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Urban Development Boundary Setting Versus Ecological Security and Internal Urban Demand: Evidence from Haikou, China

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Abstract: Amidst rapid urbanization, the conflict between urban population and land is intensifying due to ecological degradation and imbalanced supply and demand of land resources in and around cities. Demarcating the urban development boundary is a specific measure to regulate the scale and form of urban expansion while considering internal urban demand as well as ecological security. This study took Haikou City, China, as the study area, exploring a new way to take into account the external constraints and endogenous mechanisms of urban expansion, constructing a comprehensive ecological security pattern (ESP) using the MCR model, demarcating recent rigid development boundaries, and demarcating future elastic development boundaries using the CA–Markov model. The results were the following: (1) By identifying the current urban boundary in 2020, the urban land area of Haikou City was found to be 261.64 km^2. (2) Using the MCR model to construct comprehensive ESP and demarcate a rigid development boundary revealed that the total area within the boundary was 398.37 km^2, with an additional growth potential of up to 136.73 km^2. (3) Demarcating elastic boundaries for Haikou City in 2030, 2040 and 2050 using the CA–Markov model while considering natural and socio-economic driving factors and constraints showed the internal areas within these boundaries to be calculated at 451.80, 489.46 and 523.37 km^2, respectively, which were higher than that in 2020 by 190.16, 227.82 and 261.73 km^2. (4) Some suggestions, such as establishing a comprehensive technical system, ensuring robust policy support and legal protection, and improving the responsibility management system, were proposed in the implementation of urban development boundaries. Scientifically and reasonably demarcating the recent rigid urban development boundary and future elastic urban development boundaries can ensure sustainable urban development while preserving the ecological environment and satisfying urban development demand.

Keywords: ecological security pattern (ESP); urban socio-economic development; urban development boundary; MCR model; CA–Markov model; Haikou City

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1. Introduction

The process of urbanization in China has been accelerated by the deepening of reform and opening up, as well as continuous socio-economic development. From 1978 to 2022, China's urbanization rate experienced a rapid increase from 17.9% to 65.2%, and it is expected to reach 67% by 2030. Additionally, China's resident urban population grew from 170 million to 920 million during this period. While urbanization is an inevitable requirement for modernization, accelerating industrial transformation and promoting coordinated regional development, its rapid progress has also brought about several drawbacks. For instance, the extensive expansion of urban land (referred to as "big cake" expansion) has resulted in the haphazard development and utilization of land resources, leading to significant erosion of high-quality farmland and ecological land, thereby exacerbating internal ecosystem vulnerability. This uncontrolled growth has given rise to a myriad of ecological and environmental issues including non-point source pollution in cultivated land, air pollution, water scarcity, and declining levels of biodiversity [1–4]. These have significantly altered the ecological environment in rural areas surrounding the city, imposing severe constraints and implications on the sustainable development of urban regions [5,6]. In response to this, China has released a series of programmatic documents aimed at restraining urban sprawl and promoting the intensive and efficient utilization of urban land [7]. For example, in May 2019, the Ministry of Natural Resources identified demarcating urban development boundaries as a core element in preparing territorial spatial planning and supervising its implementation. Simultaneously, China has issued a series of programmatic documents to tackle urgent challenges such as severe environmental pollution and ecosystem degradation, while actively promoting the establishment of an ecological civilization. Therefore, within the context of a new urbanization strategy and ecological civilization construction, guiding urban growth pattern transformation and optimizing national territory spatial distribution, scientifically demarcating urban development boundaries has become an important current concern.

