hence, we develop a CC-CA model for Beijing metropolitan area covering an area of 16410 km^2 with a spatial resolution of 500m. The model is based on ESRI ArcObjects 9.0 and Visual Basic 6.0, attempting to simulate the urban growth scenarios under various complex constrained conditions.

Beijing metropolitan area lies in north China, to the east of Shanxi altiplano and to the south of Inner Mongolia altiplano. Its southeastern part is plain, 150 km away from the Bohai sea (see Fig. 1), and it has an mountainous area of 10,072 km^2, which is 61% of the whole. In 2006, it had a GDP of 787 billion, a total population of 15.81 million, and an urban built-up area of 1,324 km^2.

3.2 Date of complex constraints

We classify the spatial data in the CC-CA model into six types, i.e., LANDUSE, CONSTRAIN, LANDRESOURCE, PLANNING, LOCATION, and SOCIO-ECONOMY.

3.2.1 LANDUSE

The data of Land-use is of the years 1986, 1991, 1996, 2001 and 2006, and is classified into six land-use types, that is urban construction land, rural construction land, farmland, forest and vacant land. In the model, all the land-use types, except urban construction land, are

Fig. 1 Studied area for CC-CA modeling: Beijing Metropolitan Area
Source: GIS generated.

merged as non-urban construction land, since the competing land-use simulation is not considered in the model.

3.2.2 CONSTRAIN

The 110 CCFs are included in the Constrain data to signify the urban growth control condition (complex constraints are discussed in Long et al (2006) in detail). The CCFs can be classified into 17 types as follows: wetland protection, water source protection, groundwater overexploitation prevention, flooding control, steep area, green land protection, green belt, cropland protection, historical relic protection, geological vestige protection, geological condition for engineering, seism prevention, geological disaster prevention, centralized treatment facility prevention, radiation pollution prevention, civil infrastructure protection, and noise pollution prevention.

According to the current laws, legislations, and standards of China, the CCFs can be congregated into three zones (see Fig. 2): Non-construction Area (7,130.1km^2), Restricted Construction Area (8,697.4km^2), and Construction Area (527.1km^2). All the urban and rural constructions are forbidden in the Non-construction Areas, and urban constructions are restricted in terms of scale, type, height, or density in the Restricted Construction Areas.

For the reason of the large amount of CCFs in Constrain, one factor always overlaps with others. Thus, we synthesis all the CCFs into one Unified Analysis Zone (UAZ in short) layer, so as to conduct further analysis (see Fig. 3). It means that the points within one UAZ have the

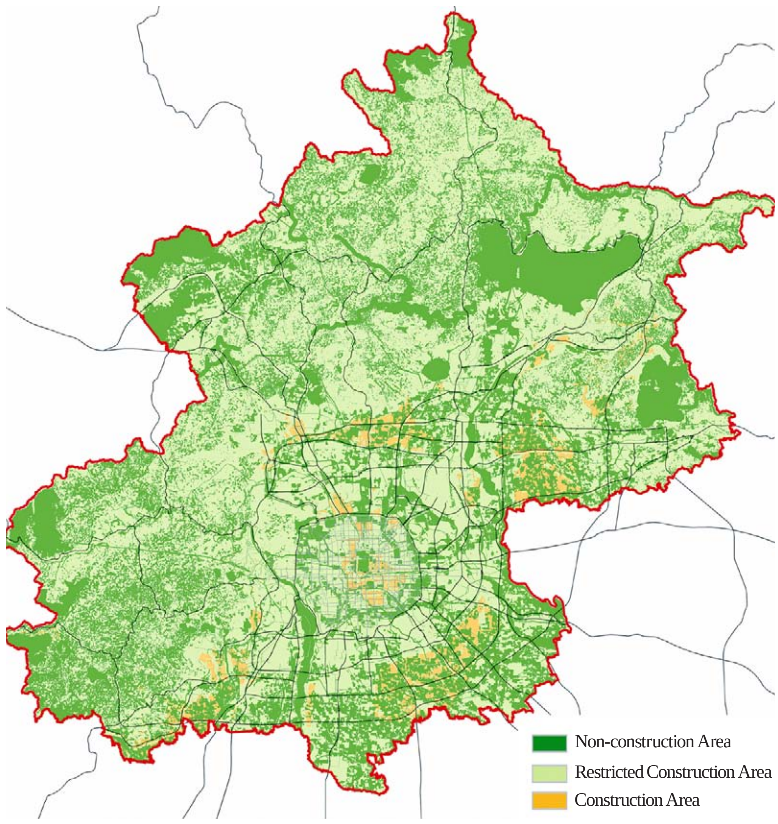

Fig. 2 Spatial distribution of CONSTRAIN
Source: GIS generated.

