



Urban growth boundaries of the Beijing Metropolitan Area: Comparison of simulation and artwork ☆

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ABSTRACT

Urban growth boundaries (UGBs) have been extensively studied and applied in the USA as an effective tool to curb urban sprawl. The “People’s Republic of China Town and Country Planning Act” requires the establishment of urban construction boundaries (UCBs) in Chinese city master and detail plans. We consider planned UCBs in China to be Chinese UGBs, as they have similar implementation mechanisms to their counterparts in the USA. However, different from UGBs in the USA, Chinese UGBs often resemble “artwork” by urban designers. Accordingly, they lack sound analytical basis and fail to sufficiently accommodate market mechanisms of land use. When measured by the criterion that the UGB should result in a spatial pattern that corresponds to its map, the Chinese UGBs are not well implemented. In this paper, we propose a method to support establishing UGBs through constrained cellular automata (CA). Our approach takes into account influence factors related to urban growth and generates UGBs based on spatiotemporally dynamic simulations. This method is applied to establish UGBs for the central city, new cities and small towns in the Beijing Metropolitan Area. The results indicate that there are significant differences between the UGBs based on constrained CA simulations and those in the previously established city master plan. We argue that our method could be a helpful planning tool for the establishment of UGBs in Chinese cities.

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Introduction

Urban sprawl and some other urban deficiencies arising from the rapid development of cities are a major challenge for sustainable urban development. Consequently, it is crucial to design appropriate methods to establish effective control of urban growth. Among the various urban growth management policies, urban containment policies have been widely adopted to increase urban land use density and protect open space from being developed (Long, Shen, & Mao, 2011; Nelson & Duncan, 1995). An urban containment policy usually has three components – greenbelts, urban growth boundaries (UGBs), and urban service boundaries (USBs) (Pendall, Martin, & Fulton, 2002). UGBs are

currently the most widely discussed tool in academia. Through zoning, land development permits and other land-use regulations, UGBs demarcate urban and rural uses and aim to contain urban development within the predefined boundaries (Pendall et al., 2002).

In China, concepts similar to UGBs have recently begun to develop. The “Urban Planning Compilation Guideline”, which was issued on April 1st, 2006, by the former Ministry of Construction (the current name is Ministry of Housing and Urban–Rural Development), requires that city master plans propose “development exclusion areas”, “development control areas” and “suitable development areas”. Such development exclusion areas and development control areas help to confirm the planning boundaries of urban construction areas (Long et al., 2011), which have been defined by the most recent “People’s Republic of China Town and Country Planning Act” as the legal boundaries to distinguish urban areas from rural areas (Han, 2009). Planning UCBs (urban construction boundaries) are applied by the urban planning administrative department as the basis for issuing building permits, and they have played a crucial role in containing urban growth in China. In terms of urban containment, development

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exclusion areas, development control areas, and planned urban construction areas in China have a similar mechanism to UGBs in the USA and other Western countries in that they are operated by delineating the boundaries between urban areas and rural areas, zoning, development permit controls, and other land-use regulations. Therefore, in a broad sense, the boundaries of these areas can be considered as Chinese UGBs, and the planned UCBs, which are the most explicit legal urban containment boundaries, can be narrowly defined as Chinese UGBs (the terms “Chinese UGBs” and “planned UCBs” are used interchangeably in this paper).

The establishment of UGBs involves the comprehensive consideration of various factors related to urban spatial developments. In Chinese cities, conventional methods of delineating UGBs are based on planners’ personal experiences; thus, they lack an adequate scientific basis and quantitative support. Consequently, the UGBs often fail to contain urban growth. According to Han, Lai, Dang, Tan, and Wu (2009)’s study on the examination of the implementation of planned UGBs within the sixth ring road of Beijing using multi-temporal remote sensing images, more urban land development was found outside than inside the UGBs during the two previous planning periods (1983–1993 and 1993–2005). Tian, Lv, and Shen (2008) and Xu, Shi, and Fan (2009) also suggest that substantial urban development occurred outside of UCBs in Guangzhou and Shanghai in recent years. The reason for the inconsistencies between the predefined UGBs and the practical urban developments was assumed to be the lack of market incentives in the UGBs due to the planners’ conventional methods, which were primarily based around Chinese architecture of the last several decades. In addition, the conventional approach to establishing UGBs is not appropriate when taking into consideration the comprehensive forces that quantitatively influence urban growth process. Therefore, new methods that can account for all of the forces driving urban growth are necessary for improving the development of UGBs.

In China, urban planners, most of whom work in state-owned planning institutions, tend to retain the notions of the planned economy before the reform and opening-up policy of 1978 when they propose spatial urban plans (Gu, 2011). This approach has resulted in wide-spread ignorance with respect to market factors (such as locations of commercial centers and roads). The normal procedure for urban planning is to propose the desired planned form first and to consider the required spatial policies to implement the desired urban form second. The planned urban form proposed by planners cannot be implemented solely by enforcing land use plans (or zoning), as it is also influenced by other related urban spatial policies, such as eco-sensitive land protection, infrastructure development, and other market factors. In Chinese cities, actual urban growth often departs from planned forms. Planning departments tend to neglect policies in support of planned forms of growth while also disregarding the coherence of policies over time. Therefore, there is an urgent need to develop a method to link supporting policies to the desired urban forms (Gu, 2011; Long, Shen, & Mao, 2012).

Cellular automata (CA), which can simulate the form and pattern of urban growth, has been extensively applied in modeling urban growth and used as an analytical tool for complex spatio-temporal systems (Clark & Gaydos, 2008; Tobler, 1970; White & Engelen, 1993; White & Engelen, 1997; Xie, 1994). Due to the complexity of urban growth, urban growth models should consider various factors that influence urban growth process. The pure CA model only considers neighborhood effects, setting aside important factors such as policy and geographical constraints. Therefore, many researchers have introduced constraints into the CA model—constrained CA—thereby rendering the simulation

of urban growth closer to real world outcomes (Clark & Gaydos, 2008; Engelen, White, & Uljee, 1997; Guan, Wang, & Clark, 2005; Li & Yeh, 2000; Ward & Murray, 1999; Ward, Murray, & Phinn, 2000; White, Straatman, & Engelen, 2004; Wu, 1998). Institutional factors and market incentives can be regarded as constraints in constrained CA to simulate future urban forms while taking into account comprehensive urban development considerations.

Planners can use constrained CA as a planning support system (PSS) to establish planned urban forms, in particular UGBs. The constrained CA simulation results—as an alternative future urban form or a possible land use scenario—can be applied as the basis for Chinese UGBs, as there are usually more explicit policy constraints in Chinese cities than in cities with mature market economies. Constrained CA can be conveniently applied to predict future urban forms if future development policies are known (Li & Yeh, 2000; Long, Mao, & Dang, 2009; Wu, 1998). In addition, the impact of the policies related to the control and guidance of urban growth can be simulated as different scenarios in constrained CA. The planners’ particular visions can be embedded as the constraints of constrained CA. However, to our knowledge, little literature to date has addressed using constrained CA simulation to establish UGBs although there are extensive publications on urban growth simulation using constrained CA. This paper aims to bridge this gap.

