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Delimiting Urban Growth Boundary through Combining Land Suitability Evaluation and Cellular Automata

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Received: 2 November 2017; Accepted: 29 November 2017; Published: 30 November 2017

Abstract: China's domestic urban planning only worked on researches of urban space control, the scope definition of urban development is not clear enough. The purpose of this study is to present a new urban growth boundary (UGB) delimitation method which combined land suitability evaluation (LSE) and cellular automata (CA). This method gave credence to LSE's advantage in sustainable land use, and CA's advantage in objective dynamic simulation. The ecological limitation areas were defined by LSE, which were regarded as the restricted areas of urban growth; meanwhile, it was taken as an important model input to guide intensive land allocation in urban growth model (CA model). The future urban growth scenarios were predicted by CA model and the corresponding UGB lines were delineated by ArcGIS 10.1. The results indicated that this method had good performance in Ningbo's urban growth simulation. When compared to the planned UGB in urban master planning, the simulated UGBs under port development and regulated scenarios showed more intensive and suitable spatial layout of land. Besides, the simulated UGB under regulated scenario had the most reasonable space structure and the largest ecological protection effect among the UGBs. Hence, the simulated UGBs were superior to the planned UGB. The study recommends that this UGB delimitation method can promote sustainability of land development and ecological environment in Chinese cities.

Keywords: urban growth boundary; land suitability evaluation; cellular automata; urban growth scenario; sustainable land use; spatial-temporal simulation; Ningbo

1. Introduction

Since China's reform and opening up policy came into effect in the late 1970s, the country has witnessed an unparalleled period of urbanization [1–3]. The urbanization level has soared from 17.9% in 1978 to 56.1% in 2015 [4]. The consequence of urban sprawl at this rapid level is not only the threatening impacts to the ecological environment and protection of important farmland [5]—it also leads to an unmanaged "loose" urban structure, which reduces the space efficiency, and impedes the healthy development, of cities [6]. To alleviate the adverse effects of blind expansion of cities, as well as to promote sustainable development, many scholars have designed and applied plentiful planning policies and decision-making tools, such as land-use zoning system, urban growth boundary (UGB), and the China urban land system reform [7,8]. Among these policies and tools, UGB is the most commonly used tool to shape reasonable urban internal space and protect ecological and agricultural space from being developed. The aim of UGB is to limit urban growth occurring within the given boundary, and to guide sustainable urban development [9–13]. It is worth noting that the UGB mentioned in this study includes urban growth areas within the boundary and boundary lines.

In China, the similar concept of UGB was put forward in "Urban Planning Compilation Guideline", which was published in 2006 [14]. According to this guideline, urban master planning must delimit three zones: "construction prohibited zone" (strictly protected areas without any urban construction), "construction control zone" (areas in which urban development should be controlled), and "suitable construction zone" (areas which are suitable for urban development). The suitable construction zone and construction control zone contribute to defining the specified areas of urban development spaces [15]. This means that China's domestic urban planning did not entirely introduce the concept of UGB, but only worked on similar research from the perspective of urban space control. For instance, Hong Kong formulated the "Planning Vision and Strategy in 2030", which required the delimitation of "development exclusion areas" to protect natural resources and scenic areas; however, urban development areas were not clearly defined [16]. Although these planning practices have provided a basis for UGB research, there is a lack of clear UGB results and delimitation methods. Therefore, it is crucial to design a scientific UGB delimitation method which follows the principle of sustainable land use, and reflects urban development characteristics.

The delimitation of UGB embodies the complete evaluation of diverse elements which are in connection with spatial-temporal growth of urban areas [17]. In Chinese cities, many researchers delineated UGBs based on land suitability evaluation (LSE) [6,16]. Land suitability can be defined as the suitability of land for a certain purpose, which is determined by hydrological, geological, topographical, ecological, and cultural conditions [6]. In this study, the concept of LSE is conducted by the quantitative analysis of different lands' suitability to develop into urban lands, from the perspective of ecological protection and sustainable land use [18]. Many previous studies have proved the availability of LSE by using different sized cities in China, such as Changzhou, Harbin, Beijing, Fangchenggang, and Suzhou [6,19–24]. The UGB delimitation method based on LSE can effectively determine the advantageous locations of future urban development and guide the compact development of the city [25,26]. Hence, LSE is beneficial in changing the original Chinese urban growth pattern, which results in resource consumption and environmental pollution. Besides, LSE will help to realize the coordination mechanism of resource protection and land development [6]. However, because LSE is a top-down layout mode, it is difficult to reflect the space layout which is derived from the dynamic impact of neighborhoods and the interaction of local rule. Meanwhile, due to the lack of objective dynamic simulation, and ignoring of the bottom-up self-organization rule of urban development, the LSE-based UGBs may easily deviate from the actual situation of future urban growth [25,26].

In foreign cities, the most commonly used technology of UGB establishment is urban modeling, which has been widely used with the help of remote sensing (RS) and Geographical Information Systems (GIS) [27]. Over the last 20 years, cellular automata (CA) was the most famous emulation tool for testing and simulating urban expansion [28–30]. Since then, many constraints such as planning policies, urban development tendency, and ecological environmental protection have been imported into CA to simulate urban growth more scientifically and comprehensively [31–41]. The CA model can be used as planning support tool to reveal prospective city development patterns, especially UGBs [17,42]. Furthermore, the CA model has the ability to simulate different situations of urban growth which are accordance with various development strategy and policy considerations [17,41]. The CA model is a bottom-up layout mode which can reflect the dynamic impact of neighborhood superiorly. Although the spatial layout of urban development based on the CA model may be relatively scattered when compared to that based on LSE, it has higher goodness of fit with the actual situation of urban growth [25,26]. However, due to paying more attention to urban development rather than sustainable land use, the CA-based UGBs may easily overlook the land suitability and supply, which causes the waste of land resources.

So far, although there are extensive publications which have utilized LSE or CA to simulate urban sprawl and to delineate UGBs, little literature has combined LSE and CA technology. In this article, we aimed to realize this combination and gave credence to LSE's advantages in ecological protection and sustainable land use, as well as CA's advantage in objective dynamic simulation. Three major goals in this article were as follows: (a) reducing the waste of land resources and promoting sustainable land use in the process of UGB delimitation; (b) conducting scientific and quantitative simulation of urban growth, and delineating growth boundary lines; and (c) generating three different urban growth scenarios and corresponding UGBs, and providing reference for local planning and policy decision.

2. Materials and Methods

2.1. Study Area

The study area, Ningbo City, Zhejiang Province, China, lies between latitudes 28°51′ N–30°33′ N and longitudes 120°55′ E–122°16′ E, and encompasses a total land mass of 9816 km^2 (excluding ocean). Ningbo City includes six districts (Haishu, Jiangdong, Jiangbei, Zhenhai, Beilun, and Yinzhou), two counties (Ninghai and Xiangshan), and three county-level cities (Fenghua, Yuyao, and Cixi) (Figure 1). Ningbo is suitable for this study because it is a typical eastern coastal city in China which is undergoing a prosperous period of port economy growth and rapid urban sprawl. Starting in 1978, GDP of Ningbo has grown to 800.36 billion CNY in 2015, 396.2 times that in 1978 (2.02 billion CNY), with the population increasing to 5.87 million in 2015, compared to 4.58 million in 1978 [43]. The built-up urban area has increased 27 times, from 18.3 km^2 in 1978 to 501.4 km^2 in 2015 [43,44]. In addition, urban growth tends to increase in the future in accordance with the development strategy of "Port Economic Circle", which aims to carry forward the resource advantage of the port and raise the overall strength of Ningbo. Thus, it is significant to formulate scientific, distinctive, and sustainable UGB in Ningbo.

