An urban model using complex constrained cellular automata: long-term urban form prediction for Beijing

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Abstract: In recent years, simulating urban growth using cellular automata (CA) has attracted extensive attention for investigating the dynamic urban system. Distinguished from the pure CA, the CA model applied for urban growth simulation should not only include the neighbourhood influence, but other factors related with urban developments. We proposed the term 'complex constrained CA' (CC-CA), which integrates constraints of neighbourhood, macro socioeconomic, spatial and institutional types. Particularly, the constructing constrained zoning planning, as an institutional constraint, is introduced into the CC-CA model. We applied the CC-CA model for the Beijing Metropolitan Area. Parameters of constraints are calibrated for various historical phases of Beijing, with which the baseline scenario with current developing trend is build to simulate the long-term urban form of Beijing. In addition, we set the planning controlled scenario via adjusting institutional constraints' parameters, and compare the results with the baseline scenario. The impact of institutional constraints on future urban form is then visualised for policy makers. The CC-CA is proved to have its policy implications for Beijing.

Keywords: constrained cellular automata; urban growth; Beijing; institutional constraint.

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1 Introduction

In this paper, we aim to propose an urban model based on complex constrained cellular automata (CC-CA) for predicting urban form in long term. Institutional constraints are introduced into our urban model for better reflecting the government policies, which are necessary for simulating urban growth process. With the development of geographical information system (GIS) and complex adaptive systems, urban models, based on artificial life or discrete dynamics, are dominating relevant academic researches. In recent years, simulating urban growth using CA, which is based on the self-organising theory and different from models using the system-dynamic approach, has been paid extensive attention.

Distinguished from pure CA, CA models for simulating urban growth should not only consider neighbourhood influence, but other factors with respect to urban developments in the context of the complex urban system. So constraints are introduced into CA for simulating a more practical urban growth procedure (White et al., 1997). For instance, an exclusive layer is set to constrain urban growth in SLEUTH (Clark and Gaydos, 1998). White et al. (1997) initiated the concept of constrained CA via taking spatial constraints into account. Engelen et al. (1997) took macro socio-economic constraint into account in a planning support system incorporating CA, GIS and other toolkits. In Simland developed by Wu (1998), constraints for land developments were also considered. Ward et al. (1999, 2000) employed physical constraints, geographic constraints and institutional controls, in addition to the macro socio-economic constraint. Li and Yeh classified all constraints into three types, local, regional and global (Li and Yeh, 2000; Yeh and Li, 2001). O'Sullivan and Torrens (2000) integrated macro socio-economic as global constraint. White, et al. (2004) employed not only macro constraint, but also physical characteristics, accessibility and zoning as constraints. Alkheder and Shan (2005) regarded rivers and lakes as constraints, similar to the exclusive layer in SLEUTH. In Guan et al.'s (2005) urban model using CA and artificial neural network (ANN), macro socio-economic and institutional constraints were introduced. Zhao and Murayama (2007) developed an urban growth model using CA for the Tokyo Metropolitan Area, in which suitability, zoning status and accessibility factors were included as constraints. Liu et al. (2007) developed a CA model based on niche, and applied it to simulate the sustainable land development of Guangzhou considering macro and spatial constraints.

Generally, constraints in CA urban models can be classified into three types, macro socio-economic constraints, spatial constraints and institutional constraints. The macro socio-economic constraints are used to control the total amount of urban built-up land in simulations. The spatial constraint indicates the location condition, such as the accessibility of residential areas or public facilities. The institutional constraint represents the government policies, such as the urban planning, zoning, and natural area protection. Among constraints in current CA urban models, it is not obvious for one model simultaneously to consider all these three types of constraints. Especially, less attention has been paid to institutional constraints by existing CA models, and institutional constraints are often set in an over-simplified manner. Furthermore, on the one hand, the role of institutional conditions in historical urban growth phases cannot be well identified, thus, calibrating the CA model in an over-subjective process without identifying historical trends. On the other hand, various specific institutional policies cannot be included in a detail way due to lacking of data in existing CA urban models. Therefore, we aim to bridge this gap in this paper via introducing more detailed institutional constraints into our CA model as well as calibrating their parameters.

Accordingly, in this paper we will propose the term 'complex constrained CA' (CC-CA) integrating macro socio-economic, spatial and institutional constraints. Particularly, the constructing constrained zoning planning, as one of institutional constraints, is introduced our CC-CA model. This planning is generated via combining 110 constructing constrained factors (CCFs) relevant to natural resources protection and hazard prevention (Long et al., 2006). Without taking above 110 CCFs into account during urban growth management, not only the natural protected area may be encroached in some degree, but also environmental hazard may take place. Supported by this CC-CA model, the role of constraints in urban growth can be identified and compared among various historical phases, thus, providing possibility to simulate urban form influenced by various constraints.