In the present paper, a constrained CA model that considers macro-level socio-economic constraints, locational constraints, neighborhood effect and institutional constraints is developed to simulate future urban growth and establish the UGBs for the Beijing Metropolitan Area. The “Urban growth simulation using constrained cellular automata” section introduces the methodology to establish UGBs through constrained CA in detail. The “Case study in the Beijing Metropolitan Areas (BMP)” section shows how to use constrained CA to establish UGBs in the Beijing Metropolitan Area. The “Conclusion and discussion” section presents and concludes our findings.

Urban growth simulation using constrained cellular automata

Constrained cellular automata

The conceptual model of the constrained CA is shown as follows:

$$V_{ij}^{t+1} = f(V_{ij}^t, A_{mac}, A_{loc}, A_{ins}, A_{nei}^t) \quad (1)$$

where V_{ij}^{t+1} and V_{ij}^t , respectively, are the cell status at ij of time $t + 1$ and t and f is the transition rule of the constrained CA model. In this paper, the cell status represents 0 for no development or 1 for developed from rural to urban. Constrained conditions in the urban growth process, namely, development policies, consist of four types, which include the macro socio-economic constraint A_{mac} (a non-spatial explicit variable), locational constraints A_{loc} , institutional constraints A_{ins} , and neighborhood effect A_{nei}^t . Locational and institutional constraints are assumed to remain static during the future urban growth process, and they do not change across simulation iterations, a condition that is widely adopted by constrained CA studies. The macro-level socio-economic constraint reflects the total number of built-up cells to be developed in the future. The neighborhood effect, however, continues to change with simulation iterations of the constrained CA. To differentiate the neighborhood effect from other constraints, we consider locational and institutional constraints to be spatial constraints in this paper.

The status transition rules in constrained CA are illustrated in Formula (2) (Wu, 1998):

$$LandDemand = \sum_t stepNum^t$$

In iteration $t + 1$:

$$s^t = x_0 + \sum_{k=1}^{n-1} x_k * x_n * a_n^t = s_0 + x_n * a_n^t$$

$$p_g^t = \frac{1}{1 + e^{-s^t}} \quad (2)$$

$$p^t = \exp \left[\alpha * \left(\frac{p_g^t}{p_{gmax}^t - 1} \right) \right]$$

If $p_{ij}^t \geq p_{threshold}(p^t, stepNum^{t+1})$ then $y_{ij}^{t+1} = 1$

Otherwise $y_{ij}^{t+1} = 0$

where $LandDemand$ is the total number of cells to be developed, $stepNum^t$ is the number of cells developed in iteration t reflecting the land development demand as the macro-constraint, ij is the cell's coordinate, s^t is the development suitability of cell ij , p_g^t is the initial transition potential, p_{gmax}^t is the max value of p_g^t across the whole lattice, α is the dispersion parameter ranging from 1 to 10, indicating the rigid level of urban development, p^t is the final transition potential, p_{ij}^t is the final transition potential of cell ij , x_0 is the constant item, a_n is the neighborhood development policy, x_n is the weight of a_n , a_k is the spatial constraint (the neighborhood effect excluded), x_k is the weight of a_k , s_0 is the constant part (except the neighborhood effect) of s_{ij}^t among all iterations, y_{ij}^{t+1} is the cell ij 's status at iteration $t + 1$, and $p_{threshold}(p^t, stepNum^{t+1})$ is the development threshold to control the development speed and quantity, which varies from the value of p^t and $stepNum^{t+1}$ to guarantee $stepNum^{t+1}$ cells will be developed in iteration $t + 1$.

Model calibration

The parameters that need to be calibrated in the CA model include $stepNum^t$, x_k , and x_n , in which various approaches can be adopted. $stepNum^t$ is assumed to be constant through the entire simulation period and can be calculated as follow:

$$stepNum = \frac{C_{T_2} - C_{T_1}}{(T_2 - T_1)/t_0} \quad (3)$$

where C_{T_2} and C_{T_1} are the total number of developed cells of urban form in time T_2 and T_1 , respectively, and t_0 is the time in the real world corresponding to one simulation iteration in CA.

To calibrate x_k and x_n to reflect the weight of policies, the logistic regression and heuristic approaches can both be applied. The weight of x_k for spatial constraints can be retrieved by the logistic regression in which whether a cell is developed from non-urban to urban is the dependent variable (1 or 0) and the spatial constraints are the independent variables. Holding x_k static, x_n can be calibrated using the *MonoLoop* method (for details see Long et al., 2009), where x_n is continually sampled from 0 to $x_{n,max}$ with an interval of $x_{n,max}/M$. $x_{n,max}$ can be set based on the user's experience, and M is set to 100 in this paper. The sampled x_n and the calibrated x_k are used as the input variables for the constrained CA model. The simulated urban form is compared on a cell-by-cell basis with the observed urban form to obtain the *Kappa* index, which was initially introduced by Cohen (1960) and adapted for the accuracy assessment in remote sensing applications by Congalton and Mead (1983). *Kappa* is significantly correlated with overall accuracy in the confusion matrix for comparing two maps. In the present paper, the *Kappa* index is calculated to analyze the degree of similarity (goodness-of-fit) between the observed and the simulated urban forms cell by cell. The x_n with the maximum *Kappa* index is specified as the final weight for a_n . Finally, x_n and x_k as the calibrated weights are used in the constrained CA model to simulate future urban growth (the baseline urban growth scenarios).

It should be mentioned that, in theory, x_n and x_k should be calibrated simultaneously. The difficulty lies in the dynamic variation of the neighborhood effect across simulation iterations, and Monte Carlo based approaches, though requiring heavy computation, would be suitable for the simultaneous process. A simulation process (a run) of our current CA (which is similar to other existing CA models) requires minutes and tens or hundreds of simulation iterations. To calibrate eight parameters (in our model) simultaneously, there should be 10^8 runs if we assume that every parameter has only ten options. This requirement is not acceptable in the current computational hardware environment. Therefore, as a compromise, we propose the *MonoLoop* approach, thereby only tuning one parameter to save computation time. It should be noted that in addition to the cell-by-cell map comparison method *Kappa* used in this paper for comparing two maps, we further applied other map comparison methods for calibrating our constrained CA model using the Map Comparison Kit 3 (MCK3) developed by Research Institute for Knowledge Systems, The Netherlands (Visser & de nijs, 2006). These methods are fuzzy-based and include fuzzy *kappa* and the fuzzy inference system. The objective of fuzzy-based map comparison is to propose a method that mimics human comparison and provides a detailed assessment of similarity. In the fuzzy inference system, a global agreement value termed fuzzy global matching can be derived by the fuzzy summation of local matching.