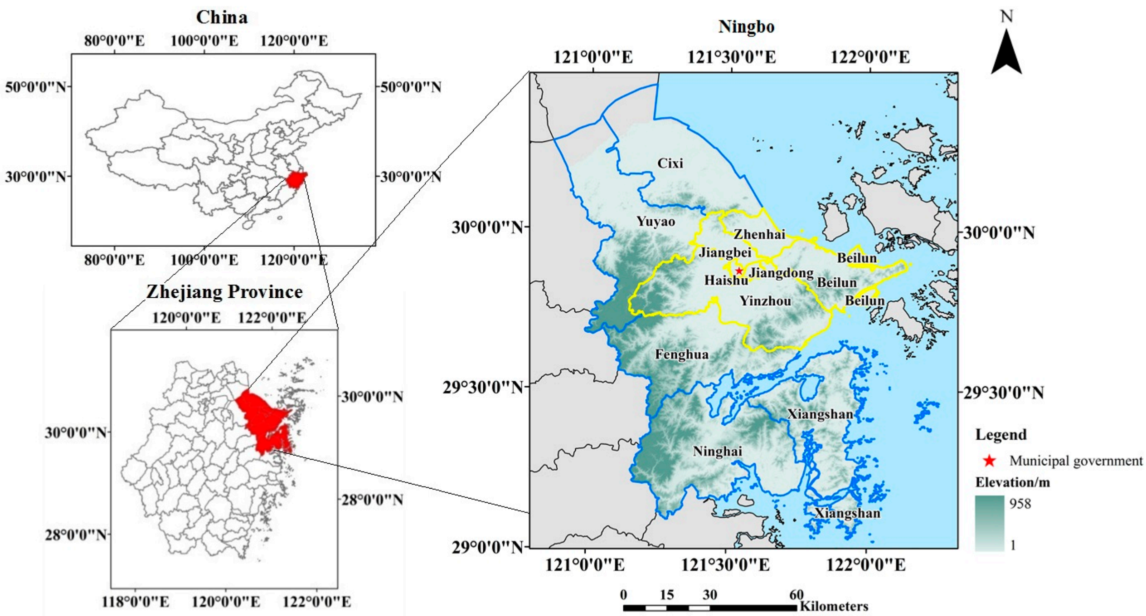

Figure 1. Location of Ningbo; the yellow line area: central city; the blue line area: the surrounding counties and cities. Note: the administrative division within Ningbo city was adjusted in 2016, but the overall administrative region of the city was not changed. Due to the study period in this paper was 2002–2015, we used the old administrative division.

2.2. Data Preparation

The data sources of this study contained remotely sensed data, topographic data, social and economic data, ecological safety data, planning maps, etc. Remotely sensed data covering the study site were acquired which had been geometrically corrected and registered (Table 1).

Table 1. Remote sensing data.

Date of Acquisition	Data Source	Path/Row	Spatial Resolution
23 August 2002	Landsat 7-ETM +	118/39	30 m
23 August 2002	Landsat 7-ETM +	118/40	30 m
17 July 2009	Landsat 5-TM	118/39	30 m
17 July 2009	Landsat 5-TM	118/40	30 m
3 August 2015	Landsat 8-OLI	118/39	30 m
3 August 2015	Landsat 8-OLI	118/40	30 m

Preprocessing these data contained radiometric calibration, atmospheric correction, mosaic, and image cutting. A Maximum Likelihood algorithm in supervised classification was used to categorize built-up and non-developed land. As this study only paid attention to urban growth, a binary classification of remote sensing image was sufficient [11]. The preprocessing and classification procedures were conducted in ENVI RSI 5.1 (Exelis Visual Information Solutions, Boulder, CO, USA).

In terms of accuracy assessment of land classification, due to paucity of data at appropriate and finer resolution in 2002 and 2009, we utilized a GF1-WFV image acquired in 2015 to assess the accuracy of the classified image in 2015, which can represent the accuracy of all classified images. The overall accuracy was 94.68% and Kappa coefficient was 0.97; detailed results can be seen in Table 2.

Table 2. Confusion matrix between classification result and the observed data.

Class	Prod. Acc. [1] (%)	User Acc. [2] (%)	Prod. Acc. (Pixels)	User Acc. (Pixels)	Overall Accuracy (%)	Kappa Coefficient
Built-up land	95.97	92.96	2644/2755	2641/2841	94.68	0.97
Non-developed land	93.90	96.02	3480/3706	3476/3620		

[1] Prod. Acc. is the abbreviation of producer's accuracy; [2] User Acc. is the abbreviation of user's accuracy.

Topographic data was derived from a DEM. The image registration and correction of DEM were processed in ERDAS 9.2 (Hexagon Geospatial, Madison, AL, USA), while elevation and slope information was extracted in ArcGIS 10.1 (Esri Inc., Redlands, CA, USA). Moreover, we obtained social and economic data, ecological safety data, and planning maps from the Ningbo Municipal Bureau of Land and Resources, and the Ningbo Municipal Bureau of Planning.

2.3. Ecological Limitation Identification

We defined ecological limitation areas as unsuitable construction regions to limit urban growth and to realize high-efficient and intensive utilization of land resources [45]. The LSE method considers that resources and ecological carrying capacity are prerequisites for urban land selection; it should analyze the economic, social, cultural, and historical conditions of lands in advance, and then discuss the urban development direction [14]. LSE included three sequential steps:

(1) Suitability evaluation index system was established based on the construction conditions of Ningbo, the "Port Economic Circle" strategy, and consideration of ecological protection. This system included thirteen indexes which were divided into three types: natural, socio-economic and ecological safety factors, and their weights were defined by an analytic hierarchy process (AHP) (Table 3) [6,20,37,46].

(2) Index quantitate grading was represented by scores (i.e., 1, 2, 3) for each index, in accordance with the suitability zoning rules. Suitability evaluation zoning rules can be seen in Table 4 and the detailed information of index quantitate grading can be seen in Table 5. We imported each index map into ArcGIS 10.1 and assigned corresponding scores for them. After this step, suitability zoning map for the single index can be achieved.

(3) Rasterize process was implemented by dividing the study area into 50 m × 50 m grids. Then, superposition of index score of each grid, namely comprehensive suitability evaluation value, was calculated through overlay analysis in ArcGIS 10.1.

Table 3. Suitability evaluation indexes and weights.

Interlayer	Weight	Index Layer	Weight	Weight (for Overall Objective)
Natural factor	0.25	Elevation	0.20	0.05
		Slope	0.30	0.075
		Geological disaster	0.15	0.0375
		Geomorphic type	0.05	0.0125
		River	0.20	0.05
		Lake/reservoir	0.10	0.025
Socio-economic factor	0.5	Built-up area	0.40	0.20
		Transportation	0.20	0.10
		Port	0.20	0.10
		Population density	0.20	0.10
Ecological safety factor	0.25	Coastline	0.30	0.075
		Basic farmland	0.30	0.075
		Ecological preservation area [1]	0.40	0.10

[1] Ecological preservation area consists of nature reserve, scenic area, ecological non-commercial forest, forest park, drinking-water source protection area, important wetland, historical and cultural heritage protection area, and marine protected area.

Table 4. Suitability evaluation zoning rules.

Suitability Evaluation Zoning	Description	Score
Suitable region	Priority as construction land	3
Basic suitable region	Effect of construction land is not obvious	2
Unsuitable region	Not used as construction land	1

Table 5. Suitability evaluation indexes quantitate grading.

Evaluation Factor	Evaluation Index	Grading Basis	Grading Conditions	Score
Natural factor	Elevation	Construction conditions of Ningbo City	>200 m	1
			100–200 m	2
			<100 m	3
	Slope	Construction conditions of Ningbo City	>25°	1
			15–25°	2
			<15°	3
	Geological disaster	Prevented and cured plan of geological disaster	Easy-happening area	1
			Not easy-happening area	3
	Geomorphic type	Construction conditions of Ningbo City	Water area	1
			Hill	2
			Plain and basin	3
	River	Ningbo integrated planning of water resources	River area	1
			Not river area	3
	Lake/reservoir	Delimiting method of lakes, reservoirs and drinking-water source protection areas	<1 km buffer area	1
			1–3 km buffer area	2
			>3 km buffer area	3

Table 5. *Cont.*

Evaluation Factor	Evaluation Index	Grading Basis	Grading Conditions	Score
Socio-economic factor	Built-up area	Current urban growth trend in Ningbo	>2 km buffer area <2 km buffer area Built-up area	1 2 3
	Transportation	Traffic radiation radius in Ningbo	>2 km buffer area 1–2 km buffer area <1 km buffer area	1 2 3
	Port	Current urban growth trend around ports in Ningbo	>2 km buffer area 1–2 km buffer area <1 km buffer area	1 2 3
	Population density	The actual population size and planned population in Ningbo City Master Plan (2006–2020, 2015 revision)	<500 people/km^2 500–1000 people/km^2 >1000 people/km^2	1 2 3
Ecological safety factor	Coastline	Ningbo City marine functional zoning and relevant provision	<1 km buffer area 1–2 km buffer area >2 km buffer area	1 2 3
	Basic farmland	Ningbo City general land use planning (2006–2020)	Basic farmland area Not basic farmland area	1 3
	Ecological preservation area	Ecological red line delimitation scheme	Ecological preservation area Not ecological preservation area	1 3

2.4. Urban Growth Simulation

We utilized Dinamica EGO 3.0.17 (Remote Sensing Center of Minas Gerais Federal University, Belo Horizonte, MG, Brazil) to test and predict urban growth. This software is a platform for spatiotemporal simulation and is designed by Remote Sensing Center of Minas Gerais Federal University. Dinamica EGO is written by object-oriented C++ language and exists in a CA environment. All Dinamica parameters can be set through image interface, then the model is designed as chart form and its operation will follow the data flow chain [47–49]. The six operating steps of Dinamica EGO were as follows:

(1) Annual global transition rates for a single transition type—from non-developed land to built-up land, were calculated through cross-tabulation for the maps in 2002, 2009, and 2015 (binary classification map).
(2) Local transition probabilities (i.e., transition probability of each cell) were calculated by the weights of evidence (WoE), which is a Bayesian method [47,48]. Spatial variables were selected as model input and were divided into two subsets based on their static and dynamic nature [47]. One subset was the static spatial variable, seven variables were chosen for WoE, and the detailed information and their maps are shown in Table 6 and Figure 2. Another subset was the dynamic spatial variable, which was automatically generated based on the initial landscape map. The WoE coefficients for all spatial variables can be seen in Figure 3.
(3) Model calibration (2002–2009) was implemented to affirm that each pair of spatial variables was independent (Table 7). Cramer's coefficient (V) and Joint Information Uncertainty (U) were applied and the values of them are from 0 to 1; 0 means independency and 1 means complete correlation. When two values were both less than 0.5, this means there is no obvious correlation between two variables [50].
(4) Model execution (2009–2015) was carried out through a local CA rules transformation engine, which consists of two complementary conversion functions: Expander and Patcher. Expander represents the development of existing patches, while Patcher represents producing new patches. Various change forms can be revealed through changing the parameters of mean patch size, patch size variance, and isometry in both functions [50,51].
(5) Accuracy assessment (model validation) was practiced by reciprocal fuzzy comparison method to compare the similarities (spatial matching) of the simulated and actual observed land use changes. A series of similarity values of the simulated change map (between the 2009 observed

map and 2015 simulated map), and the observed change map (between the 2009 observed map and 2015 observed map), were obtained accompany with the growing window sizes, such as 1 × 1 cell, 3 × 3 cells, and 5 × 5 cells [48,52].

(6) Model prediction was implemented according to three urban growth scenarios:

(a) Unregulated scenario: This scenario presented uncontrolled urban development without any guidance of policy or planning. The parameters were adjusted based on the parameters in reference scenario (maintained 2002–2015 urban growth rates): Patcher/Expander ratio was added by 25%; transition rate was added by 10%; mean size of built-up patches was reduced by 25%; and the weight of ecological limitation in the spatial probability map was set to zero.

(b) Port development scenario: This scenario emphasized urban growth driven by the "Port Economic Circle" strategy. The parameters were adjusted as follows: Patcher/Expander ratio was reduced by 25%; mean size of built-up patches was added by 50%; the weights of distance to ports and distance to transportation were set to 2 and 1.5, respectively; and the influence of ecological limitation was introduced according to the reference scenario.

(c) Regulated scenario: This scenario emphasized planning control and natural conservation. The parameters were adjusted as follows: Patcher/Expander ratio was reduced by 50%; transition rate was reduced by 50%; mean size of built-up patches was added by 85%; and the weights of unrestrained and restrained options in ecological limitation were set to 2 and −2, respectively. The values of parameters in different scenarios can be found in Table 8.

Table 6. Datasets of static spatial variables.

Number	Variable	Description	Value (m)	Data (Source)	Year	Variable Data Type
a	Distance to municipal and county governments	Attractiveness of municipal and county governments	0–10,000	Ningbo Municipal Bureau of Land and Resources	2015	Continuous
b	Distance to satellite town governments	Attractiveness of satellite town governments	0–5000	Ningbo Municipal Bureau of Land and Resources	2015	Continuous
c	Distance to town governments	Attractiveness of town governments	0–2000	Ningbo Municipal Bureau of Land and Resources	2015	Continuous
d	Distance to rivers	Attractiveness of rivers	0–2000	Ningbo Municipal Bureau of Land and Resources	2015	Continuous
e	Distance to transportation	Attractiveness of transportation	0–2000	Ningbo Municipal Bureau of Planning	2015	Continuous
f	Distance to ports	Attractiveness of port cluster areas	0–2000	Ningbo Municipal Bureau of Planning	2015	Continuous
g	Ecological limitation	Urban growth restriction	Unrestrained and restrained	Comprehensive suitability zoning	2015	Categorical

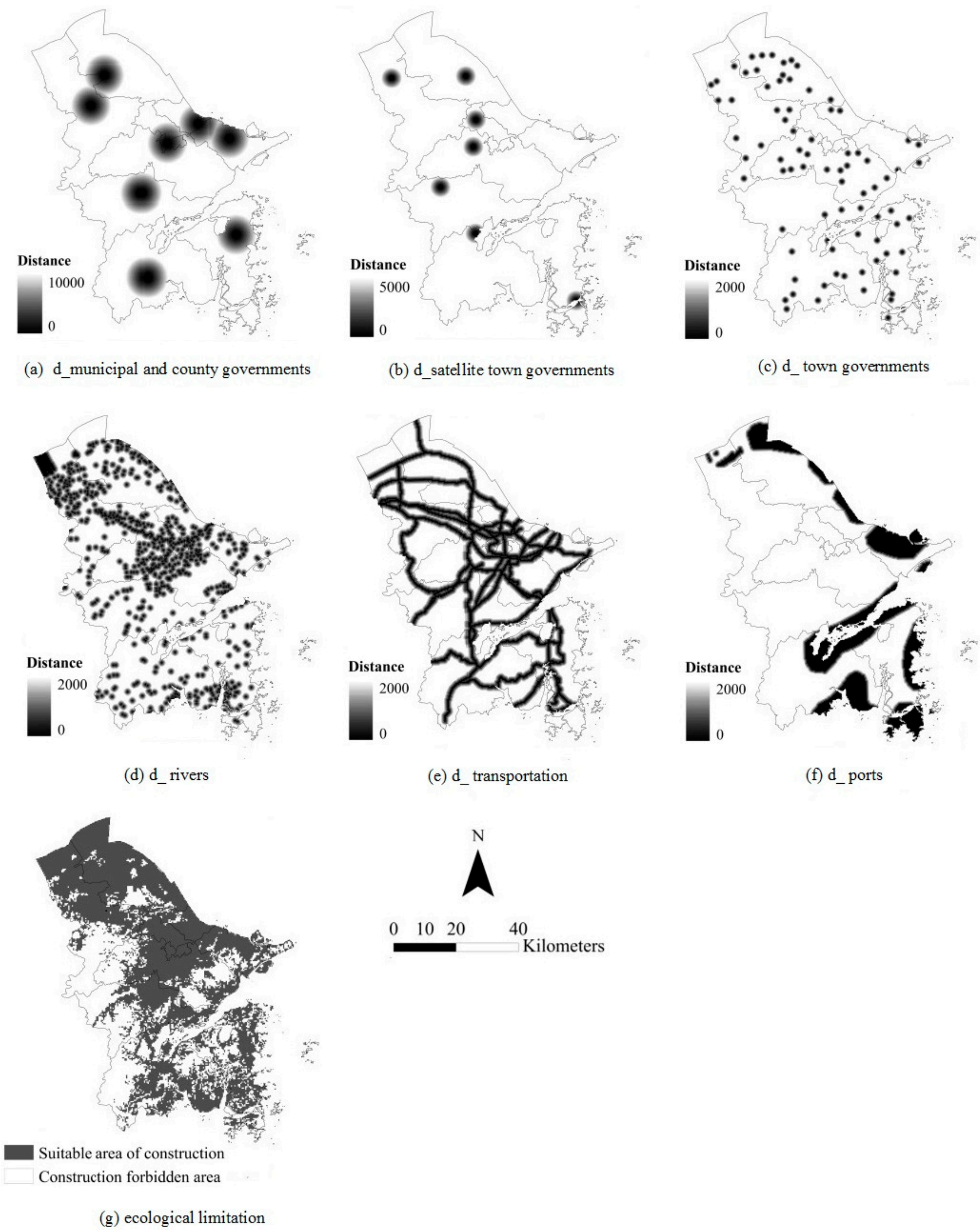

Figure 2. Maps of static spatial variable layers: (**a**) distance to municipal and county governments; (**b**) distance to satellite town governments; (**c**) distance to town governments; (**d**) distance to rivers; (**e**) distance to transportation; (**f**) distance to ports; (**g**) ecological limitation.