This paper is organised as follows. In Section 2, the conceptual model of the CC-CA model is elaborated together with the transition rule of CA. In Section 3, the CC-CA model for Beijing will be developed, and we will discuss the data for this model in Beijing. In Section 4, we will identify the effect of complex constraints in various historical phases, and apply the results to build up a baseline scenario with current developing trend followed by a planning controlled scenario strengthening implementation of institutional constraints. Finally, the concluding remarks will be summarised in the last section.

2 Approach

We use the hedonic approach for selecting variables related with urban growth process. The hedonic approach assumes that the commodity price is determined by the total utility of its various properties, and its price differs from the composition of commodity's properties (Lancaster, 1966). For example, Butler (1982) argued that three types of factors, the location, architecture structure and neighbourhood, affect residential price, which reflects the total preferences of consumers. With the same logic, the urban development process is quite similar to the real estate price, and its probability is the reflection of relevant parameters of the lot or block by developers. Therefore, we chose spatial variables in the CC-CA model as follows.

1 the location type of variables (spatial constraints): including the minimum distance to urban or town centres of various hierarchies (the main city, *d_tam*, important new city *d_vcity*, new city *d_city*, important town *d_vtown*, town *d_town*), to wetlands *d_river*, to regional roads *d_road*, to township divisions *d_bdtown*, and the attracting force by the greater Beijing area *f_rgn*

2 the neighbour type of variable (spatial constraint): corresponding to the developing intensity within the neighbourhood neighbour (the number of urban built-up cells divided by the total neighbour cells)

3 the government type of variables (institutional constraints): including the urban planning layout planning, the suitability for cultivation *landresource*, and the constructing constrained zoning *con_f*.

In the CC-CA model, the location and neighbour types of variables are both spatial constraints. The government type of variables stand for institutional constraints, in which *planning* indicates the land use scheme in urban master plan as a land development policy. *landresource* indicates the suitability for cultivation corresponding to the cropland protecting policy. With respect to *con_f*, it stands for the CCFs curbing urban growth, and provides it possibility to simulate natural resources protecting and environmental hazard preventing policies by the government. Generally, the three institutional constraints correspond to the urban growth management measures by the government.

Moreover, macro socio-economic constraints are also included in the CC-CA model. Since population control and economic development factors have great influence on the speed of urban growth, it can be reflected by some macro parameters, such as the GDP, urban population, average urban salary, communication cost, cropland product, as well as industrial land area. Through adjusting macro-level urban policies, the urban growth speed and total amount are both possible to be altered to regulate the future urban form.

The conceptual model of CC-CA using CA is expressed as follows:

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

where *i, j* (we use *ij* hereafter) is the location of a cell, $V_{i,j}^{\;t}$ is the cell status at *ij* of time *t*, $V_{i,j}^{\;t+1}$ is the cell status at *ij* of time $t + 1$, and *f* is the transition rule of the CC-CA model. Generally, the status of a cell is determined by itself status in the last iteration, neighbour cells, macro socio-economic, spatial and institutional constraints.

The multi-criteria evaluation (MCE) approach is implemented to establish the status transition rule of the CC-CA model. The MCE formatted transition rule has the capability to transparently include urban growth promoting and control factors within one framework. We integrate the methods of Wu (2002) and Clark and Gaydos (1998) to retrieve the weights in the transition rule as follows:

$$
\begin{aligned}
s_{ij}{}^{t} &= \beta_0 \\
&+ \beta_1 * d\_tam_{ij} + \beta_2 * d\_vcity_{ij} + \beta_3 * d\_city_{ij} + \beta_4 * d\_vtown_{ij} \\
&+ \beta_5 * d\_town_{ij} + \beta_6 * d\_river_{ij} + \beta_7 * r\_road_{ij} + \beta_8 * d\_bdtown_{ij} \\
&+ \beta_9 * f\_rgn_{ij} + \beta_{10} * planning_{ij} + \beta_{11} * con\_f_{ij} + \beta_{12} * landresource_{ij} \\
&+ \beta_{13} * neighbour^{t}{}_{ij} \\
p_g{}^{t} &= \frac{1}{1+e^{-s_{ij}{}^{t}}} \\
p_{ij}{}^{t} &= \exp\left[\alpha\left(\frac{p_g{}^{t}}{p_g{}^{t}{}_{\max}} - 1\right)\right] \\
&\textit{if } p_{ij}{}^{t} > p_{threshold} \text{ then } V_{ij}{}^{t+1} = 1
\end{aligned}
\tag{2}
$$

where s_{ij}^{t} is for the development suitability, β is coefficients in logistic regression, p_g^t is the initial transition probability, $p_{g\max}^{t}$ is the max value of p_g^t in iteration t, p_{ij}^{t} is the final transition probability, $p_{threshold}$ is the urban growth threshold, and α is the dispersion parameter ranging from 1 to 10 indicating the rigid degree for urban developments.