In order to curb urban sprawl, many scholars have carried out extensive research on the demarcation of urban development boundaries. American scholars were the first to carry out relevant research, which mainly studied the dynamic changes of urban space by establishing models, so as to demarcate the urban development boundaries, and mainly took the natural growth state of cities as the main basis for demarcating the boundaries [8,9]. Chinese scholars have proposed two methods for demarcating urban development boundaries. The first is also concerned about the natural urban growth, using models to simulate the temporal and spatial trend of future urban growth [10,11]. The second mainly considers the external constraints of urban development and demarcates the urban development boundaries by excluding the unfavorable factors of urban development. For example, many scholars are exploring the connection between the construction of an ecological security pattern (ESP) and the demarcation of urban development boundaries [12–14]. ESP, also known as an ecological security framework, is a spatial arrangement consisting of localities, points, and spatial relationships that play a crucial role in upholding the security of ecological processes [15,16]. It facilitates active intervention through the layout, design, and integration of various natural and human elements within an area to obtain a spatial configuration program comprising points, lines, surfaces, and networks. By strategically arranging these elements in the region while considering their multi-level and multi-category characteristics, it enables effective human intervention to promote optimal allocation within coupled systems. This ensures healthy, stable, and sustainable ecosystem development, ultimately leading to improved regional ecological security conditions [17]. The urban ESP emphasizes the spatial presence of urban ecological security. It represents the spatial arrangement of urban ecological land, along with its combination of points, lines, and surfaces within an integrated urban ecosystem during land use growth. This pattern plays a pivotal role in maintaining both the city's overall ecology level as well as important ecological processes [18]. The construction of an urban ESP serves as a foundation for defining cities' bottom lines regarding ecology [19]. The principle of constructing the urban ESP to demarcate the urban development boundaries is as follows. Drawing upon the "source–sink" system theory and employing the methodology of constructing an ESP, the current urban land use is considered as the "source", while different levels of ESPs are regarded as constraining factors. Subsequently, simulations are conducted to determine the spatial extent of urban growth under varying levels, ultimately leading to the delineation of an urban growth boundary [20].

However, the demarcation of urban development boundaries should consider both urban built-up land development and ecological protection. It should not only consider the external constraints on urban expansion, but also take into account the internal urban development demand, namely its endogenous mechanisms. It should consist of two components. On the one hand, a "rigid" part, primarily determined by the preservation of crucial ecological resources within the city that cannot be encroached upon by urban growth, aiming to control ecologically sensitive areas or those with restricted construction conditions unsuitable for development. On the other hand, the "elastic" development boundaries are also required, to accommodate future population growth, industrial expansion, natural elements, etc., thereby reserving space for future urban expansion within a specific timeframe. Therefore, previous studies either applied ESP to demarcate urban development boundaries, mainly focusing on the ecological bottom line, as a means to maintain urban ecological security and basic ecosystem services, and demarcated rigid development boundaries, or applied models to simulate urban natural growth, and demarcated elastic development boundaries. It is imperative to consider not only the preservation of high-quality ecological resources by establishing a well-defined rigid development boundary in the immediate future, but also to anticipate and allocate suitable space for future urban expansion, ensuring both quantitative and spatial requirements are met, while demarcating elastic urban development boundaries for subsequent phases.

Therefore, this study aims to address the limitations of previous research and to investigate a novel approach to demarcating urban development boundaries, with Haikou City, Hainan Province, China as the study area, comprehensively considering both external constraints and endogenous mechanisms of urban development. Concretely, using land use remote sensing monitoring data and Landsat satellite remote sensing images, we firstly identified the current urban land use boundary of Haikou City in 2020 as the source of urban expansion. Secondly, based on the MCR model and considering the characteristics of the study area, we selected appropriate resistance factors to determine different levels of ESP. This allowed us to establish a rigid development boundary for Haikou City in the near future. Next, employing the CA–Markov model and taking into account natural and socio-economic driving factors as well as constraints, we simulated land use scenarios for Haikou City over the next 10, 20, and 30 years using the land use remote sensing monitoring data from 2000, 2010, and 2020. Subsequently, we demarcated elastic development boundaries for urban expansion. Finally, some suggestions were proposed for the implementation of urban development boundaries of Haikou City. These findings contribute to enriching the research related to demarcating urban development boundaries while providing a theoretical foundation for rationalizing strategies for urban land use expansion aimed at improving efficiency while maintaining ecosystem stability. Moreover, the scientific demarcation of Haikou City's urban development boundaries can effectively manage disorderly spreading expansions and realize urban smart growth during its ongoing process of rapid urbanization by coordinating ecological preservation efforts with the spatial needs required for sustainable growth.