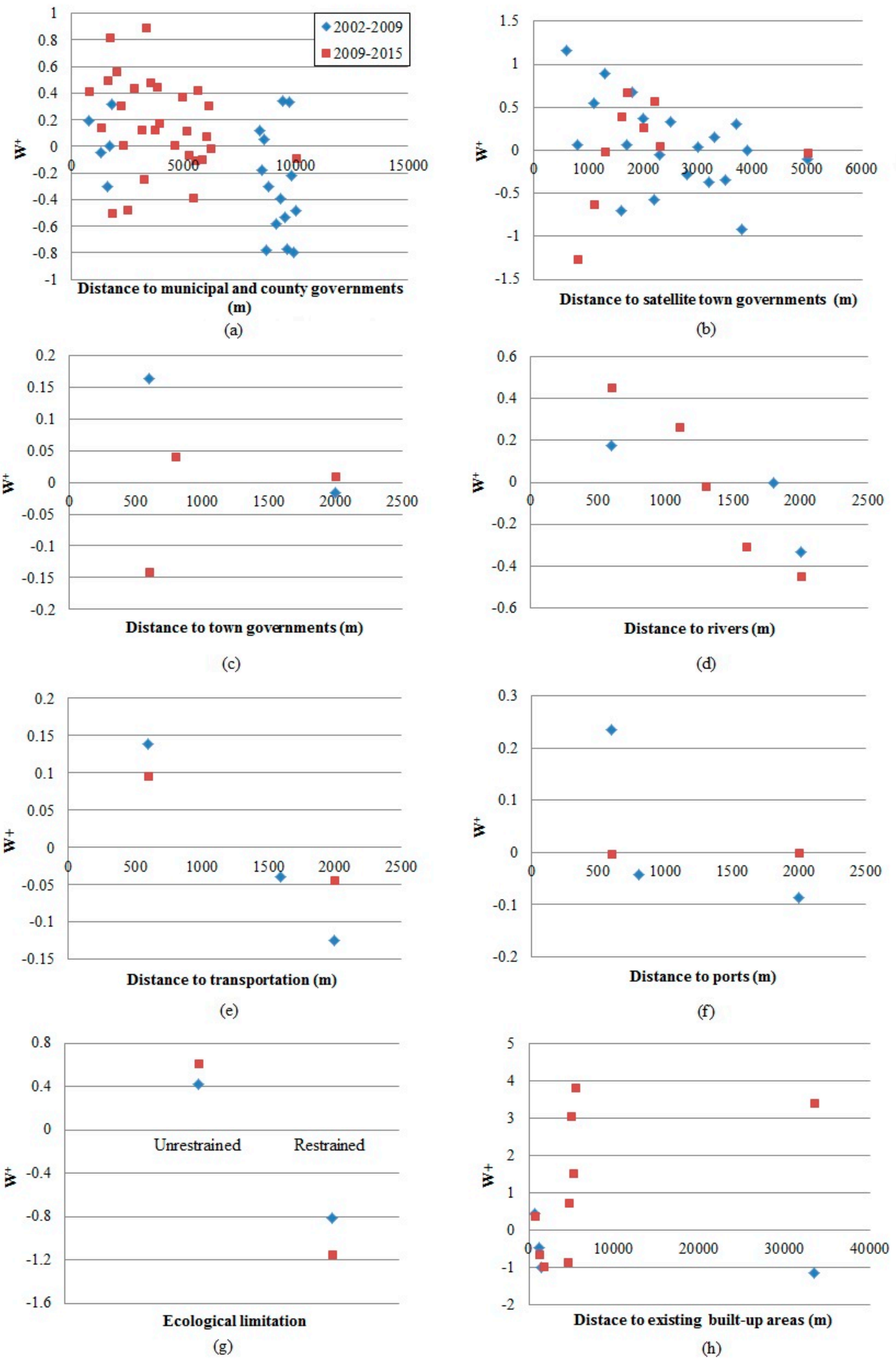

Figure 3. Weights of evidence coefficients for spatial variables of change from non-developed land into built-up land for the calibration and validation periods: (**a**) distance to municipal and county governments; (**b**) distance to satellite town governments; (**c**) distance to town governments; (**d**) distance to rivers; (**e**) distance to transportation; (**f**) distance to ports; (**g**) ecological limitation; (**h**) distance to existing built-up areas.

2.5. Urban Growth Boundary (UGB) Lines Delineation

We delineated three future UGBs in accordance with the urban growth areas under three scenarios. The procedures were as follows: firstly, the format of the simulated built-up patches was transformed from raster to vector. Then, some small areas with low concentration in the vector map of built-up lands were deleted. Finally, UGBs were depicted in the light of the boundaries of other big built-up areas. Further, developable lands in the future were calculated through deducting pre-existing built-up lands from the total built-up lands in UGBs [17].

2.6. Framework of UGB Delimitation

In this study, RS, GIS, LSE, and CA models were integrated to simulate urban growth and delineate UGBs in Ningbo. The framework of UGB delimitation consisted of four sequential phases, as shown in Figure 4: (1) Preparing data using RS and GIS technologies; (2) Identifying the restricted areas of urban growth through LSE and importing this result into the CA model as fundamental spatial variable; (3) Establishing urban growth model and predicting future urban growth under three scenarios by the CA model; (4) Delineating UGB lines.

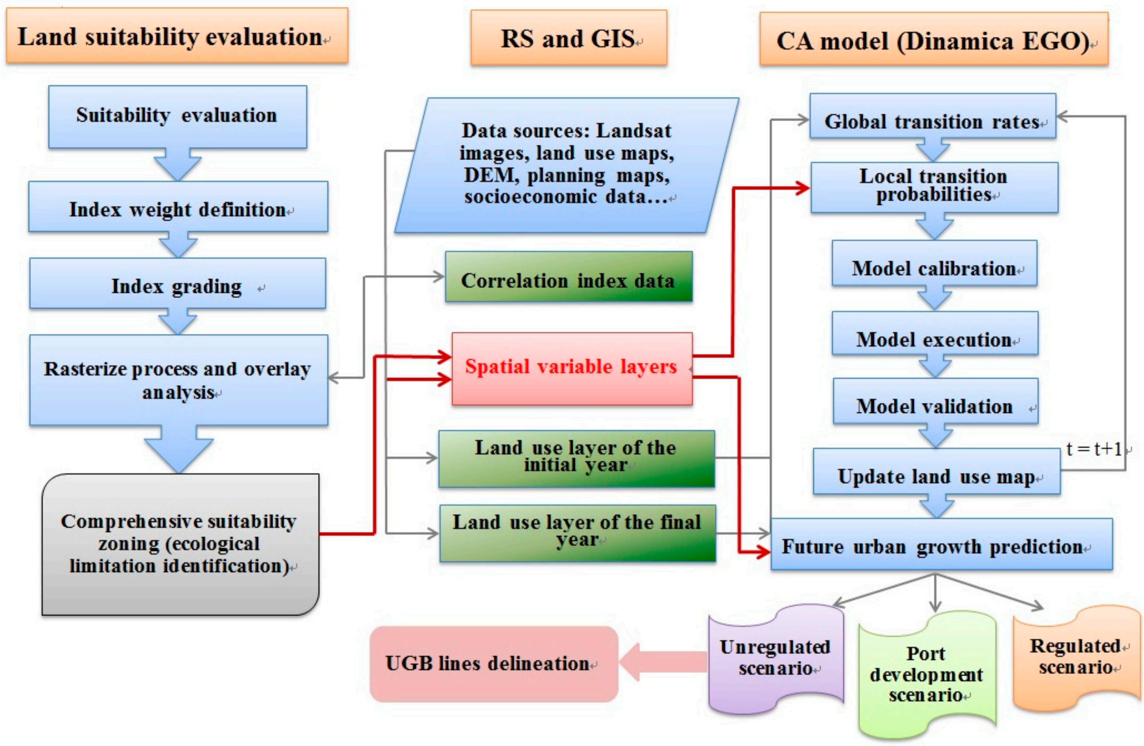

Figure 4. Framework of urban growth boundary (UGB) delimitation.

The concrete operation of combining the LSE and CA models were as follows: the result of LSE, namely comprehensive suitability zoning (emphasis on ecological protection), was imported into the second step (allocating local transition probabilities) of the CA model as the most important spatial variable (i.e., ecological limitation). In the model execution step, this spatial variable was integrated with other guiding spatial variables to increase the likelihood of urban growth in suitable regions and to prohibit the possibility of urban sprawl in unsuitable regions. In addition, through changing the weight of ecological limitation in the sixth step (predicting future urban growth) of the CA model, we closely linked the LSE result with simulations of future urban growth under different scenarios, especially under port development and regulated scenarios.

Table 7. Cramer's coefficient—V (white cells) and Joint Information Uncertainty—U (grey cells) values used to represent correlation between spatial variables.

Cramer's Coefficient/Joint Information Uncertainty	Distance to Built-up Areas	Distance to Municipal and County Governments	Distance to Satellite Town Governments	Distance to Town Governments	Distance to Rivers	Distance to Transportation	Distance to Ports	Ecological Limitation
Distance to built-up areas	—	0.11	0.08	0.05	0.08	0.09	0.06	0.43
Distance to municipal and county governments	0.02	—	0.04	0.15	0.07	0.10	0.27	0.18
Distance to satellite town governments	0.02	0.03	—	0.09	0.10	0.12	0.31	0.11
Distance to town governments	0.00	0.02	0.03	—	0.04	0.02	0.23	0.02
Distance to rivers	0.01	0.01	0.02	0.00	—	0.03	0.11	0.13
Distance to transportation	0.01	0.00	0.01	0.00	0.00	—	0.05	0.05
Distance to ports	0.00	0.04	0.06	0.05	0.01	0.00	—	0.01
Ecological limitation	0.11	0.02	0.01	0.00	0.01	0.00	0.00	—

Table 8. Parameters in simulations of urban growth scenarios.