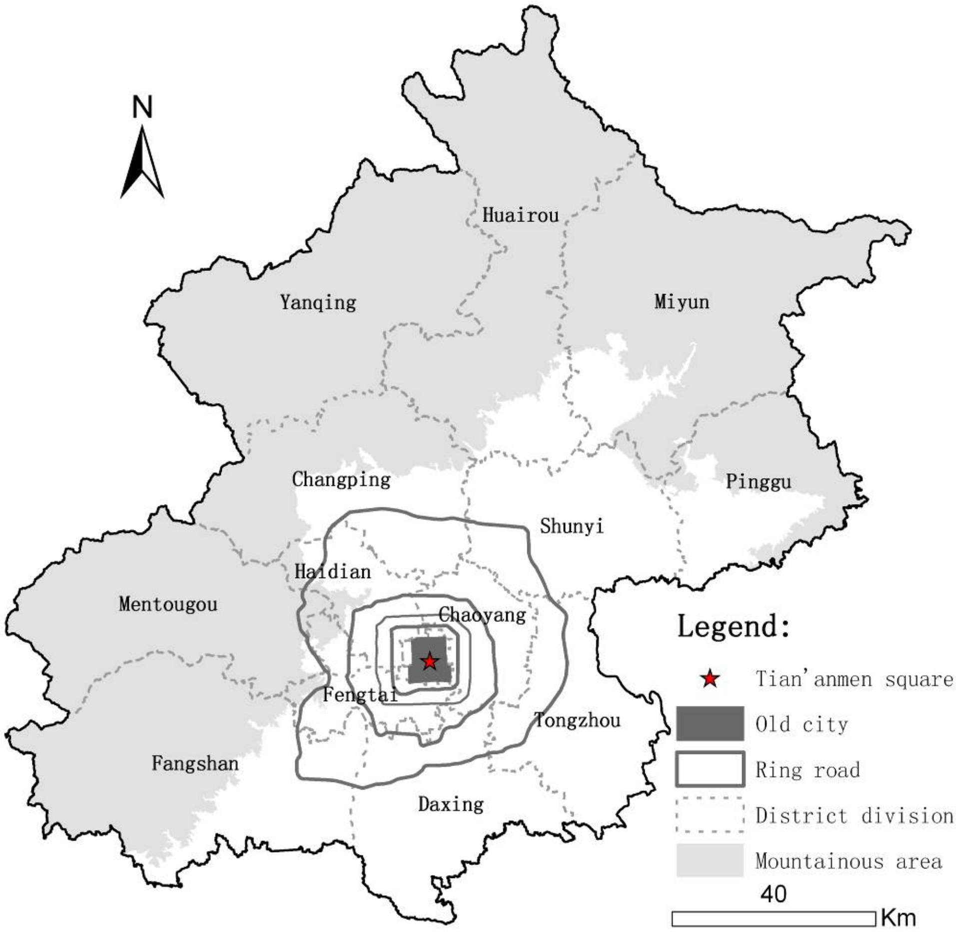
In the CC-CA model, all spatial variables, except *neighbour*, are included in the logistic regression, and the corresponding coefficients are obtained. After that, the weight for *neighbour* (*wN**) can be calibrated using the MonoLoop approach discussed in Long, et al. (2009) in detail, rather than looping all parameters' weights like Clark and Gaydos (1998). Various *wN* values are calibrated to identify wN* with the best matching index while keeping other spatial variables' weights constant. Then, all calibrated parameters are inputted into the transition rule of CC-CA to simulate the future urban form. The *goodness-of-fit* (GOF) indicator is selected to assess the matching degree between the simulated and observed urban forms, and its maximum value is 100%.

3 Study area and data

3.1 Study area

Under the boom of Chinese macro-economy and Olympic economy, there is a great need for predicting the long-term urban form in Beijing. Therefore, we developed the CC-CA model for the Beijing metropolitan area (see Figure 1) with an area of 16,410 km^2, and the model's spatial resolution is 500 m. The CC-CA model was implemented using ESRI ArcObjects 9.0 and Visual Basic 6.0. This model attempts to simulate urban growth scenarios influenced by various sets of constraints. The South Eastern part of the study area is plain, and is mountainous with an area of 10, 072 km^2 covering 61% of the whole region. The GDP was 787 billion, total population was 15.81 million, and urban built-up area was 1,324 km^2 in 2006.

Figure 1 The study area of CC-CA (see online version for colours)



3.2 Data

We classify spatial datasets in the CC-CA model into six types, including landuse, constrain, landresource, planning, location, as well as socio-economic.