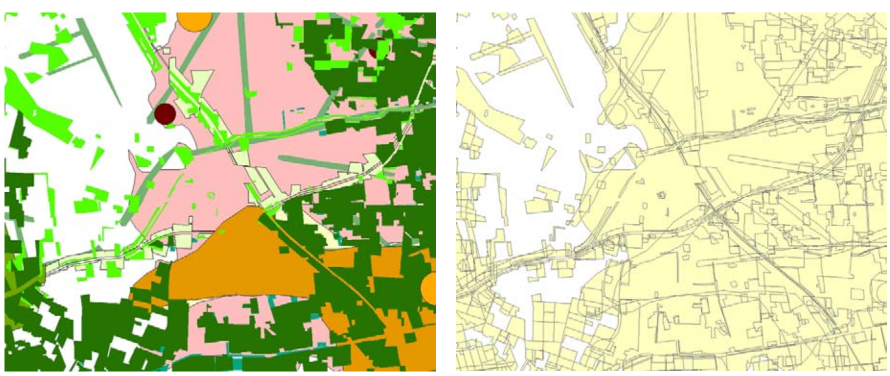

Fig. 3 CCFs (left) and corresponding UAZ (right) in some area
Source: GIS generated.

same spatial distribution conditions as all the 110 factors.

The index showing the degree of construction restriction is put forward after the zoning process, considering that one factor may differ from other factors, although they may reflect the same construction constraints, not to speak of the UAZs under different construction constraints defined by different CCFs set. For instance, regarding the Restricted Construction Area, UAZ1 contains CCF a, b, and c, while UAZ2 contains CCF a, b, c, and d. From the view of zoning condition, they are same; however, the restriction degree for UAZ2 is definitely greater than that for UAZ1, for there is one more CCF for UAZ2. Construction restriction index supplies the possibility to simulate more detailed and practical construction constrained conditions.

In addition to the zoning and index approaches, the construction restriction zoning for each type of urban land-use, including residencel, commerce, industry, etc., are done in view that the construction constraints vary for different types of urban land-use. This provides a fundamental support to simulating the competing land -uses in the further research.

In the model, we regard the Non-construction Area as one of the institutional constraints, namely, variable *con_f* (the Restricted Construction Area is not included because the correlation coefficient between it and *con_f* is -0.936, meaning negative correlation). The greater the *con_f* is, the more Non-Construction Areas will be encroached during the urban growth. Meanwhile, for the government, it should control the urban growth by means of setting more national parks, eco-protected areas, etc. to change the spatial distribution of the Non-construction Areas.

3.2.3 LANDRESOURCE

It stands for the cultivation suitability which is classed into eight categories ranging from 1 to 8, with 1 for most suitable and 8 for least suitable. The variable landresource obtained from LANDRESOURCE involving the factors of soil, climate, terrain, etc. can represent an objective evaluation on the cultivation suitability. According to our analysis, the most cultivable land lies in the central plain area, the southeastern Changping District, and the Yizhuang New City where the main existing urban built-up area stands. It is clear that the current urban growth overlaps the best cropland in its spatial distribution. Accordingly, the cropland protection policy can also be reflected by using the same kind of analysis on institutional constraints; and the more attention the government pays to cultivable land, the less cropland will be encroached by urban growth.

3.2.4 LOCATION

It stands for the location conditions, and the variables *d_tam, d_vcity, d_city, d_vtown, d_town, d_river, d_road, d_bdtown, f_rgn* are retrieved from Location.

3.2.5 PLANNING

The variable planning is retrieved from PLANNING which refers to the five City Master Plans of Beijing made in 1958, 1973, 1982, 1992 and 2004 respectively and is classified into urban construction land and non urban construction land (see Fig. 4). For the government, the planned urban construction land will mean more opportunities of development if the urban planning policies, as institutional constraint, are strictly implemented. In addition, the government is capable to control the urban growth pattern through adjusting the urban planning scheme.