Scenario/Parameter	Mean Patch Size (ha) (Patcher)	Mean Patch Size (ha) (Expander)	Patch Size Variance	Isometry	Patcher/Expander Ratio	Transition Rate (%)	Weight Change
Reference scenario	0.3	0.36	0.72	1.5	0.43	5.24	No change
Unregulated scenario	0.225	0.27	0.72	1.5	0.54	5.77	Ecological limitation—0
Port development scenario	0.45	0.54	0.72	1.5	0.33	5.24	Distance to ports—2, Distance to transportation—1.5
Regulated scenario	0.56	0.67	0.72	1.5	0.22	2.62	Ecological limitation: unrestrained—2, restrained—−2

3. Results

3.1. Extraction of Ecological Limitation Areas

LSE yielded suitability zoning maps of a single index, which was divided into three categories: natural factor maps, socio-economic factor maps, and ecological safety factor maps (Figures 5–7). In addition, the results of comprehensive suitability zoning can be seen in Table 9 and Figure 8. Suitable regions occupied 2531.25 km^2, mainly distributed in the plains of northern areas, and the middle and eastern areas of the central city. Basic suitable regions were found in the junction areas of plains and hills with an area of 3555.44 km^2, which widely existed in north, middle, and southern areas of the city. Unsuitable regions covered an area of 3648.74 km^2, where it gathered around the hills in southwest areas, southern areas of the central city, and the junction areas of Ninghai and Xiangshan Counties. Suitable regions and basic suitable regions were merged and regarded as suitable areas of construction, while unsuitable regions were supposed to be construction forbidden areas. This was because of a focus on ecological protection and limiting urban growth. This binary classification map was called ecological limitation, and was used as fundamental spatial variable layer which applied in the CA model (Figure 2g).

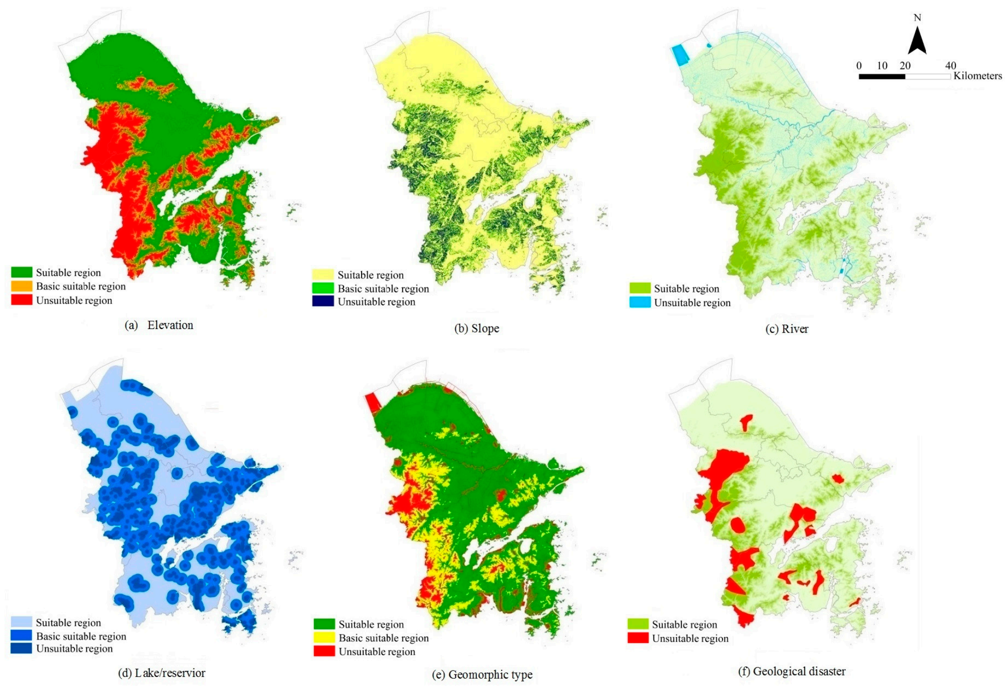

Figure 5. Suitability zoning maps of single index (natural factor): (**a**) elevation; (**b**) slope; (**c**) river; (**d**) lake/reservoir; (**e**) geomorphic type; (**f**) geological disaster.

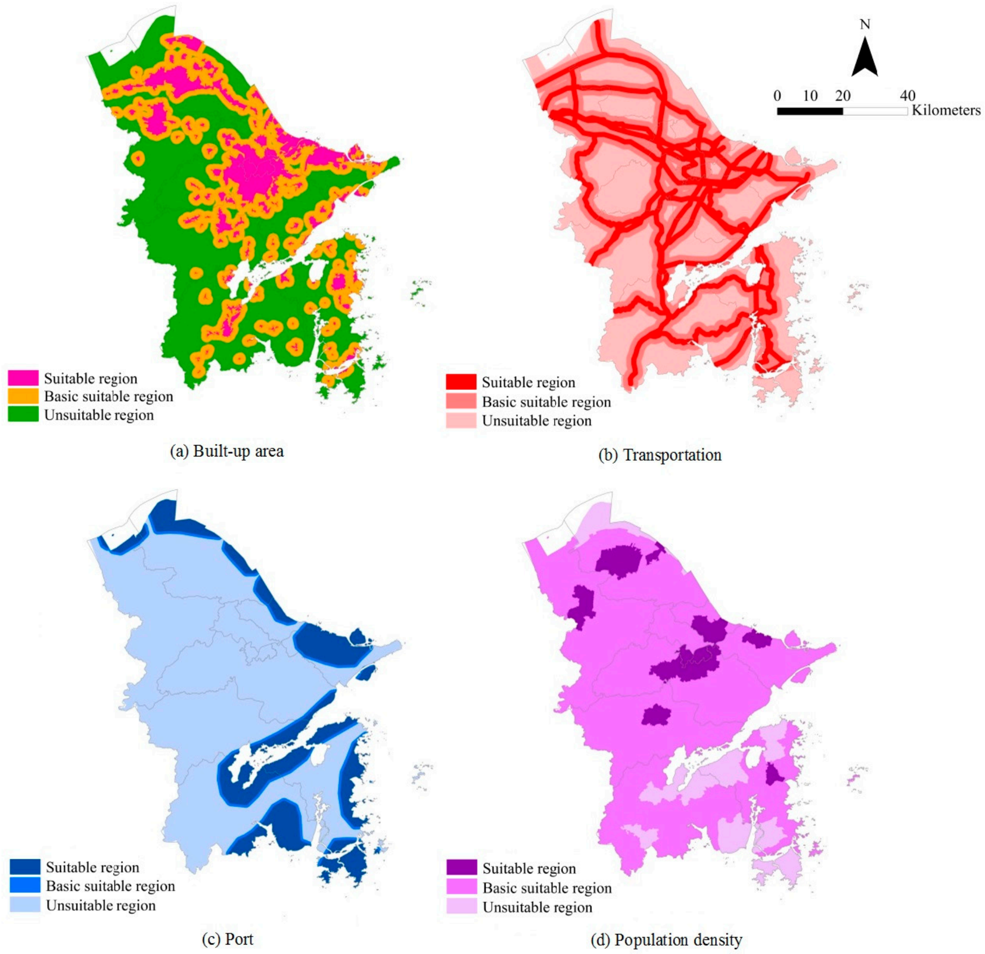

Figure 6. Suitability zoning maps of single index (socio-economic factor): (**a**) built-up area; (**b**) transportation; (**c**) port; (**d**) population density.