1 Landuse

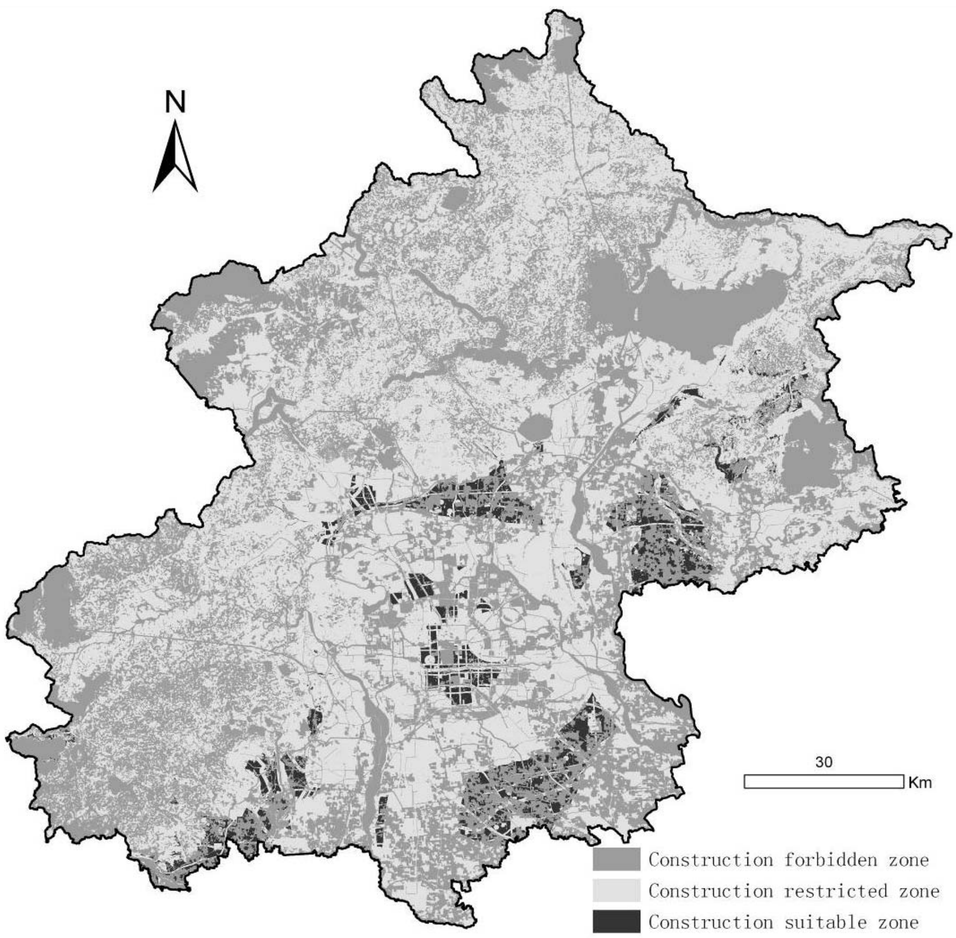
The time points of landuse cover 1986, 1991, 1996, 2001 and 2006. This data is classified into six land use categories, including the urban built-up area, rural built-up area, agriculture area, forest area and vacant area. In the model, all land use types except the urban built-up area type are merged as non-urban built-up areas since that competing land-use simulating is not considered in our presented model.

2 Constrain

Totally 110 CCFs are merged as the constrain layer to signify urban growth control conditions. Complex constraints are extensively discussed in (Long, et al., 2009). CCFs can be classified into 17 types in terms of administrative departments as follows, the wetland, water source protection, groundwater over-exploitation 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, pollutant centralised treatment facilities prevention, environmental radiation prevention, municipal infrastructure protection, and environmental noise prevention.

According to current laws, legislations, and standards of China, CCFs can be aggregated into three zones (Figure 2): the constructing forbidden area (7,130.1 km^2), constructing restricted area (8,697.4 km^2), and constructing suitable area (527.1 km^2). All urban and rural constructions are forbidden within the constructing forbidden area. Within the constructing restricted area, urban constructions and activities are restricted in terms of the constructing scale, type, height, as well as density. In this paper, we regard the constructing forbidden area as one of institutional constraints of the CC-CA model. This constraint is defined as the variable *con_f*.