The above status transition rules are different from those proposed by Wu (2002), $p_c^t = p_g * con(s_{ij}^t = suitable) * \Omega_{ij}^t$. In this status transition rule, p_g is the observed global potential that does not change across simulation iterations, $con()$ converts the state of suitable land into a binary variable, and Ω_{ij} is a neighborhood evaluation function. The weight of neighborhood effect in Wu (2002) is arbitrarily assigned and cannot be calibrated using historical observed datasets. According to Long et al. (2009), the simulation results are sensitive to the weighting parameter, x_n , of the neighborhood effect. In our paper, the weight of neighborhood effect can be identified using the *MonoLoop* method, enabling the comparison of the role of the neighborhood effect with other spatial constraints. By identifying the influence of the neighborhood effect on the process of urban growth, spatiotemporal comparisons of the neighborhood effect can also be conducted.

Urban growth simulation

The simulation process of the constrained CA model shown in Fig. 1 is based on the established status transition rules retrieved from the model calibration process or set by decision makers. First, the model sets the input variables and calculates the *stepNum* parameter based on macro-level socio-economic conditions. Then, the land use suitability, the initial transition potential and the final transition potential are calculated. The cells with the maximum final transition potential are consequently identified and marked in the allocation progress (Fig. 1, in gray). Finally, continuous iterations are run in the model until the entire simulation is completed with a simulated urban growth pattern generated.

Establishing UGBs

The constrained CA simulation results in some time (iteration or step); that is, the scheme for the corresponding stage of urban growth can be considered a UGB in the corresponding development period if the simulation is conducted according to the desired or planned pathways. The simulated urban form in the raster format can be converted into a vector format comprised of many polygons. Polygons with low compactness and a small area (<1 ha) should be eliminated, as they are not feasible for urban developments. The remaining polygons can then be regarded as

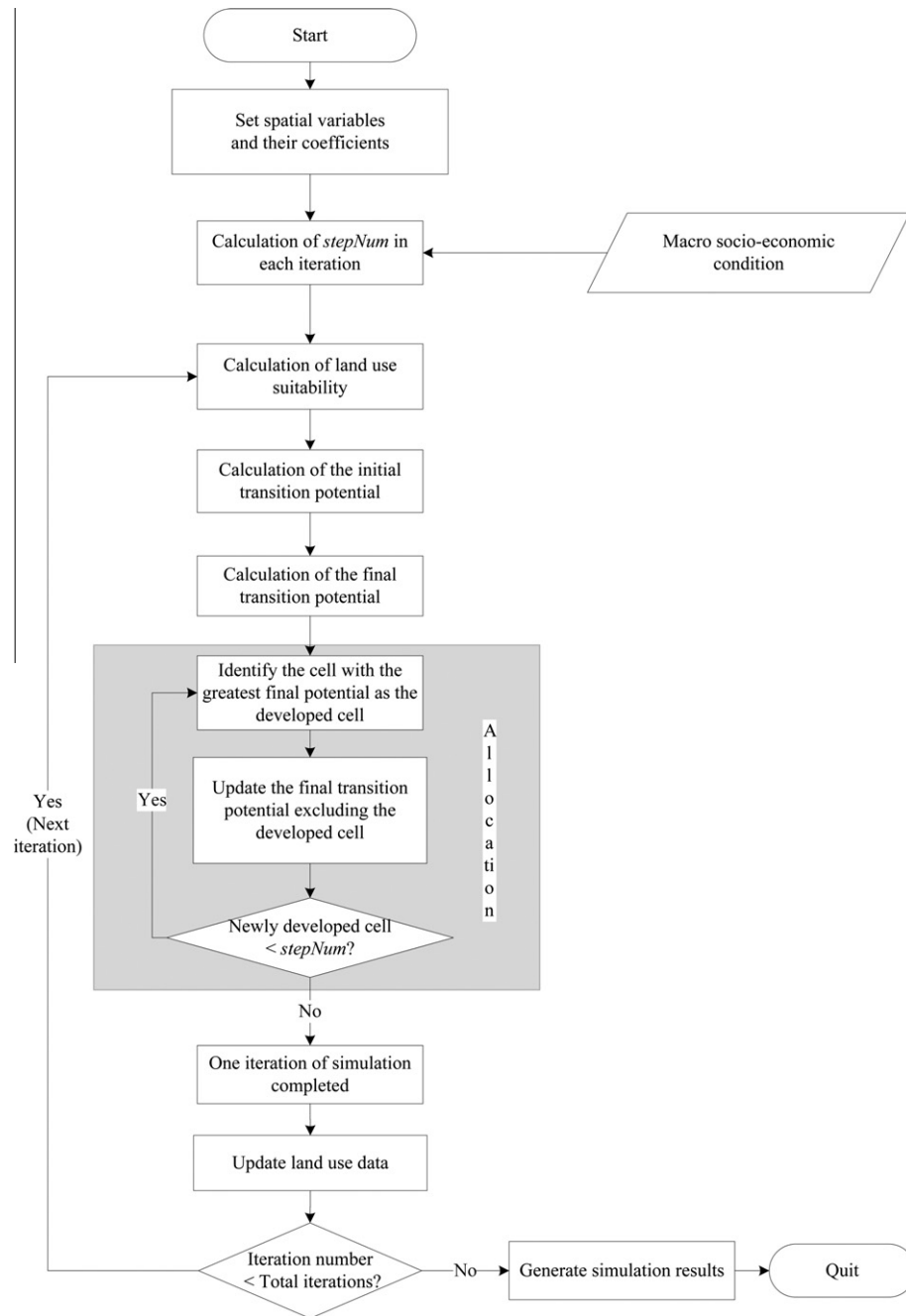


Fig. 1. Flow diagram of the constrained CA model.

UGBs for different urban hierarchies (e.g., central city, new cities or small towns). The areas to be developed can be calculated by subtracting the existing urban construction areas from the established UGBs. Notably, the UGBs in most metropolitan areas in China are not only one or two polygons but may comprise numerous polygons, quite different from UGBs in the USA.

Case study in the Beijing Metropolitan Areas (BMA)

Urban growth processes in China

UGBs can be established based on the simulation results of future urban growth. To simulate urban growth alternatives for Chi-

nese metropolitan regions, the urban growth process in China must be analyzed. Such analysis requires consideration of both the top-down governmental response to the process and the bottom-up development by individual landowners. The governmental response should establish development objectives based on the macro-level socio-economic conditions through, for instance, plans for land supply. Developers for a specific development project seek the best land for that project based on the land use suitability assessment and the supply constraints established by the government. Individual landowners can develop land based on the restriction of institutional conditions (such as the urban plans and the ecological protection policies) and natural conditions (such as the slope and disaster risks). Both market incentives and institutional forces drive bottom-up development. In addition, urban

development may deviate from the layout of urban forms projected in urban plans.