2. Materials and Methods

2.1. Study Area

This study took Haikou City, China, as the study area. Haikou is the capital city of Hainan Province and a core city of Hainan Free Trade Port, serving as an important pivot for China's "Belt and Road" strategy. Situated at the northern tip of Hainan Island, it is bordered by Wenchang to the east, Chengmai to the west, Ding'an to the south, and Qiongzhou Strait to the north, separating it from the continental plate by the Qiongzhou Strait, with a geographic location of 19°31′ N~20°04′ N, 110°07′ E~110°42′ E (Figure 1). Haikou City encompasses four administrative districts, including Xiuying, Longhua, Qiongshan and Meilan, with a total land area of 3.15 thousand km^2 (2.29 thousand km^2 on land and 0.86 thousand km^2 at sea). The terrain features a slightly heart-shaped overall form with gentle terrain, while its tropical monsoon climate boasts an average number of annual sunshine hours of about 2000 h., a temperature around 25 °C, precipitation approximately 2000 mm, evaporation roughly1800 mm, and relative humidity averaging around 85% [21]. The land use types of Haikou City in 2000, 2010 and 2020 are shown in Figure 2, where the areas of built-up land are 141.70, 187.33 and 296.91 km^2, respectively. In terms of economic development, in 2022 the gross regional product (GRP) of Haikou City reached CNY 213.48 billion, with the structure ratio of the three industries being 4.7:19.0:76.3.