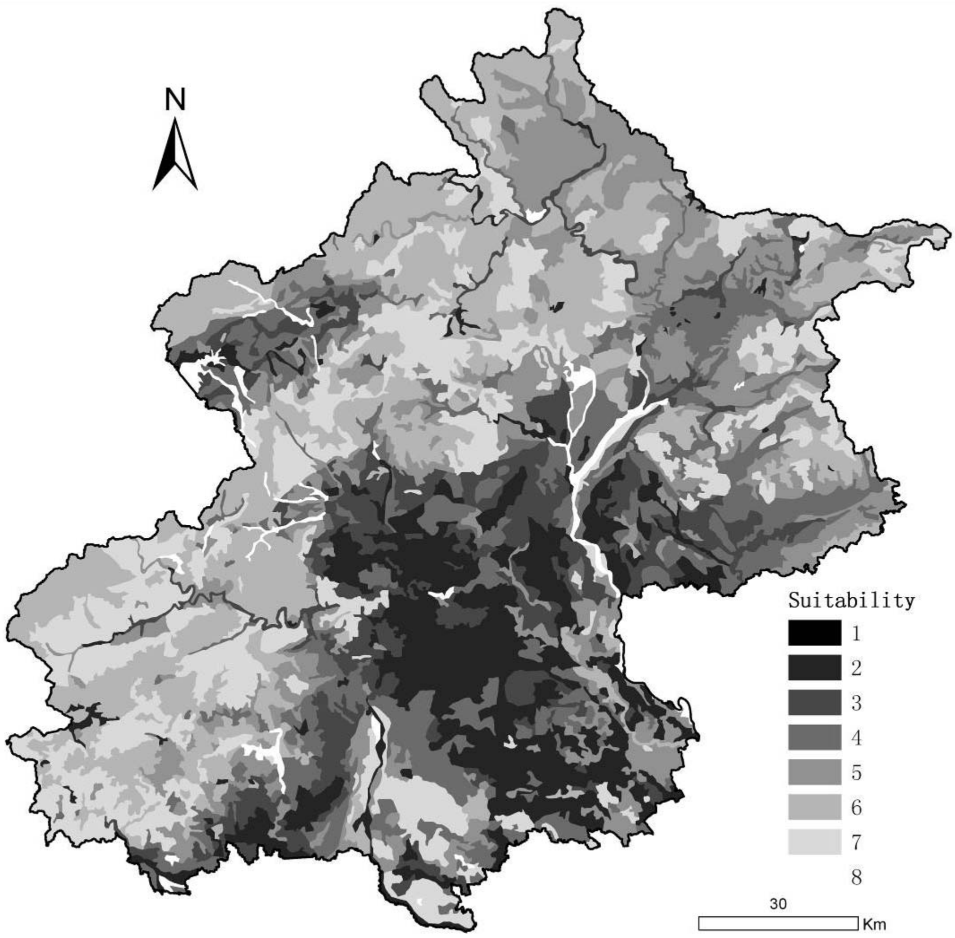
Figure 2 The spatial distribution of constrain



3 Landresource

It stands for the suitability of cultivation, which is classed into eight categories ranging from 1 to 8 (Figure 3), in which 1 stands for the most suitable while 8 for the least suitable. The variable *landresource* is obtained from the LANDRESOURCE data. The most cultivating suitable area lies in the central plain area, the South Eastern Changping district, and the Yizhuang New City. The cropland protection policy can be reflected using this institutional constraint. The more attention for suitable cultivating area paid by the government, the less cropland will be encroached by future urban growth.

Figure 3 The spatial distribution of landresource



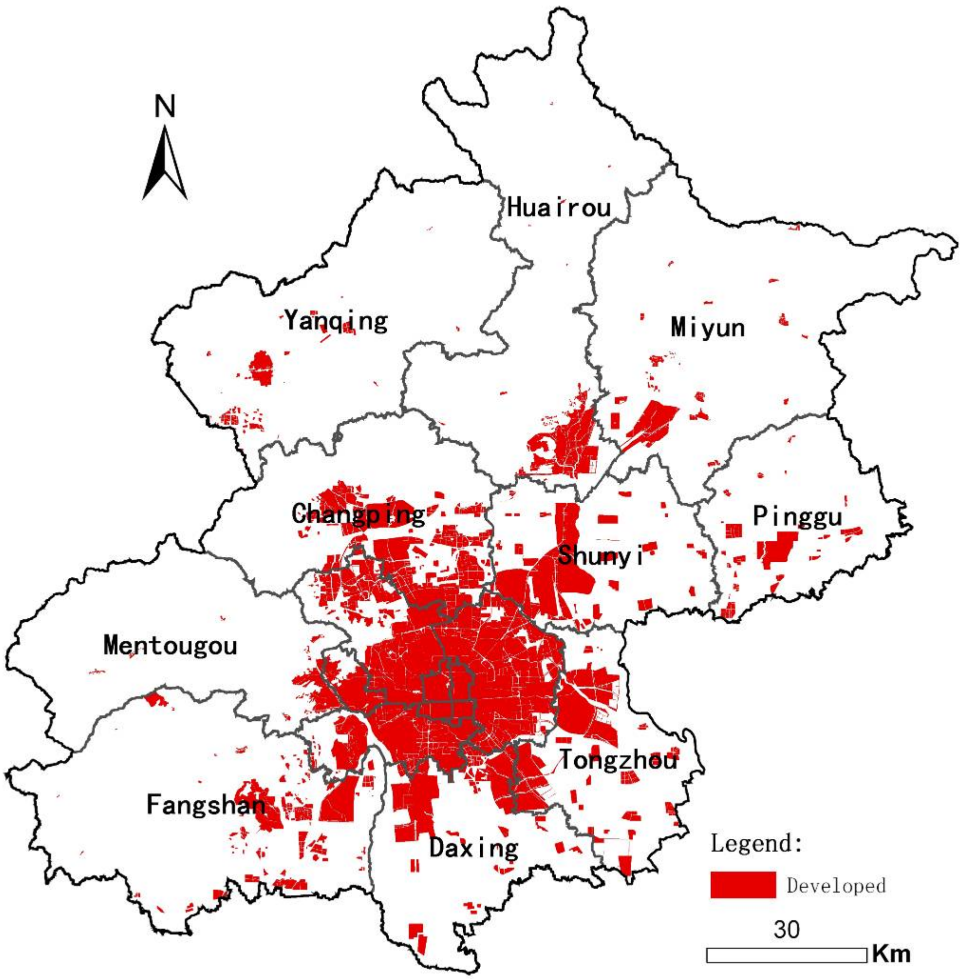
4 Location

It stands for the location condition. Variables *d_tam*, *d_vcity*, *d_city*, *d_vtown*, *d_town*, *d_river*, *d_road*, *d_bdtown*, and *f_rgn* are retrieved from the location data.