With reference to the actual urban growth process in China, the simulation of urban growth using constrained CA can be conducted through two steps according to the “Constrained cellular automata” subsection in the “Urban growth simulation using constrained cellular automata” section and practical urban growth processes in China, as noted in the previous paragraph. First, the land demand in each development stage is confirmed based on the macro-level socio-economic constraints (exogenous variables in the model). Second, with the consideration of other constraints in the constrained CA model at the micro-level, the spatial distribution of cells to be developed is simulated by taking other constraints into consideration in the constrained CA model and calculating the potential of development for all the individual cells in different stages. Several constraints are applied in the constrained CA model based on the theoretical framework of the hedonic model and taking into consideration the availability of spatial data in our study area.

Study area

The methodology we proposed was tested in the Beijing Metropolitan Area (BMA) (Fig. 2), an area of 16,410 km². The BMA has experienced rapid urbanization in terms of GDP and population growth since the 1978 Reform and Opening-up. The GDP in 2006 was 787 billion CNY, 83.7 times that in 1976 (9.4 billion CNY). The population in 2006 was 15.81 million, 1.9 times that in 1976 (8.29 million, Beijing Municipal Statistics Bureau & NBS Survey Office in Beijing, 1987; Beijing Municipal Statistics Bureau & NBS Survey Office in Beijing, 2007). The built-up urban area in 2006 was 1324 km², nearly 3 times that in 1976, which was 495 km². Moreover, urban growth is predicted to continue increasing in

the next two decades, according to the Beijing municipal government. Five versions of urban master plans for the BMA have been proposed since 1958 to manage urban growth: in 1958, 1973, 1982, 1992 and 2004 (Beijing Municipal Planning Committee & Beijing Academy of Urban Planning, 2006). According to our latest urban planning implementation evaluation research on the five master plans, the practical urban developments in the BMA were significantly different from the planned form (Long, Han, Mao, & Qi, 2011). Therefore, how to establish more reasonable UGBs for Beijing is an issue of great concern in Beijing.

To preserve precious undeveloped open spaces and to curb widespread urban sprawl, it is necessary to confine future urban growth within the specified urban form by establishing UGBs. In the most recent master plan to be implemented, the Beijing City Master Plan (2004–2020) (BCMP), the spatial distribution of UGBs in the BMA was determined by urban planners to meet urban development requirements with respect to industrial development, population growth, and eco-space protection. This plan has projected a population of 18 million, a developed land scale of 2300 km², and an urban spatial structure of “two axis, tow belts and multi-sub-centers” (see Fig. 3). In our opinion, this plan over-emphasized the urban morphology rather than presenting a valid means to realize it. Therefore, a simulation at the same scale in the present research can be applied to compare the current UGBs in the BCMP established through the conventional method.

Data

A constrained CA model with a cell size of 100 m * 100 m (1 ha) and a total of 1,640,496 cells is applied in the BMA to account for different urban development policies. This model is developed based on the Python script language incorporating ESRI Geopro-

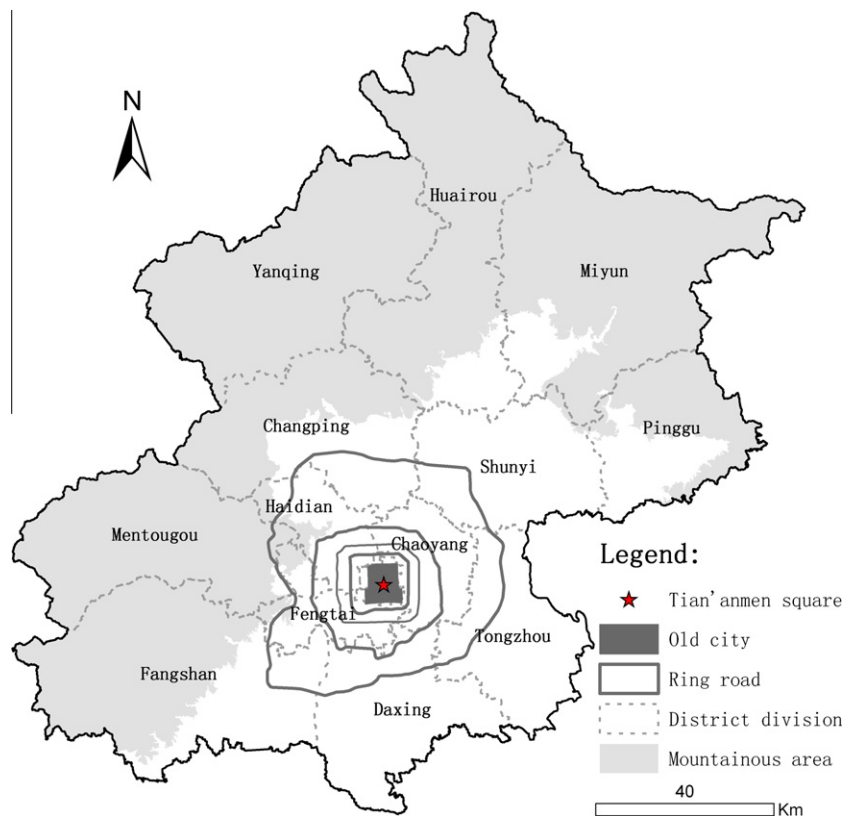


Fig. 2. The Beijing Metropolitan Area as the study area for the constrained CA model.