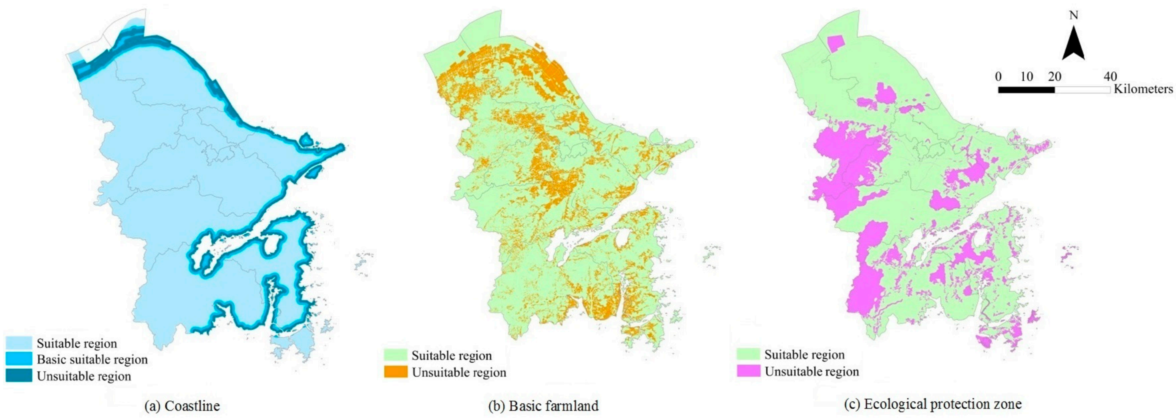

Figure 7. Suitability zoning maps of single index (ecological safety factor): (**a**) coastline; (**b**) basic farmland; (**c**) ecological preservation area.

Table 9. Results of comprehensive suitability zoning.

Comprehensive Suitability Zoning	Comprehensive Suitability Evaluation Value	Area (km^2)	Percent (%)
Suitable region	(1, 1.5)	2531.25	26.00
Basic suitable region	(1.5, 2.5)	3555.44	35.52
Unsuitable region	(2.5, 3)	3648.74	38.48

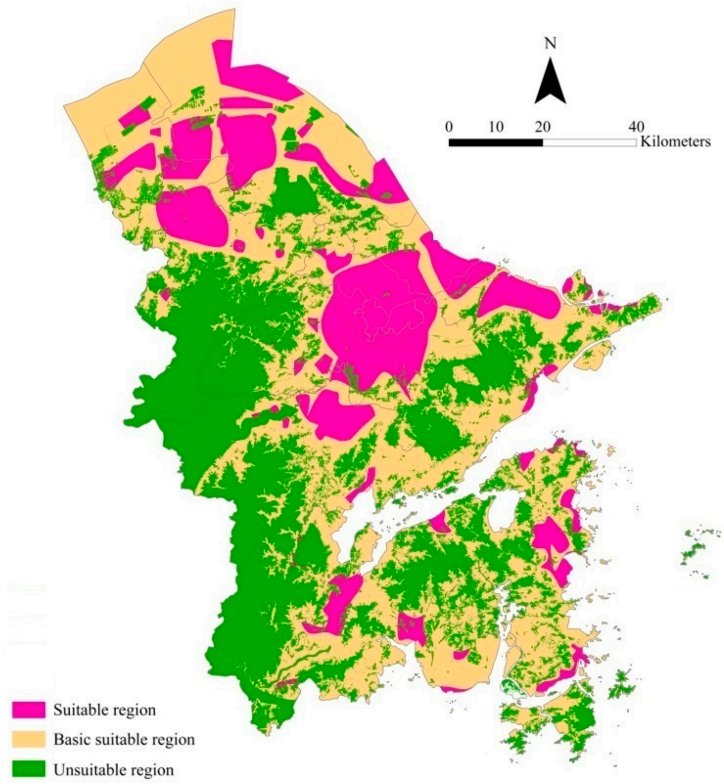

Figure 8. Comprehensive suitability zoning map.

3.2. Accuracy Assessment of Urban Growth Model

The testing of urban growth model from 2009 to 2015 can be seen in Figure 9. A visual inspection of comparing the new built-up patches confirmed that there was good spatial fitting in the northern and central areas, and a poor spatial fitting in the southern areas, of Ningbo. In addition, the multiple resolution fitting procedure showed that the mean fuzzy similarity of the simulated change map and the observed change map (model accuracy) was heightened when the window size became increasingly larger. The mean fuzzy similarity started from 35% in the window size of 30 m, and stopped to 87% in a window size of 330 m. A mean fuzzy similarity exceeded 50% at a spatial resolution of about 60 m (Figure 10). Through comparing the accuracies or similarities of urban growth models in other studies [53–57], we thought this CA model was able to simulate future urban growth.

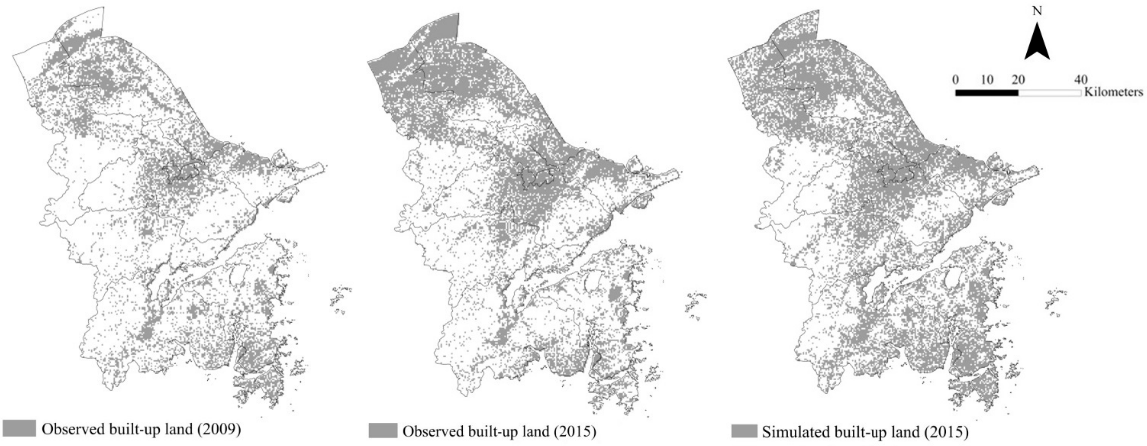

Figure 9. Observed landscape maps for the years 2009 (**left**), 2015 (**center**), and the simulated landscape map for 2015 (**right**).

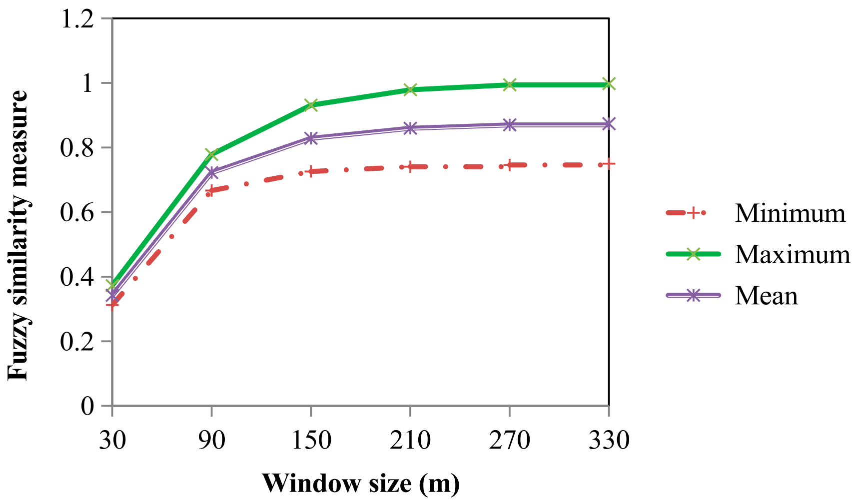

Figure 10. Multiple window fuzzy similarity obtained from the comparison of simulated changes and observed changes from 2009 to 2015.

3.3. Simulation of Future Urban Growth Scenarios and UGBs

The simulation results of the unregulated, port development, and regulated urban growth scenarios, as well as their corresponding UGBs for 2020, were presented in Figures 11 and 12. (a) Unregulated scenario showed the largest scope of built-up lands and produced a pattern of the smallest and the most dispersive patches. Meanwhile, the development of this scenario was not under the control of ecological limitation. The total area of the corresponding UGB was 5085.99 km^2 and developable area was 1366.43 km^2. (b) Port development scenario gave rise to a moderate amount of built-up land, and guided the cluster growth of built-up patches around the port areas and arterial traffic. This scenario also took into consideration the influence of ecological limitation, in which the total area and developable area of this UGB occupied 4448.92 km^2 and 730.36 km^2, respectively. (c) Regulated scenario led to the smallest number of new built-up patches and generated a pattern of the most concentrated and compact built-up patches. Furthermore, this scenario reflected a situation whereby the ideas of intensive land use and ecological protection were imposed. This UGB covered an area of 4005.84 km^2 and only 287.28 km^2 lands can be developed in the future.