3.2.6 SOCIOECONOMY

The data of population, resources, environment, economy and society since 1952 are included in SOCIOECONOMY in order to identify the relationship between the amount of urban construction land (or the annual urban growth) and various macro socio-economic constraints.

4. Planning scenarios

4.1 Complex constrained conditions in history

The spatial variables in different historical phases are available via logistic regression, thus providing preconditions for identifying and comparing the complex constrained conditions in various development phases. Furthermore, the calibrated parameters can be applied in the simulation as input parameter, which is the fundamental work for model application.

The transition rules of urban growth in various historical phases, i.e. 1986 – 1991, 1991 – 1996, 1996 – 2001, and 2001 – 2006, can also be acquired by logistic regression. According to the logistic regression, the variables *d_tam, d_vcity, d_city, d_vtown, d_town, d_bdtown*, landresource, *con_f*, and *f_rgn* do not vary in historical phases, while the variables planning, *d_road*, and the dependent variables vary from time to time. The coefficients of logistic regression in different historical phases are shown in Table 1.

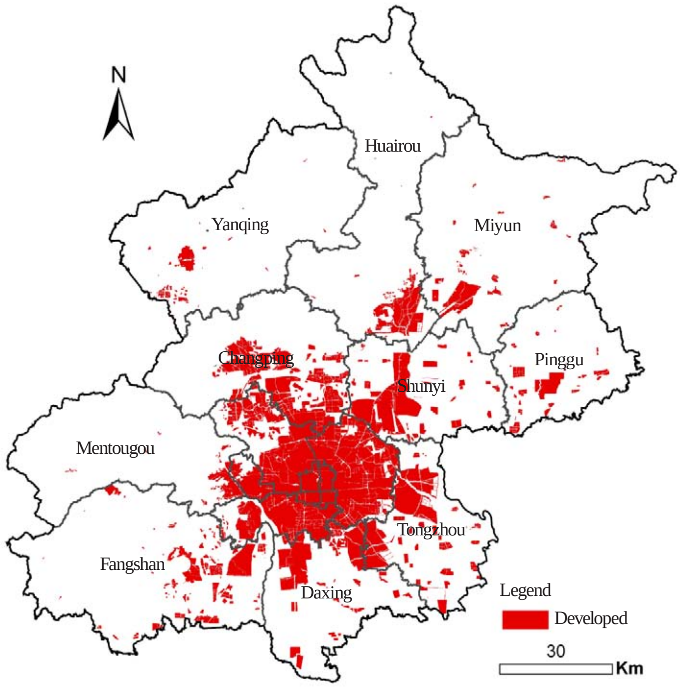

Fig. 4 Spatial distribution of PLANNING 2004
Source: Beijing municipal planning committee et al, 2006.

Table 1 Coefficients of logistic regression in various historical phases

Variable	B (2001 – 2006)	B (1996 – 2001)	B (1991 – 1996)	B (1986 – 1991)
d_tam	-0.000016*	-0.000035*	-0.000041*	
d_vcity	-0.000025*	-0.000031*		-0.000031*
d_city	-0.000019*	-0.000066*	-0.000033*	
d_vtown			0.000025*	0.000058*
d_town		0.000089*	0.000066*	
d_river	-0.000138*			
d_road	-0.000256*	-0.000804*	-0.000524*	-0.001092*
d_bdtown		-0.000377*		
f_rgn	4.302458*	-13.737258*		
Planning	-0.410472*	0.254173	0.575671*	1.310654*
con_ f	-0.521103*	-0.453115*	-0.497453*	-1.506241*
Landresource			-0.075543	-0.233262
Constant	-0.174524	0.588961	-0.998267*	-3.610055*

*Significant at 0.001 level.

Comparing the dominant factors shown in Table 1, it is clear that, in different phases, the mechanism of urban growth is quite different and the roles of market and government also vary. The variable $w^{planning}$ keeps positive except in the phase 2001-2006 and reaches its maximum value in the phase 1986 – 1991, representing the variation of various institutional constraints in different phases. For example, in the early stage of socialist market economy, urban planning played a leading role in urban growth; however, with the introduction of market mechanism into China, the leading role of urban planning was partially replaced by market factors. The variable w^{con_f} remains negative, with its absolute value reaches the peak in the phase 1986 – 1991, which shows that the protection was mostly strengthen in that phase; and in recent years, the role of protection on urban growth remains steady and has effectively influenced the urban growth process. Additionally, the variable $w^{landresource}$ was positive in the phase 1986 – 1991, while not significant after 1996, signifying that the cultivable land does not play an essential role on urban growth and urban growth has encroached the cultivable land in these years.