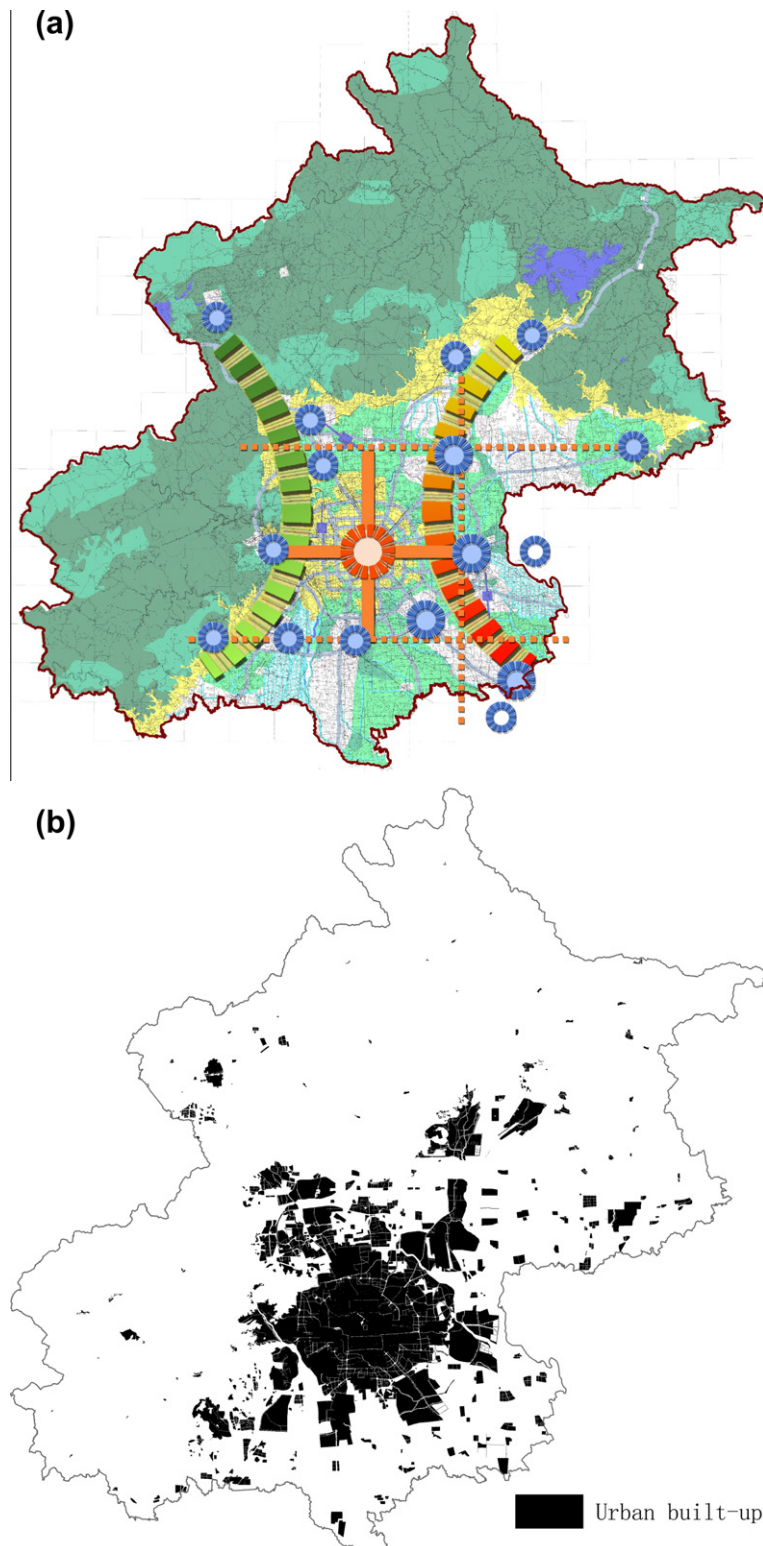


Fig. 3. The spatial structure (a) and land use pattern (b) of the BCMP (Source: BCMP).

cessing and has a discrete time iteration of 1 month. The results of this simulation are used as a basis for the UGBs.

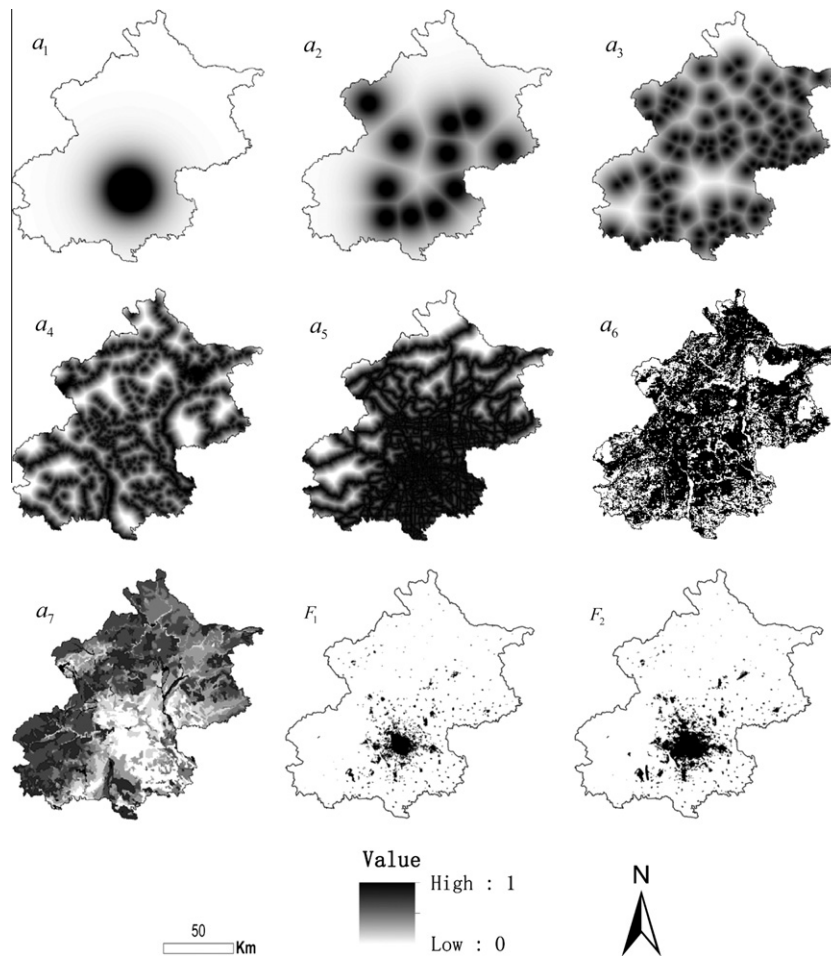
The data required for our constrained CA model are shown in Table 1. The spatial distribution of various policies is shown in Fig. 4. *stepNum*, the macro-level constraint, reflects the total amount of land developments in the future. Locational constraints represent the attractiveness of various levels of town centers,

rivers and roads. Each constraint, expressed in the form of “attractiveness”, is heterogeneously distributed in the geographical space. Attractiveness can be calculated based on accessibility to each GIS layer with spatial features, which will be further elaborated in the following paragraph. We introduce two institutional constraints into our CA model. The first constraint is the construction of forbidden areas, which represents policies restricting urban

Table 1

Datasets of the constrained CA in the BMA.

Type	Variable	Description	Value	Data source
Macro constraint	$stepNum$	Socio-economic development	>0	Socio-economic development plan or calculated from existing urban forms
Locational constraints	a_1	Attractiveness of Tiananmen (the downtown center)	0–1	Derived from spatial dataset in GIS
	a_2	Attractiveness of new cities	0–1	Derived from spatial dataset in GIS
	a_3	Attractiveness of towns	0–1	Derived from spatial dataset in GIS
	a_4	Attractiveness of rivers	0–1	Derived from spatial dataset in GIS
	a_5	Attractiveness of roads of 1991	0–1	Interpreted from Landsat TM imagery of 1991–5–16
Institutional constraints		Attractiveness of roads of 2004	0–1	Interpreted from Landsat TM imagery of 2004–5–29
	a_6	Construction of forbidden areas	0 or 1	Beijing Municipal Planning Committee (2007) (for detail see: Long et al., 2011)
Neighborhood effect Urban forms	a_7	Suitability of cultivation	0–1	Beijing Planning Commission (1988)
	a_n^t	Development intensity in the neighborhood	0–1	Calculated by CA
	F_1	Urban form in 1991	0 or 1	Interpreted from Landsat TM imagery of 1991–5–16
	F_2	Urban form in 2004	0 or 1	Interpreted from Landsat TM imagery of 2004–5–29
	F_3	Planned UGBs for 2020 proposed in the BCMP	0 or 1	Beijing Municipal Planning Committee et al. (2006)

**Fig. 4.** Maps of spatial policies and urban forms in the BMA.

development in a cell for purposes of eco-space protection or geo-disaster prevention. The second constraint is the suitability of cultivation, which reflects the government's strict protections of farmlands in the face of urban development; protecting farmlands is a principal land use policy in China. The neighborhood effect is defined as the ratio of developed cells to all cells in the neighborhood (excluding the cell itself).