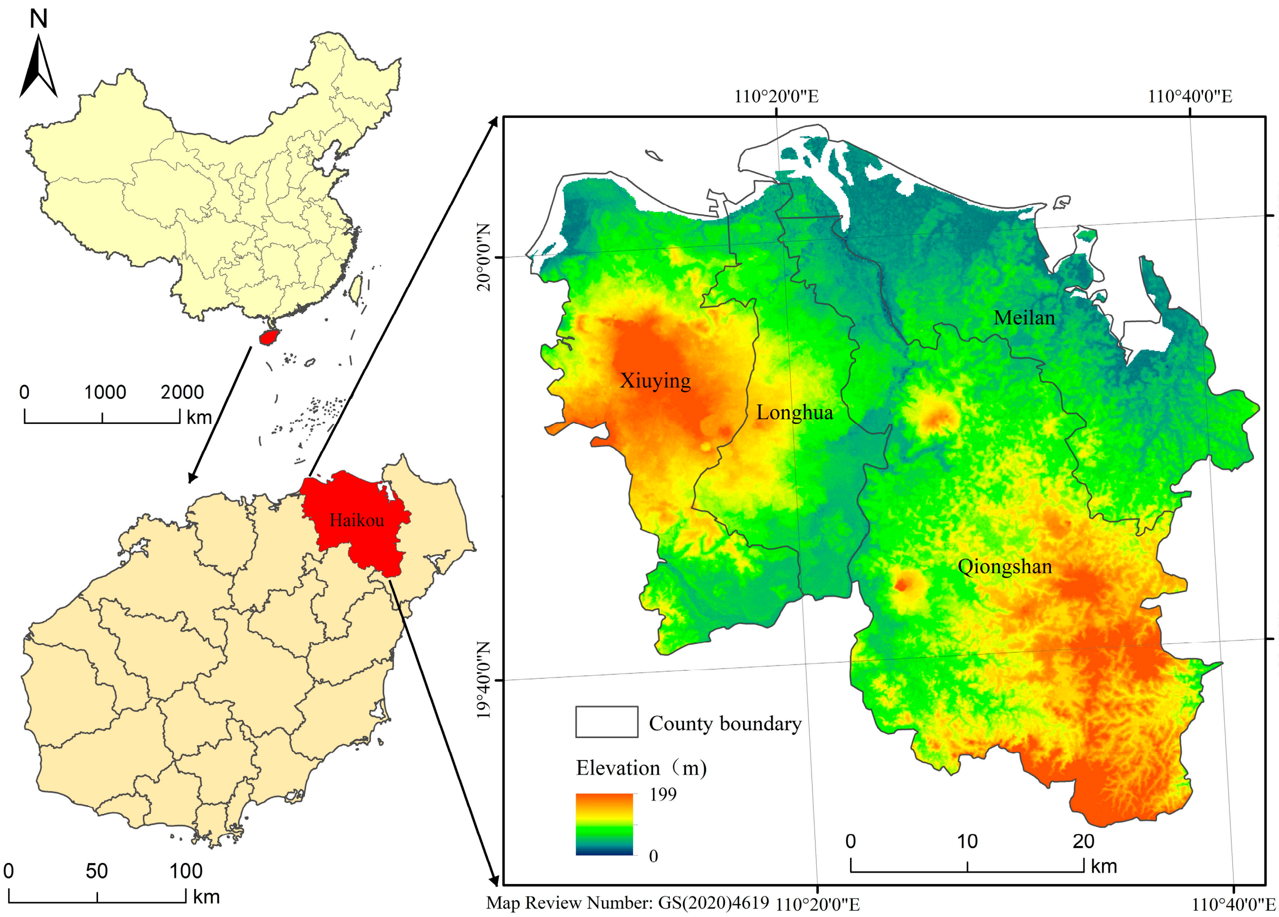

Figure 1. Location of the study area.

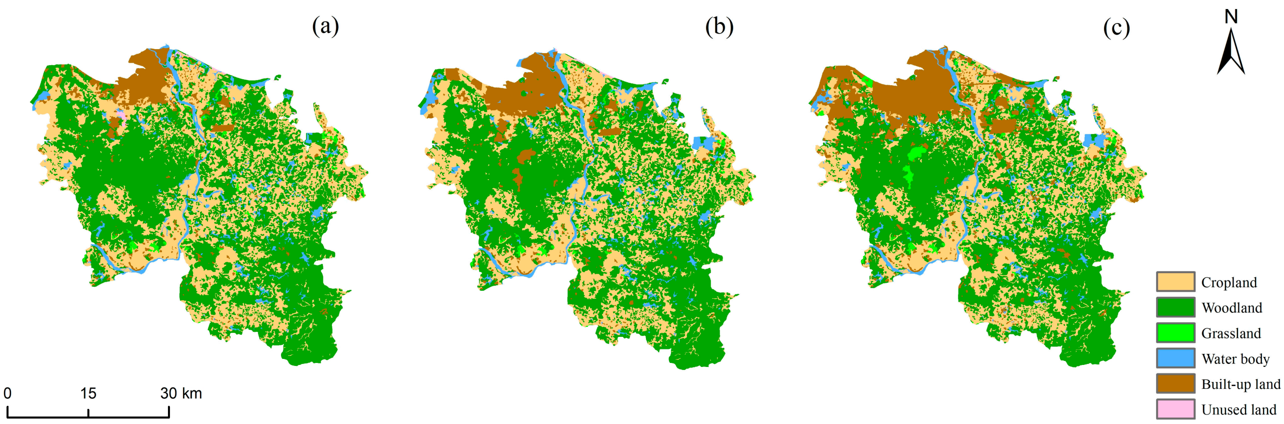

Figure 2. Land use types of Haikou City in (**a**) 2000, (**b**) 2010 and (**c**) 2020.

Haikou has witnessed an acceleration in its urbanization process since the reform and opening-up era. From 1978 to 2022, Haikou's urban population increased from 709.2 thousand to 2.43 million, with an accompanying rise in the urbanization rate reaching a high level of 82.73%. The urban expansion of Haikou City has continuously encroached upon the high-quality cropland and scarce ecological green space (such as volcanic wetlands and forests), leading to habitat fragmentation within Haikou City and the consequential loss of a significant number of species. Therefore, timely research on the demarcation of rigid and elastic development boundaries of Haikou city is helpful to clarify the rigid constraint boundaries of recent urban expansion, curb disorderly urban expansion, maintain the balance of the ecosystem, and reserve the elastic space for the future social and economic development of Haikou City. The results of this study can provide an important reference for the demarcation and implementation of urban development boundaries and urban functional areas in the territorial spatial planning of Haikou City, and can also provide an important reference value for the development and construction policies of other coastal cities in China.