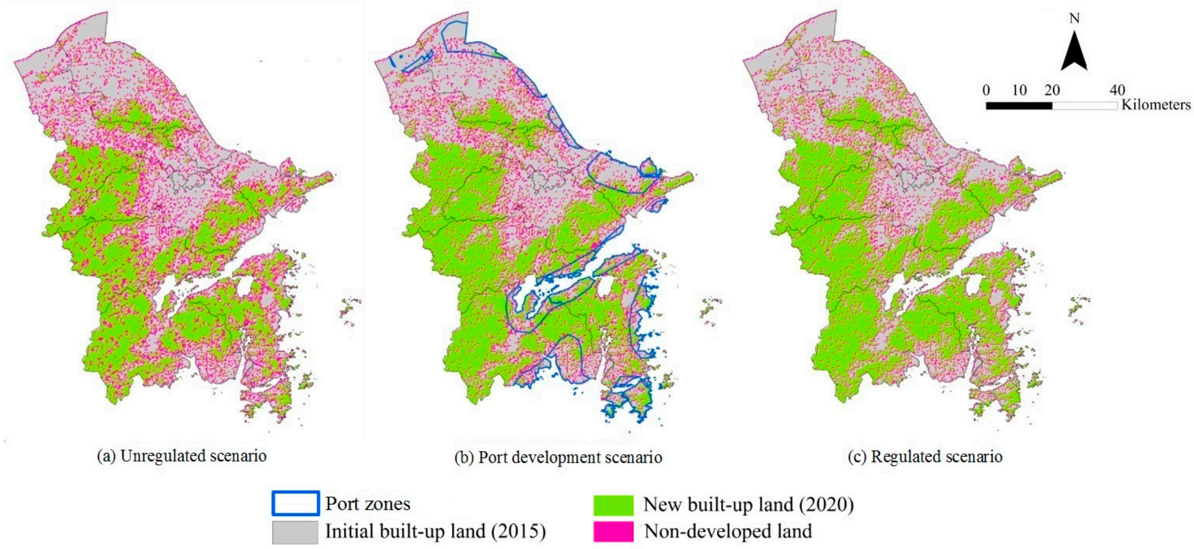

Figure 11. Simulation results under the (**a**) unregulated; (**b**) port development; and (**c**) regulated scenarios in 2020.

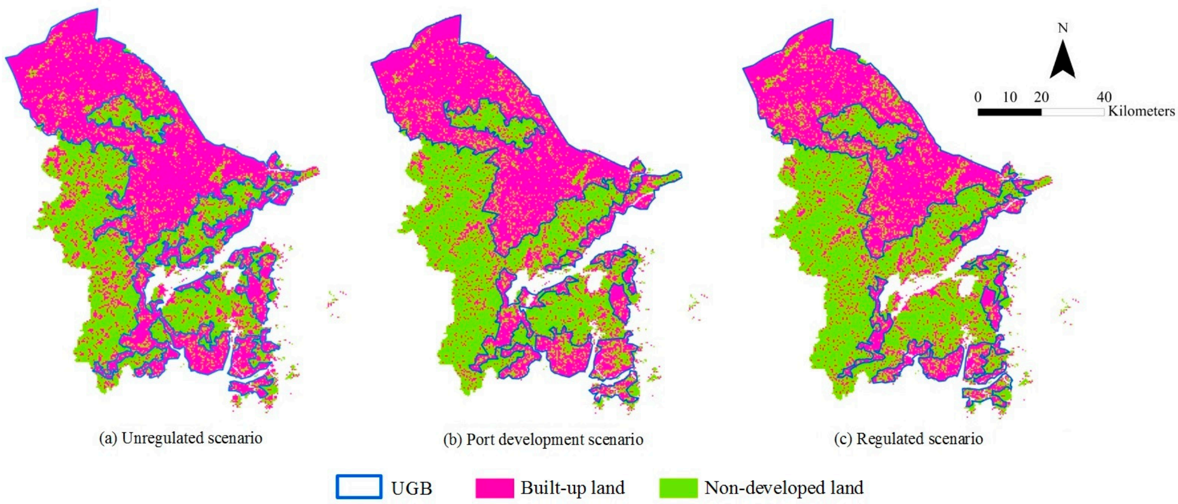

Figure 12. UGBs under the (**a**) unregulated; (**b**) port development; and (**c**) regulated scenarios in 2020.

4. Discussion

The urban growth model and UGBs of Ningbo were established in this study through combining the LSE and CA models, with the support of RS and GIS techniques. In contrast to the conventional Chinese UGB development methods based on LSE and urban planning zoning results, and the foreign UGB development methods only based on urban modeling, this improved method considered a combination of sustainable land use and urban growth simulation. It not only avoided the waste of ecological and land resources, but also objectively reflected historical and future development trends, and the impacts of development strategy and ecological limitations on city succession. This study demonstrated that this method was able to offer useful experiences in establishing and optimizing UGBs, and to promote land development and eco-environmental sustainability in Chinese cities.

4.1. Accuracy of Urban Growth Model

Through the accuracy assessment of urban growth model, it could be found that although the urban growth model produced an acceptable mean fuzzy similarity of the simulated changes and the observed changes from 2009 to 2015, poor spatial fitting appeared in southern areas of Ningbo, and the simulated results overestimated the extent of new built-up lands in these areas (Figure 9). The reasons may be derived from the positioning of surrounding counties and cities in Ningbo City Master Plan (2006–2020, 2015 revision) (NCMP), which guided city development since 2006. In NCMP, Ninghai and Xiangshan Counties were defined as the national marine ecological civilization demonstration areas, which required these two counties to pay more attention to implement environmental renovation projects, exert marine resources advantage, and maintain high quality of marine ecological environment. Hence, urban developments of Ninghai and Xiangshan were relatively lagging behind the central city and northern areas (i.e., Cixi and Yuyao Cities). Meanwhile, due to the limitation of topography, such as poor conditions of elevation and slope for land development, and being far from the central city, the gathering radiation effects of these two counties were weak and consequently, urban growth rates were slow. Thus, it can be seen that the urban growth model should take more planning and policy guidance factors into consideration, in order to avoid overestimating the demand of urban growth.

4.2. Comparison of Simulated UGBs and Planned UGB

To verify the advantage of this UGB delimitation method, we conducted a comparative analysis of the simulated UGBs in three scenarios and the planned UGB in 2020 established in the NCMP. The planned UGB was defined based on the results of urban planning zoning, namely that we merged suitable construction zone and construction control zone, and delineated the boundaries of these regions. Many inconsistencies have been found between the simulated UGBs and the planned UGB (Figure 13). From the perspective of quantity, the area of planned UGB was 4900.28 km^2 and the developable area was 1181.72 km^2. These two values were smaller than that of the UGB under unregulated scenario, but larger than the UGBs under port development and regulated scenarios. This meant that the UGBs under port development and regulated scenarios may provide better guidance for the land intensive utilization, and thus enhance land use efficiency. From the perspective of spatial distribution, the discordances covered the whole city. In northern areas, the main contradiction came from the prediction of coastal shoal reclamation in Cixi City. The simulated UGBs had larger reclamation areas along Hangzhou Bay (i.e., the most northern areas of Ningbo city) than those of the planned UGB. According to the results of local transition probabilities in Figure 3, urban development probabilities around transportation and ports were relatively high in previous years. The simulated UGBs followed the development trend and extended reclamation areas that have good accessibility to Hangzhou Bay Bridge and Shanghai. In central areas, the planned UGB designed a "Green Ring" around the central city, but there was no similar design in the simulated UGBs. Through setting this green corridor, the planner aimed to avoid unlimited urban expansion, and to promote the coordination of the city spatial structure and ecological pattern. The simulated UGBs lacked this beneficial subjective human design. In southern areas, the planned UGB had larger areas than those in the UGBs under port development and regulated scenarios. In view of the development lag of southern areas have been explained previously, the two simulated UGBs were more suitable for these areas' urban growth in the future. These findings recommended that the UGBs under port development and regulated scenarios were superior to the planned UGB, but these two simulated UGBs can be improved by considering rewarding subjective planning and design.