The coefficients in the logistic regression can be helpful to simulate the short-term and long-term urban growth. This can be seen from the explanation on the urban growth scenario based on the current development trends.

4.2 Basic scenario based on current development trends

As it is known, 2020 is the ending year of the new City Master of Beijing drafted by Beijing Municipal Planning Committee, and 2049 is the centennial of Beijing as the capital of China. To prepare for the next round of urban planning of Beijing, it is necessary to predict the urban form from 2020 to 2049, especially the situation in 2049. It will be more accurate to predict Beijing's urban form in 2049 basing on the planned urban form in 2020, rather than the observed urban form in 2006. In China, land development is controlled by the governments by means of urban planning, and the planned urban form can explain most of the urban development activities which are mostly located in the planned urban areas. Therefore, it is reliable to forecast the long-term urban growth based on the planned urban form of a certain middle year, so as to reduce the uncertainty of long-term forecasting.

The basic scenario of Beijing's urban form in 2049 is generated based on the assumption that the annual urban growth speed keeps at 30 km^2 construction land per year along with the development trends in the period of 2001-2006, resulting in the urban built-up area of 3,412 km^2 or 13,650 urban built-up cells (see Fig. 5). It can be seen from the scenario that, in general, the urban growth takes place in a sprawling way centering on the Central City, with the main increase of urban construction land happening in the New Cities of Shunyi, Changping and Tongzhou. Moreover, the urban growth in the southern part of Beijing is a little bit slower than that in northern part, which can also be obviously observed in today's land-use map.

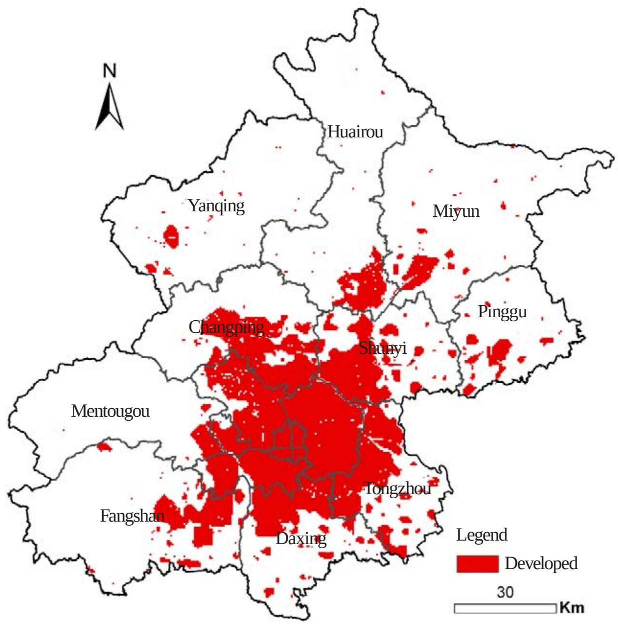

Fig. 5 Basic scenario of Beijing's urban form in 2049 based on the development trends in the phase 2001 – 2006
Source: Simulation result.

4.3 Scenario based on planning controls through adjusting complex constrained conditions

Based on the basic scenario mentioned above mentioned, it is possible to simulate the urban growth scenarios constrained by policies on population, economy, and so on by means of adjusting the macro socio-economic constrained conditions. The institutional constrained conditions can be set or changed, such as building the 7th ring road or setting new development areas, to simulate the corresponding urban growth patterns, and the intensity of policy implementation by governments as institutional constrained conditions can also be used to simulate the different urban growth scenarios with various development goals. Therefore, the scenario based on planning controls can be generated through adjusting the intensity of policy implementation as institutional constrained conditions, taking into consideration not only positive factors but also all kinds of constrained conditions to urban growth. Moreover, both the planning controls of governments and the actual urban development trends are involved to reflect the domestic urban growth circumstances.