Note: The map of a_5 in this figure is for 2004. The map of F_3 is illustrated in Fig. 3b.

For ease of comparing weights between various constraints, the constraints are standardized to range from 0 to 1, with 1 denoting the greatest potential for development and 0 the least. The locational constraint a_k , using the corresponding spatial feature class as the data source, is processed by the “distance/straight line”

toolbox of the spatial analyst module in the ESRI ArcGIS package to acquire $dist_k$, followed by $a_k = e^{-\beta^* dist_k}$, to calculate the attractive potential, where $\beta = 0.0001$, according to our experience. In most related papers, in the context of geosimulation (e.g., constrained CA), β is set based on the user's experience rather than calibration to an established standard. In addition, β in the model calibration process and β in the model simulation process are the same in our research, which will decrease the possibility of arbitrarily setting β . Regarding institutional constraints, if the construction forbidden policy a_6 and the suitability for agriculture development policy a_7 are equal to 0, there will be the least potential for development, and vice versa.

Parameter calibration

The data in 1991 and 2004 are applied in this paper to account for the historical status transition rules, determine the values of the parameters and provide the basis for urban growth predictions. The parameter calibration is established through the following steps (see Table 2 for parameter calibration results):

- (1) The number of developed cells is 80,343 (803.43 km²) in 1991 and 125,928 (1259.28 km²) in 2004. There are 156 months in this period. Therefore, the developed cells increased by approximately 292 (2.92 km²) in each simulation iteration (*stepNum*).
- (2) The weights of the seven spatial constraints excluding x_n for 1991–2004 are calibrated using logistic regression in SPSS (see Table 2). All these variables are significant at the 0.001 level. The *Kappa* index between the observed 2004 urban form and the regressed urban form is 43.4%.
- (3) The *MonoLoop* method is used to calibrate the weighting coefficient x_n for the neighborhood effect with the maximum *Kappa* index. In simulations of the *MonoLoop* process, the neighborhood configuration adopts the frequently used Moore neighborhood, which comprises eight cells surrounding a central cell on a two-dimensional square lattice. We acknowledge that the neighborhood configuration affects the simulation results, as also reported by Kocabas and Dragicevic (2006). The “best” neighborhood configuration will be calibrated after this procedure. x_n is identified as 13 using this method. The *Kappa* index between the observed 2004 urban form and the simulated urban form using weights from both logistic regression and *MonoLoop* procedures is 80.9%. The significant increase of *Kappa* compared with the *Kappa* from the logistic regression further indicates that the neighborhood effect plays an important role in urban growth processes. In addition, the *Kappa* value greater than 80% indicates that our constrained CA model can replicate

historical urban growth and suggests that it is possible to simulate future urban growth, based on which UGBs will be established.

We need to calibrate the neighborhood configuration for our constrained CA model. In this research, the circular neighborhood is adopted and various radiuses of the neighborhood are tested to find the best one, a process similar to the *MonoLoop* process. The calibrated x_k and x_n are used in the neighborhood calibration process. We find that the neighborhood with a radius of four cells has the greatest *Kappa* value (81.2%), and this radius is adopted as the neighborhood configuration in our constrained CA model for further urban growth simulation. Note that we also calibrate α in Formula (2), and we find that an α value of 2 could best replicate historical urban growth from 1991 to 2004. Under this condition, the fuzzy *Kappa* value for calibration is 79.8% and the fuzzy global matching for calibration is 80.1%. Generally, the fuzzy *Kappa* and fuzzy global matching are both slightly lower than *Kappa*. However, these values are both high enough to prove the applicability of our constrained CA model.

Urban growth simulation for 2020

The calibrated parameters in 1991 and 2004 are applied to urban growth simulation for 2004 and 2020 (the baseline scenario based on the calibrated historical trend). The area of the planned UGBs in the BCMP is 2388 km² in 2020. As there are 192 months between 2004 and 2020, the *stepNum* value should be 588 (5.88 km²). Urban growth from 2004 to 2020 is expected to maintain the development trend of 1991–2004. Accordingly, this scenario is termed the baseline scenario, in which the weights of all the spatial variables and that of the neighborhood effect remain constant, as do the calibrated historical weights. The simulation result of 2004 is shown in Fig. 5a. The *Kappa* index for the comparison of the simulation results and the planned UGBs in the BCMP is 68.3%, suggesting that there is a relatively high degree of difference between the simulation results and the planned UGBs (Fig. 5b). This finding also shows that it is quite possible that the future urban form will differ from the planned UGBs in the BCMP, resulting in the failure of planned UGBs to contain urban growth. It should be noted that other urban growth scenarios are also available for simulation using our constrained CA model by adjusting the development speed *stepNum* and preferences for spatial constraints.

Establishing UGBs

The UGBs of the central city, new cities and small towns in the BMA are established in the present study according to the methodology used to develop UGBs based on constrained CA simulations—methods that were introduced in the “Urban growth simulation using constrained cellular automata” section. The UGBs for the central city and 11 new cities are shown in Fig. 6, while those for the 142 small towns are not depicted on the map due to space limitations.

Note: New city boundaries are determined by the BCMP.

Table 3 shows a comparison of the proposed UGBs based on simulations with the planned UGBs established in the BCMP through conventional methods. There are large discordances between the two types of UGBs. The UGBs based on the constrained CA simulation have a larger southern area and smaller northern area than those of planned UGBs in the BCMP. As for the new cities, the areas of the UGBs of the new southern cities (such as Daxing and Yizhuang) based on the constrained CA simulation are significantly larger than the planned UGBs in the BCMP, while the UGBs of the new northern cities (such as Changping and Huairou) are smaller than the planned UGBs in the BCMP. In the planned UGBs,

Table 2
Calibrated parameters of the constrained CA model (1991–2004).