5 Planning

Five urban master plans for the Beijing metropolitan area were conducted since 1958 (Figure 4). They were issued in 1958, 1973, 1982, 1992 and 2004, respectively. These plans classified the whole region into urban built-up areas and non-urban built-up areas. The variable planning is retrieved from the planning data. Planned urban built-up lands will get more opportunities to be developed if the urban planning policy as one institutional condition is implemented with more intensity.

Figure 4 The spatial distribution of planning2004 (the urban master plan issued in 2004) (see online version for colours)



6 Socio-economic

The population, resources, environment, economy and society data since 1952 are included in the socio-economic data, which help identifying the relationship between the amount of urban built-up area (or annual urban growth amount) and various macro indicators as to setting macro socio-economic constraints.

4 Results

4.1 Complex constraints in various historical phases

The weights of constraints in various historical phases can be identified via the logistic regression approach, thus, providing a precondition to compare complex constraints among each other in various phases. Furthermore, the weights of constraints can be applied as the model's input parameters.

Urban growth rules in various historical phases can be acquired by the logistic regression, including 1986–1991, 1991–1996, 1996–2001, and 2001–2006. In the logistic regression, variables *d_tam*, *d_vcity*, *d_city*, *d_vtown*, *d_town*, *d_bdtown*, *landresource*, *con_f*, and *f_rgn* do not vary from historical phases. However, variables planning, *d_road*, and the dependent variable vary from each historical phase. The identified coefficients of the logistic regression in various historical phases are illustrated in Table 1.

Table 1 Coefficients of the logistic regression in various historical phases

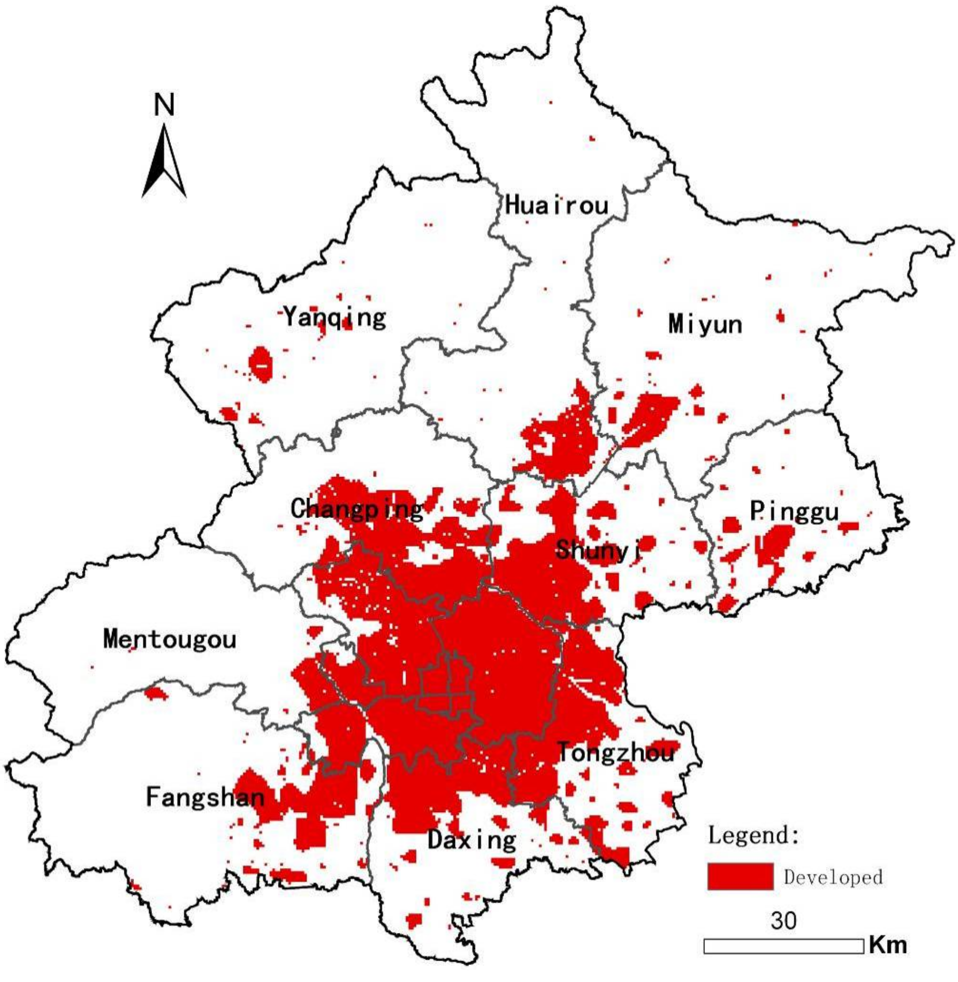
Variable	*B(2001–2006)*	*B(1996–2001)*	*B(1991–1996)*	*B(1986–1991)*
d_tam	–0.000016*	–0.000035*	–0.000041*	
d_vcity	–0.000025*	–0.000031*		–0.000031*
d_city	–0.000019*	–0.000066*	–0.000033*	
d_vtown			0.000025*	0.000058*
d_town		0.000089*	0.000066*	
d_river	–0.000138*			
d_road	–0.000256*	–0.000804*	–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*