2.2. Data Sources and Preprocessing

The input data in this study include satellite remote sensing image data, land use remote sensing monitoring data, terrain data, socio-economic data, and spatial distribution data of the highway and railway. The details of the input data are shown in Table 1.

Table 1. Details of the input data.

Data Names	Data Formats	Data Sources	Data Preprocessing
Landsat remote sensing image data in 2020	Raster data with the spatial resolution of 30 m	Geospatial Data Cloud (https://www.gscloud.cn/ (accessed on 1 December 2022))	After radiometric calibration and atmospheric correction, they were processed into false-color images.
Land use remote sensing monitoring data in 2000, 2010 and 2020	Raster data with the spatial resolution of 30 m	Resources and Environmental Science and Data Center (https://www.resdc.cn/ (accessed on 1 December 2022))	——
Terrain data	Raster data with the spatial resolution of 30 m	Digital Elevation Model (DEM) provided by Shuttle Radar Topography Mission (SRTM) system	They were processed into the slope data using ArcGIS 10.6 software.
Spatial distribution data of the railway and highway	Vector data	Resources and Environmental Science and Data Center (https://www.resdc.cn/ (accessed on 15 December 2022))	They were processed using IDRISI Selva 17.0 software into distance data from the highway and railway.
Spatial distribution data of population density in 2020	Raster data with the spatial resolution of 1 km	Global Population Density Data set published by the WorldPop Platform (https://www.worldpop.org/ (accessed on 15 December 2022))	——
Spatial distribution data of GDP in 2020	Raster data with the spatial resolution of 1 km	Yangtze River Delta Science Data Center, National Earth System Science Data Sharing Infrastructure, National Science and Technology Infrastructure of China (http://geodata.nnu.edu.cn/ (accessed on 15 December 2022)) [22,23]	——

2.3. Research Framework

In this study, we constructed a research framework from the identification of the current urban land boundary to the demarcation of the future urban development boundaries (Figure 3).

2.4. Methods

2.4.1. Construction of Urban Ecologically Based Surface-Resistance Evaluation System

Urban land expansion must first ensure ecological security and the protection of resources and environment. Therefore, it is necessary to fully consider various ecological resistance factors that hinder urban expansion, and construct an urban ecologically based surface-resistance evaluation system to demarcate the rigid urban development boundary. Considering the difference of the nature of each resistance factor, the resistance of cities in the process of expansion is different. Based on a comprehensive analysis of multiple factors influencing urban expansion and the specific situation in Haikou City, this study identified 5 Level 1 factors and 11 Level 2 factors to establish an evaluation system for an urban ecologically based surface resistance in Haikou City. The Level 1 factors include terrain, land use types, biological sensitivity, ecological risk, and water resource sensitivity. The Level 2 factors were the following: (1) Elevation. Resistance to urban expansion varies by altitude. In general, the higher the elevation, the greater the resistance to urban expansion. (2) Slope. Resistance to urban expansion varies by slope. In general, the higher the slope, the greater the resistance to urban expansion. (3) Surface toughness. The rougher the surface, the greater the resistance to urban expansion. (4) Land use types. The resistance to urban expansion varies by land use types. In general, existing built-up land is the least resistant to urban expansion, and a water body is the most resistant to urban expansion. (5) NDVI and (6) SAVI. Urban expansion should avoid damage to vegetation, and to quantify the ecological value of surface vegetation, NDVI and SAVI were calculated. (7) NDSI. Urban expansion is influenced by the degree of land degradation, so NDSI was calculated. (8) Ecological risk. In this paper, the landscape disturbance degree was calculated to reflect the ecological risk of the study area. (9) Urban-heat-island-effect risk. Due to the increasing urban development in the study area and the intensification of the urban-heat-island effect, it is necessary to incorporate the urban heat island risk into the evaluation system. (10) Low-lying and flood-prone area. The lower the terrain, the higher its susceptibility to flooding, rendering it less conducive to urban expansion and posing a greater threat to both public resources and the safety of city residents. (11) Distance from the water body. The closer the distance to the water, the less favorable it is for urban expansion.