Name	Value
<i>stepNum</i>	292
x_0	−11.877
x_1	14.266
x_2	2.870
x_3	−2.595
x_4	1.149
x_5	6.743
x_6	1.084
x_7	−0.610
x_n	13.000
Neighborhood configuration	A circle with a radius of four cells

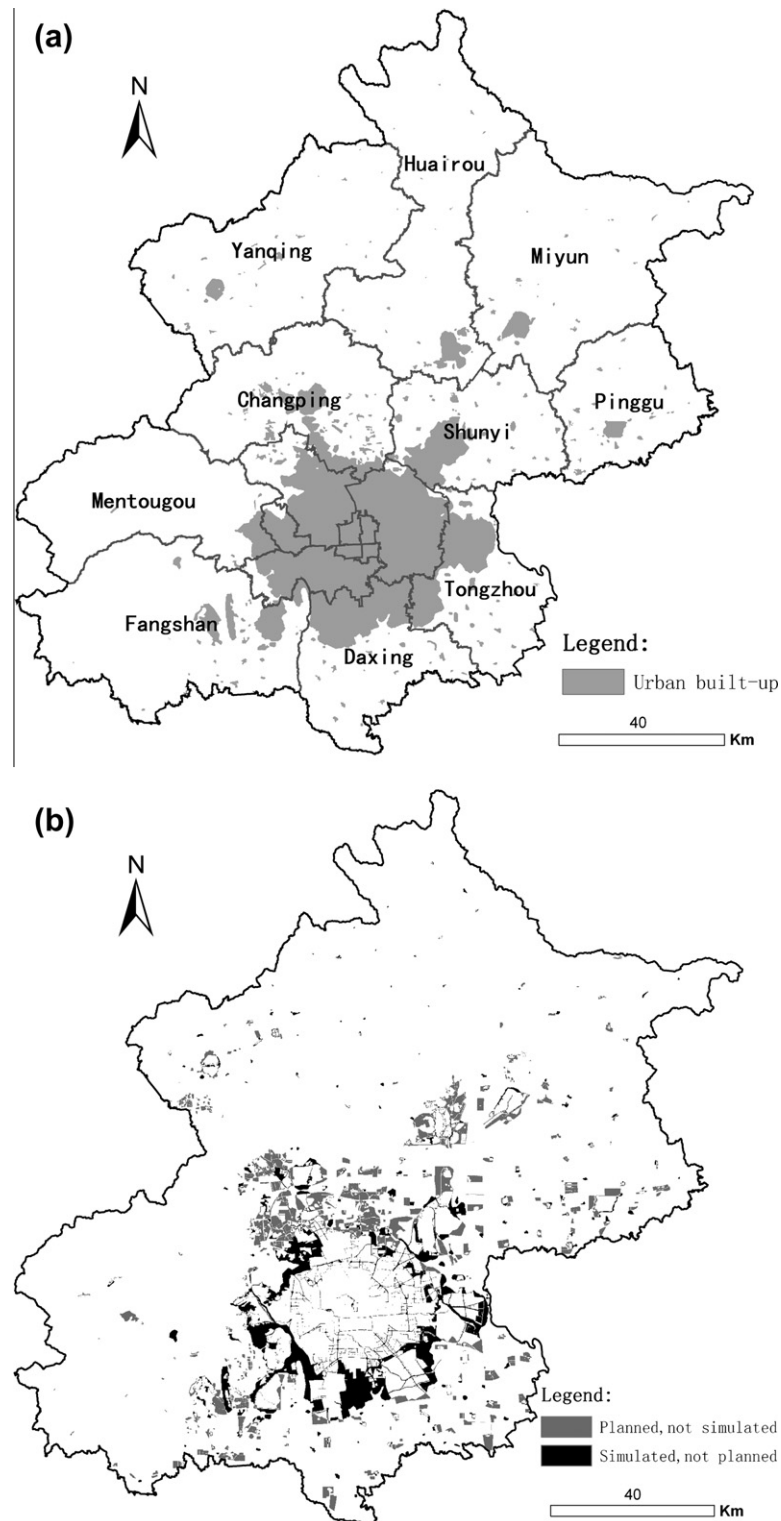


Fig. 5. Simulated urban forms in 2020 (a) in contrast with the planned forms (b).

planners intended to develop a compact urban form to curtail urban sprawl, which resulted in the new southern cities having limited development. According to the model calibration results in Table 2, urban development around Tiananmen, near new city centers and along roads was significant in certain historical years. The simulated UGBs continue the historical trend and further expand these areas (e.g., new southern cities) with good accessibility to these factors including Tiananmen, new city centers and roads.

Accordingly, the new southern cities have larger simulated UGBs than the planned UGBs. In sum, this finding suggests that the spatial distribution of the original UGBs in the BCMP may not be appropriate and can be improved by considering the results of the simulated UGBs based on the proposed constrained CA model.

In addition to establishing UGBs based on the baseline simulation, the constrained CA we developed is also suitable for generating UGBs based on other simulation scenarios by adjusting policy

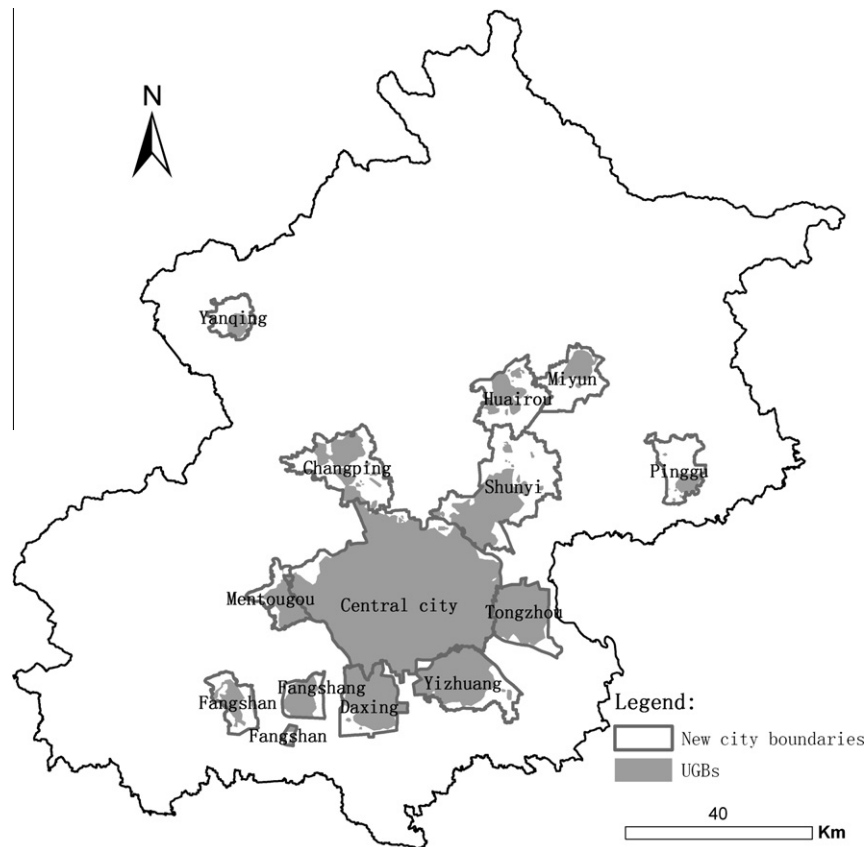


Fig. 6. The UGBs for the central city and new cities based on the constrained CA simulation.

Table 3

UGB areas of the central city and new cities in the BMA (area unit: km²).