Note: *Significant at 0.001 level

Comparing dominant factors in various historical phases listed in Table 1, it is clear that urban growth mechanisms differs from each phase to a great degree. In addition, market and government roles also vary in different phases. Generally, regional roads play an important role in promoting urban growth in all phases. Comparing the variation of institutional constraints in different phases, the weight of *planning* keeps positive except in 2001–2006, and reaches its maximum value in 1986-1991. In recent years, the effect of urban planning is fading, which reflects that in the first several years of the social-market economy, urban planning played a leading role in urban growth. However, with the introduction of market mechanism into China, the role of planning is being partially replaced by market factors. The weight of *con_f* remains negative, and its absolute value reaches its peak in 1986–1991 denoting that the protecting strength is the greatest in that phase. In recent years, its role in urban growth remains steady, and has effectively influenced the urban growth process. Additionally, the weight of *landresource* is positive in 1986–1991, while not significant after 1996, signifying that the cultivating suitable area did not play an essential role in urban growth.

The coefficients acquired from the logistic regression can be availed to simulate short-term and long-term urban growth. In the next sub-section, we will introduce the baseline urban growth scenario with current developing trend using identified coefficients.

Figure 5 The simulated urban form of the 2001–2006 trend scenario (see online version for colours)

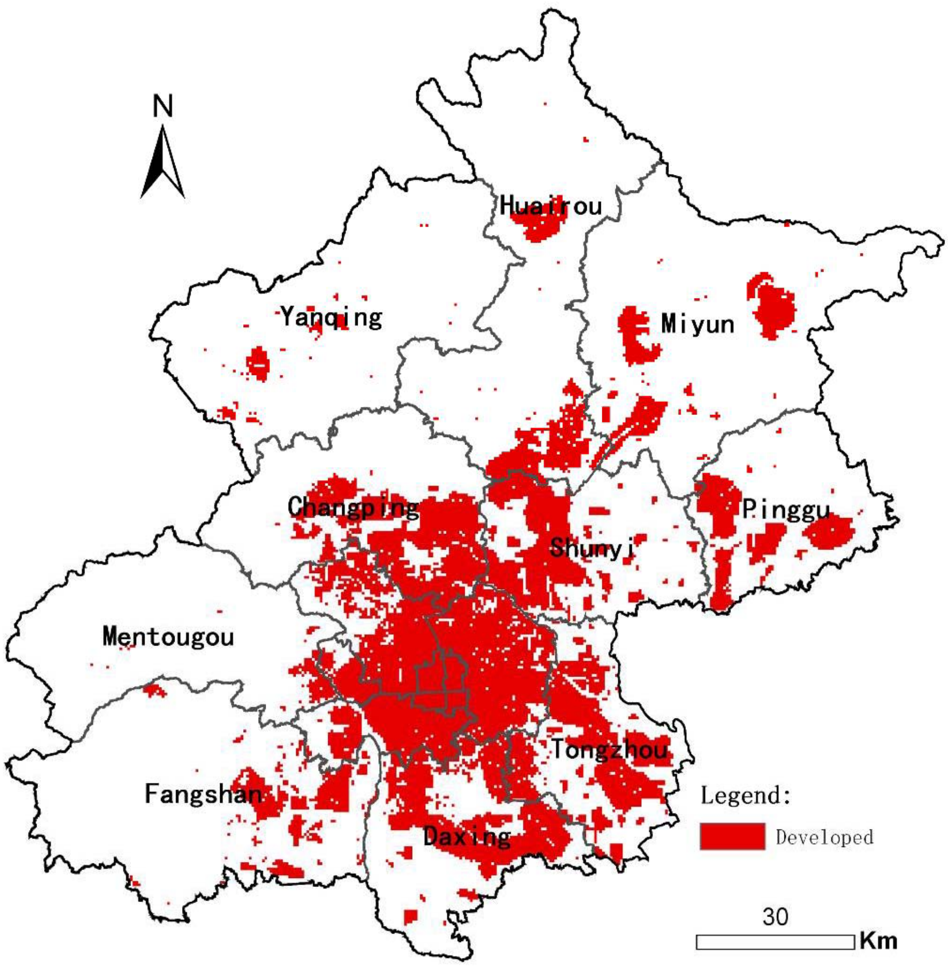


4.2 Baseline scenario with current developing trend

The year of 2020 is the ending time point of this round of urban master plan issued in 2004 drafted by the Beijing Municipal Planning Committee, and the year of 2049 is the century anniversary of Beijing as the capital of China. To prepare for the next round of urban master plan of Beijing, it is necessary to predict the urban form from 2020 to 2049, especially in 2049. It will be more accurate to predict the urban form of Beijing in 2049 based on the planned urban form of 2020 than based on the observed urban form of 2006, conditioning a higher probability for realising the planned urban form in 2020. In China, land developments are regulated by the government by means of urban planning, and the planned urban form can explain most of urban developments. Therefore, it is reliable to forecast long-term urban growth using planed urban form to reduce the uncertainty of long-term prediction.

The basis scenario for urban growth in 2049 is generated via setting the annual urban growth increasing scale as 30 km^2. Urban growth mechanism is supposed to be the same with that in 2001–2006. The simulated urban form for 2049 with current developing trend is illustrated in Figure 5. We can see that the urban sprawl phenomenon around the central city is quite obvious in the simulated urban form, and the main increased urban developments locate in new cities of Shunyi, Changping and Tongzhou. In addition, the southern part grows a little slower than that of the northern part, which is also obvious in the current urban form.

Figure 6 The simulated urban form of the planning controlled scenario (see online version for colours)



4.3 Planning controlled scenario through adjusting complex constraints

Based on the baseline scenario with current developing trend, other urban growth scenarios can be simulated via adjusting weights of complex constraints. For instance, adjusting the macro socio-economic constraint's weight can control the urban growth speed, while varying weights for spatial constraints can adjust the urban growth pattern. Besides, we can change institutional constraints, such as building the 7th ring road, setting a new development-promoting area, to simulate corresponding urban growth patterns. Meanwhile, the intensity for implementing various institutional conditions by the government can be used to simulate different urban growth scenarios with various development purposes.