In the scenario based on planning controls (see Fig. 6), the urban growth speed keeps the same as that in the basic scenario based on current development trends, and only some spatial variables are adjusted to reflect the intensity of policy implementation. In details, the intensity of policy implementation for Restricted Construction Area w_conf is increased to -2 (-0.521103 in the basic scenario based on current development trends), and that for urban planning w_planning to -3 (-0.410472 in the basic scenario based on current development trends), while the others remain the same as in the basic scenario based on current development trends. Generally speaking, the intensity of policy implementation as institutional constrained conditions is strengthened. Comparing the scenario based on planning controls with that based on current development trends, it can be seen that the urban construction land is more scattered, less natural reserves are destroyed, and environmental hazards might be reduced. It means that the scenario based on planning controls is a more sustainable urban growth pattern than that based on current development trends.

Four indicators are analyzed in order to compare the above two urban growth scenarios, that is the encroached Non-construction Area referring to "Conf", the encroached green belt referring to "Green", the encroached rural construction land referring to "Rural", and the urban sprawl degree referring to Moron I (see Table 2). It is shown that, in the scenario based on planning controls, there are, compared with the basic scenario based on current development trends, less ecologically sensitive lands encroached and there is a lower degree of urban sprawl, meaning that it is more sustainable than the later one.

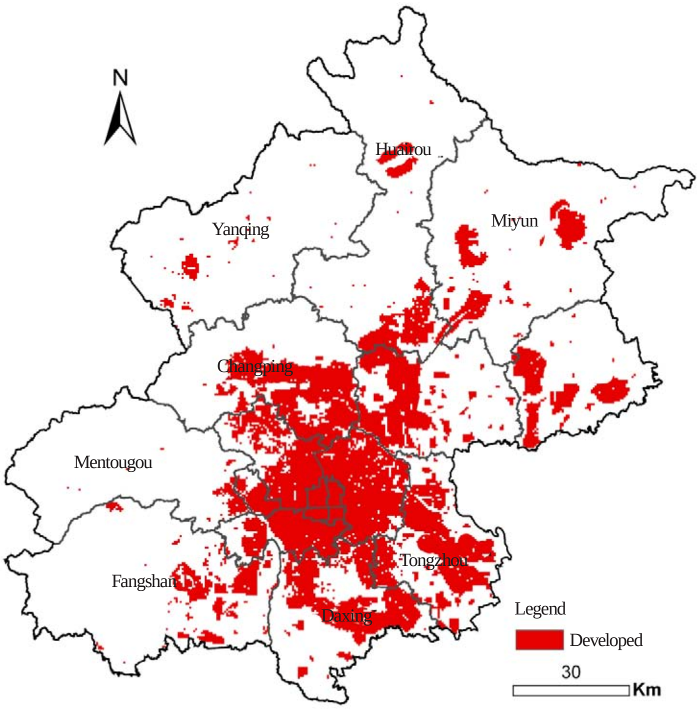

Fig. 6 Scenario based on planning controls
Source: Simulation result.

Table 2 Comparative analysis on the different scenarios (unit: km^2)

Scenario	Conf	Green	Rural	Moron I
Scenario based on planning scheme for 2020	538	1,128	169	0.14
Scenario based on current development trends	843	1,595	284	0.25
Scenario based on planning controls	765	1,181	248	0.13

5. Conclusions

The CC-CA urban model introduced in this paper includes the constrained conditions of macro socio-economy, space and institution, in particular with Restricted Construction Area as one institutional constrained condition. The 110 CCFs representing zoning, together with the variables reflecting the City Master Plan and cultivable land, make it possible to reflect the complex institutional constrained conditions for urban growth. The CC-CA urban model, integrating the complex constrained conditions into the classical CA urban model, is capable to simulate more practically and effectively the urban growth phenomenon/pattern in rapidly urbanizing areas, and can provide governments with a useful tool in urban policy decision-makings by means of scenario analysis.

In the application of the CC-CA model in Beijing metropolitan area, the role of complex constrained conditions in urban growth in various historical phases are dynamically identified by means of logistic regression, and the scenario based on planning controls is generated by highlighting the role of planning policy implementation based on the basic scenario in line with the current developing trends. It shows that the complex constrained conditions can be used to affect the urban growth process and to simulate more practically the urban growth pattern. However in our model, only the construction zoning is taken into consideration as one institutional constrained condition. In the further studies, more construction constraint index should be introduced into the CC-CA model to simulate the urban growth under more detailed constrained conditions, for example the competing land uses (e.g., residence, commerce, and industry) at the block scale through the construction constraint zoning on various urban land-use.

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