Name	Area in 2004	Simulated UGBs	Planned UGBs	Simulated–planned	Simulated–planned Planned (%)
The central city	708.9	1033.0	984.2	48.8	5.0
1. Shunyi	50.2	157.2	180.2	–23	–12.8
2. Yizhuang	25.1	156.8	116.6	40.2	34.5
3. Tongzhou	42.7	133.6	109.5	24.1	22.0
4. Daxing	55.8	132.3	84.7	47.6	56.2
5. Fangshan	52.6	86.4	88.8	–2.4	–2.7
6. Changping	35.7	82.0	109.8	–27.8	–25.3
7. Mentougou	21.2	52.9	35.5	17.4	49.0
8. Huairou	20.0	48.8	80.0	–31.2	–39.0
9. Miyun	18.9	34.8	46.9	–12.1	–25.8
10. Pinggu	13.1	19.8	31.0	–11.2	–36.1
11. Yanqing	7.3	17.3	20.2	–2.9	–14.4
Sum	1051.7	1954.7	1887.4	67.3	3.6

parameters to reflect various spatial policies. To demonstrate the applicability of our model to real-world planning practices, we provide two additional simulation scenarios (Fig. 7). The first is the grape-cluster scenario, which highlights developments along roads and around small towns. In this scenario, the policy parameter of promoting development around towns x_3 was increased from -2.595 to 2.000^1 and the policy parameter of promoting development along roads x_5 was increased from 6.743 to 10.000 (see Foot-

note ¹). Other parameters remained the same as for those of the baseline scenario. The second is the sustainable scenario, which highlights farmland protection and eco-space protection. In this scenario, the policy parameter of “Construction in forbidden areas” protection x_6 was increased from 1.084 to 3.000 (see Footnote ¹) and the policy parameter of “Suitability of cultivation” protection x_7 was increased from -0.610 to 2.000 (see Footnote ¹). Other parameters remained the same as for those of the baseline scenario. The UGBs for each scenario were then established using the same approach as for the baseline UGBs. The UGB for each scenario was significantly different from the UGB for the baseline scenario. In sum, our model serves as a planning support tool that is suitable for assisting a wide variety of spatial planners to establish UGBs according to various preferences.

¹ The values in the grape-cluster scenario are set according to our experience and the understanding of the grape-cluster scenario, which highlights developments along roads and around small towns. In addition, we set these values for demonstrating the capacity of the proposed constrained CA model for establishing UGBs that are based on scenarios other than the baseline scenario.

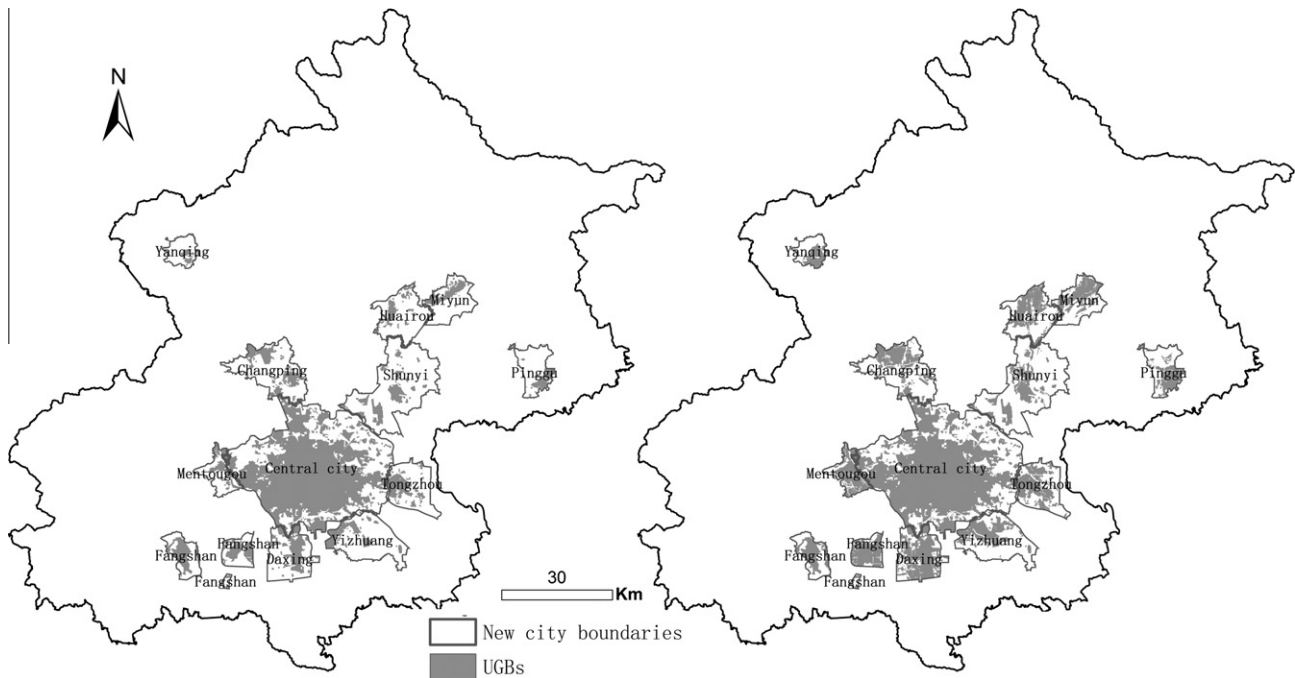


Fig. 7. Two UGB scenarios generated based on the constrained CA simulation (left: the grape-cluster scenario; right: the sustainable scenario).

Conclusions and discussion

This paper defined UGBs in China as planned urban construction boundaries based on the current urban planning regime; it also proposed a method to establish UGBs through a constrained CA model. A case study in the Beijing Metropolitan Area was developed to demonstrate how UGBs can be established using this method. After the model calibration was completed using historical observed data, the model simulated the future (year 2020) urban form based on current urban growth trends (1991–2004). We compared the results of the UGBs based on the constrained CA simulation with those based on the conventional method in the Beijing City Master Plan (2004–2020). The results suggest that there are significant differences in the spatial distribution between the UGBs established through these two distinct methods. The former presents much greater distribution than the latter in the southern part of the BMA, whereas the distribution is smaller in the northern area. This result should be considered when establishing practical UGBs.

In contrast to the conventional UGB development methods employed by planners with a background in architecture, the constrained CA model considers a combination of socio-economic factors and policy constraints. Constrained CA may better reflect the spatiotemporal dynamics of and policy impact on urban growth. This model could be applied to simulate and test how different sets of policies, zoning regulations, and development trends may or may not be conducive to the objectives of UGBs. The present paper proves that using a constrained CA model can provide the requisite theoretical guidance and technical support for establishing and improving UGBs in Chinese cities.

Much remains to be explored in future studies. For example, the spatial variation of transition rules has not been considered in the proposed model. The model's results can be improved if different transition rules can be established for different regions. In addition, this paper only simulates urban forms based on the current development trend. This model can also be applied to simulate different urban growth scenarios based on other urban

development strategies. Through the analysis and comparison of different scenarios, a preferable scenario can be selected to establish the recommended UGBs and the corresponding policy package for decision makers.

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