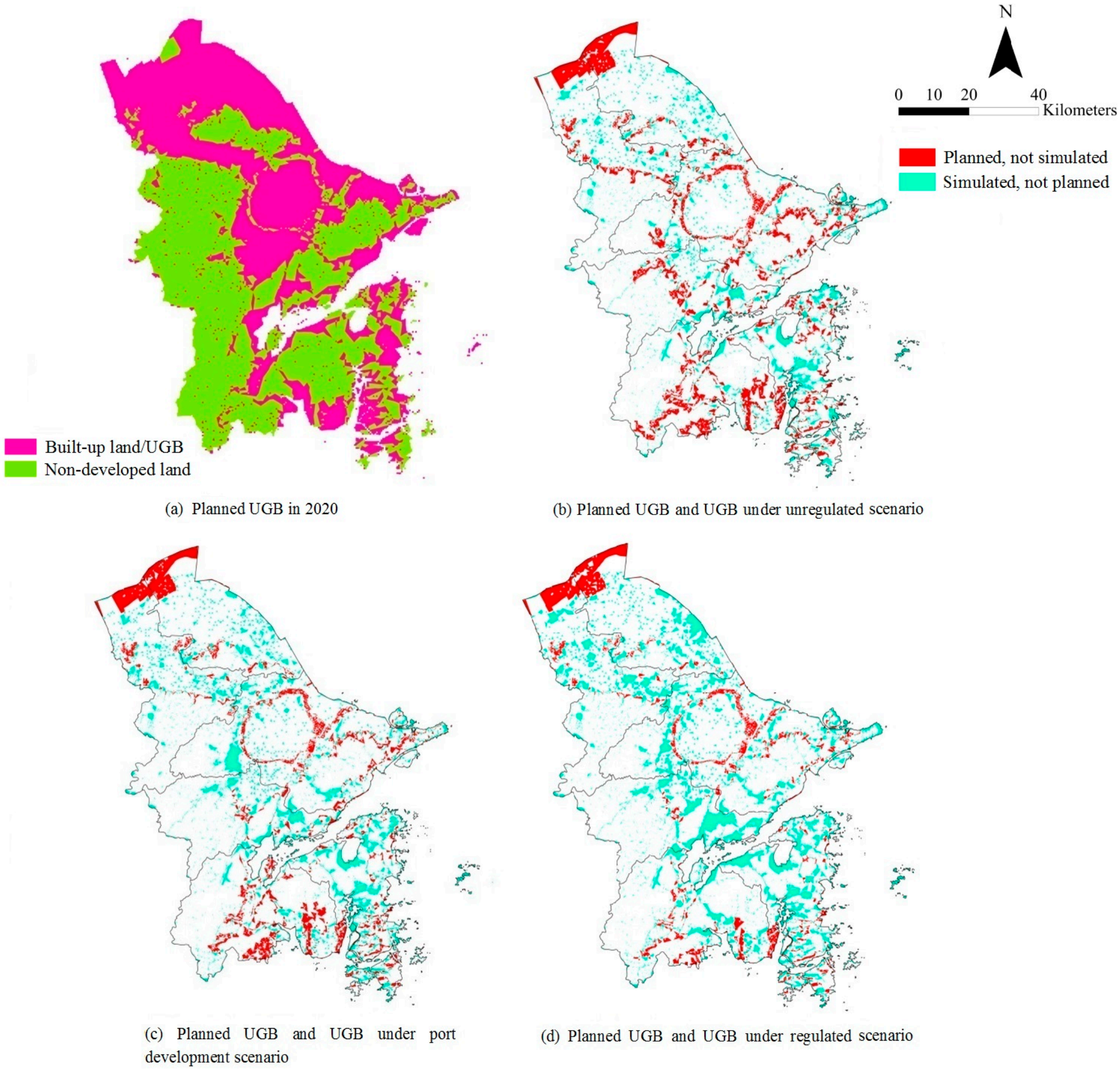

Figure 13. (**a**) Planned UGB in 2020 in contrast with (**b**) UGB under unregulated scenario; (**c**) UGB under port development scenario; and (**d**) UGB under regulated scenario.

For further comparison of the rationality of space structure of urban growth, we calculated six landscape indexes of the simulated UGBs and the planned UGB by software FRAGSTATS version 4.2 (UMass Landscape Ecology Lab, Amherst, MA, USA). Number of patches (NP), mean patch size (AREA_MN), and percentage of like adjacencies (PLADJ) can show the patch fragmentation; largest patch index (LPI) can reveal the dominant patch; edge density (ED) can display patch complicacy; and Euclidian mean nearest neighbor distance (ENN-MN) can embody patch proximity. The results of NP, AREA_MN, and PLADJ in Table 10 revealed that the UGB under regulated scenario and the planned UGB had more concentrated, larger, and compact patches than other two simulated UGBs. The values of LPI showed the planned UGB had one center patch (urban core), while the simulated UGBs formed some new urban cores. The values of ED and ENN_MN reflected the UGB under regulated scenario and took the shape of the simplest and closest patch pattern, while the planned UGB generated the most complicated and isolated patch pattern. In short, the UGB under regulated scenario had good performance in every landscape index, so this simulated UGB had the most reasonable space structure.

Table 10. Landscape indexes of the simulated UGBs under three urban growth scenarios and the planned UGB.

Scenario/Landscape Index (Unit)	NP (None)	AREA_MN (ha)	LPI (%)	ED (m/ha)	ENN_MN (m)	PLADJ (%)
Unregulated scenario	878	461.5254	11.1845	0.4368	1294.4194	70.2196
Port development scenario	698	638.3624	12.9366	0.3987	1290.6834	73.3993
Regulated scenario	406	1249.1475	16.4831	0.388	1259.6817	76.1864
Urban planning scenario	381	1287.0528	34.7989	0.4945	1598.3166	86.9651

4.3. Sustainable Urban Growth Scenario and UGBs

Based on the simulated results of urban growth scenarios and corresponding UGBs in 2020, as well as comparison results of the simulated UGBs and the planned UGB, we found evidence to distinguish sustainable urban growth scenario and UGBs in Ningbo. The UGB under an unregulated scenario corresponded to a situation in which local economic development and market forces dictated the spatial development, resulting in blind and extensive urban sprawl with a loose and fragmented urban space structure. This essentially meant that development would not follow urban planning, and the development of the built-up lands sacrificed farmlands and ecological lands. Hence, the UGB under this scenario was not sane or sustainable.

The UGB under port development scenario corresponded to a situation in which local policy, especially the "Port Economic Circle" strategy, guided the urban growth direction, and ecological protection was taken into consideration in this scenario. It produced more development of built-up lands around the port cluster areas, and a little complex and separated urban space structure. Further, the shipping channel capacity of the port economic circle was promoted with the help of a comprehensive transportation network layout. The UGB under this scenario should be further improved to support efficient port economy development in Ningbo.

The UGB under regulated scenario represented the application of growth management and ecological protection policies. The term "concentrated development" was used to describe this scenario since it generated concentrated, continuous, and compact urban growth and reduced the amount of new construction lands. In addition, urban development would not destroy farmlands and ecological lands, and urban space structure was reasonable. Hence, the UGB under this scenario was the most sustainable one among the three UGBs. In short, the improved UGB under port development and the UGB under regulated scenario can be adopted to propel efficient and sustainable development in Ningbo.

5. Conclusions

This paper introduced a UGB delimitation method by combining LSE and CA model, with technical supports of RS and GIS. This method gave play to LSE's advantage in sustainable land use, as well as CA's advantage in objective dynamic simulation. We defined ecological limitation areas by LSE, which were regarded as the restricted areas of urban growth. Meanwhile, we took ecological limitation areas as an important model input (i.e., spatial variable) to guide intensive land allocation in urban growth model (CA model). We predicted future urban growth situations by CA model and delineated the UGB lines by ArcGIS 10.1. We chose Ningbo City as study area to establish UGBs over three urban growth scenarios (i.e., unregulated, port development and regulated scenarios) in 2020.

The results indicated that this method had good performance in Ningbo's urban growth simulation. These simulated UGBs derived from this combined method had many inconsistencies with the planned UGB in NCMP. We found the simulated UGBs under port development and regulated scenarios showed intensive and suitable spatial layout of land, while the UGB under unregulated scenario and the planned UGB showed relative incompact and unsuitable spatial layout. Meanwhile the UGB under regulated scenario had the most reasonable space structure and the largest ecological protection effect among the four UGBs. In short, the simulated UGBs under port development and regulated scenarios were superior to the planned UGB. These two simulated UGBs can be adopted to propel efficient and sustainable development in Ningbo. However, we should consider more policy guidance in the simulation process, as well as incorporate beneficial planning and design into the simulated UGBs, in order to put forward the ideal pattern of the UGB. The study recommends that this UGB delimitation method can promote sustainability of land development and ecological environment in Chinese cities.

Further research should focus on introducing the scaling parameter into spatial variables in the RS and GIS phase so as to establish a closer relationship with the CA model phase. Meanwhile, using different scales and a common base of land use classification would allow for the macro scale delimitation being incorporated into GIS databases as a way to test and validate the unity and adequacy of the CA. Furthermore, we should apply various development or protection scenarios in other Chinese cities; optimize the UGB delimitation method through integrating favorable planning and design; and provide more reasonable and sustainable UGBs, and the relevant policies, for governments and planners.

Acknowledgments: The research presented in this paper was supported by the Technology Support Foundation, China (2006BAJ05A02). We also thank the anonymous reviewers for their constructive comments.

Author Contributions: Qing Zheng and Ke Wang conceived and designed the experiments; Ke Wang was responsible for recruitment and follow-up of study participants; Qing Zheng and Xuan Yang were responsible for data collection; Qing Zheng, Xuan Yang and Lingyan Huang carried out the analyses; Qing Zheng drafted the manuscript, which was revised by AmirReza Shahtahmassebi, Muye Gan and Melanie Valerie Weston. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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