The planning controlled scenario is generated through adjusting the intensity of implementing institutional constraints. The planning controlled scenario has the same urban growth speed with that of the baseline scenario, and only the weights for some institutional constraints are adjusted to alter the corresponding policies' implementing intensities. In detail, the intensity for constructing constrained zoning (the weight for *con_f*) is increased to –2 (–0.521103 in the baseline scenario), the intensity for urban planning (the weight for *planning*) is increased to –3 (–0.410472 in the baseline scenario), and all the other parameters remain the same with those of the baseline scenario. Generally, the intensity for implementing institutional constraints is strengthened in the baseline scenario. Figure 6 is the simulation result of the planning controlled scenario. Comparing with the baseline scenario, the urban built-up land is more scattered with less natural resource encroached and less environmental hazard occurring as results. The planning controlled scenario is regarded as a more sustainable urban growth pattern than that of the baseline scenario.

Table 2 Comparing the baseline scenario and planning controlled scenario (unit of area: km^2)

Scenario name	*Conf*	*Green*	*Rural*	*Morans I*
Beijing 2020	538	1,128	169	0.14
Baseline scenario	843	1,595	284	0.25
Planning controlled scenario	765	1,181	248	0.13

To compare the baseline and planning controlled scenarios, we selected four indicators, including the encroached constructing forbidden area 'conf', the encroached greenbelt area 'green', the encroached rural built-up land area 'rural', and the urban sprawl degree Morans I denoting the degree of spatial autocorrelation. The analysis results are listed in Table 2 (Beijing 2020 drafted in the Beijing master plan issued in 2004 stands for the planned urban form expected to be realised in 2020), showing that comparing with the baseline urban growth scenario, the planning controlled scenario encroached less ecological sensitive land, and the urban sprawl phenomenon is less significant than trend scenario.

5 Conclusions

An urban model using CC-CA is proposed and explained in detail in this paper. The complex constraints in the model include the macro socio-economic, spatial and institutional constraints. Particularly, the constructing constrained zoning, as an institutional constraint, is introduced into the model. This constraint, overlaying 110 CCFs, together with urban master plan and cultivating suitable area, provide opportunities to reflect complex institutional constraints for urban growth process. The complex constrained urban model, incorporating comprehensive constraints with classical CA urban model, is capable of simulating more practical and effective urban growth pattern in rapid urbanisation areas. The CC-CA model can be meanwhile applied as the testing laboratory of urban growth policies.

In the application of CC-CA for the Beijing Metropolitan Area, the role of complex constraints in urban growth can be dynamically identified in various historical phases, by means of the logistic regression. We proposed the planning controlled scenario, generated by intensifying the implementation of urban planning and constructing constrained zoning constraints based on baseline scenario with the current development trend. The planning controlled scenario shows that complex constraints can be availed to affect urban growth process, and simulate a more practical urban growth pattern. In the further research, we aim to simulate competing land uses (e.g., residential, commercial, and industrial land types) in the block scale through taking the constructing constrained zoning for various urban land uses into account.

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