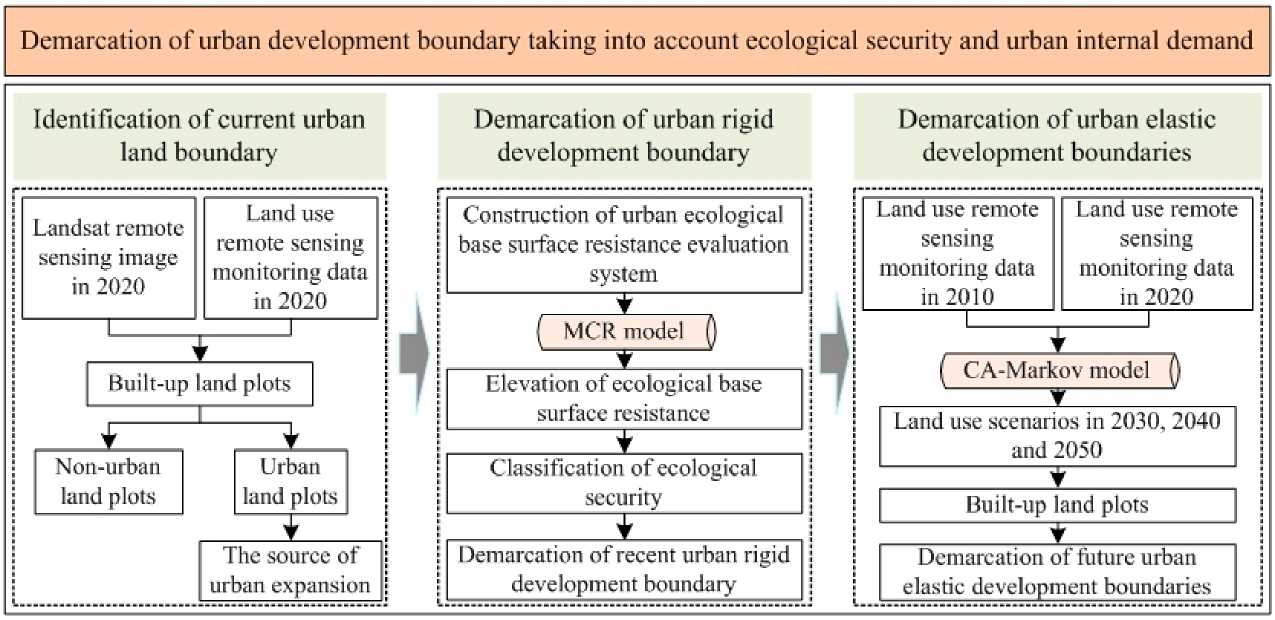

Figure 3. Research Framework.

An ecologically based surface-resistance evaluation system was constructed to assess the degree of hindrance posed by these resistance factors to city expansion. Referring to the relevant research findings [24,25], the resistance factors were assigned descending values of 9, 7, 5, 3, and 1 respectively, while the weights for each factor were determined using the Delphi method (Table 2).

Table 2. Urban ecologically based surface-resistance evaluation system.

Level 1 Factors and Weights	Level 2 Factors and Weights	Grades	Resistance Values
Terrain 0.15	Elevation 0.3	0~40 m	1
		40~80 m	3
		80~120 m	5
		120~160 m	7
		>160 m	9
	Slope 0.3	<2°	1
		2~6°	3
		6~15°	5
		15~25°	7
		>25°	9
	Surface roughness 0.4	<1.001°	1
		1.001~1.003°	3
		1.003~1.010°	5
		1.010~1.055°	7
		>1.055°	9
Land use types 0.15	Land use types 1	Built-up land	1
		Cropland	3
		Woodland, Grassland	5
		Unused land	7
		Water body	9
Biological sensitivity 0.2	NDVI 0.4	<0.1	1
		0.1~0.2	3
		0.2~0.3	5
		0.3~0.4	7
		>0.4	9
	SAVI 0.6	<0.1	1
		0.1~0.2	3
		0.2~0.3	5
		0.3~0.4	7
		>0.4	9
Ecological risk 0.3	NDSI 0.3	<−0.1	1
		−0.1~−0.05	3
		−0.05~0	5
		0~0.05	7
		>0.05	9
	Ecological risk 0.3	<0.02	1
		0.02~0.03	3
		0.03~0.06	5
		0.06~0.08	7
		>0.08	9

Table 2. *Cont.*

Level 1 Factors and Weights	Level 2 Factors and Weights	Grades	Resistance Values
	Urban-heat-island-effect risk 0.4	<29 °C	1
		29~30°C	3
		30~31 °C	5
		31~32 °C	7
		>35 °C	9
Water resource sensitivity 0.2	Low-lying and flood-prone area 0.3	0 m	1
		0~292 m	3
		292~1168 m	5
		1168~3796 m	7
		>3796 m	9
	Distance from the water body 0.7	>800 m	1
		600~800 m	3
		400~600 m	5
		200~400 m	7
		<200 m	9

2.4.2. Demarcation of Rigid Urban Development Boundary

As the background boundary of urban ecological security, the rigid urban development boundary aims to control the disorderly spread of the city and protect the natural resources and ecological environment. This study applied the minimum cumulative resistance (MCR) model to construct the urban ESP and to demarcate the rigid development boundary of Haikou City. The MCR model is a model that describes the various resistances to be overcome by a species during its movement from the source to the target location, which takes into account the source, distance, and other factors. Its essence was the minimal resistance to be overcome from the source to the target location, which reflected a kind of accessibility [26]. It was proposed by Kannpen in 1992 [27]. It has been extensively utilized in various domains, including species conservation [28], landscape patterns [29], distribution suitability of rural settlements [30,31] and ESP construction [32,33]. In this study, urban expansion is conceptualized as a dynamic process involving the competition between urban land and other land use types, initiating the overcoming of ecological resistance. Thus, urban expansion can be viewed as an endeavor to surmount the constraints posed by limited availability of suitable urban land. The MCR model is very suitable to be applied in this study to construct the urban ESP and demarcate the rigid urban development boundary. The formula for the MCR model is as follows:

$$\mathrm{MCR} = f min \sum\nolimits_{j=n}^{i=m} \left(D_{ij} \times R_i\right) \tag{1}$$

where MCR is the minimum cumulative resistance; D_{ij} is the distance from the j landscape to the i landscape; R_i is the resistance coefficient of self-expansion of the i landscape; min is the minimum value of resistance from j to i; and f is the resistance function.

The MCR model was employed in this study to overlay the resistance factors based on the ecologically based surface-resistance evaluation system, yielding comprehensive evaluations of ecologically based surface resistance within the study area. The natural breaks method was utilized for grading ecologically based resistance. A higher value of ecological resistance indicates a lesser suitability of the construction site for urban expansion. The cost–distance module in ArcGIS is subsequently employed to construct the ESP of Haikou City by discerning the surface resistance and integrating urban expansion sources, while employing the natural breaks method to demarcate the ecological safety levels. Areas exhibiting higher safety levels are deemed more suitable for urban expansion, with the boundary encompassing the highest safety level serving as a rigid constraint on urban development in Haikou City.

2.4.3. Demarcation of Elastic Urban Development Boundary

The elastic urban development boundary is a flexibly adjustable spatial framework that guides the dynamic growth of cities, serving as a dynamic limit for urban expansion. Its primary focus lies in promoting internal land optimization and stock reuse, while enhancing land utilization efficiency and fostering conservation and intensification. This study applied the CA–Markov model to simulate the future land use scenarios and demarcate the future elastic development boundaries of Haikou City. As the elastic boundaries are the maximum expansion ability needed to meet the reasonable layout of urban land in a certain period of time in the future, they are the development routes for internal urban demand. CA–Markov model is based on the number of factors and spatial development law of the city in the past period of time, and simulates the future city development law on the basis of various driving factors and limiting factors. Therefore, it is suitable for demarcating the future elastic urban development boundaries [34]. Other studies used the MCE-CA model [35], FLUS model [36] and Geo-CA model [37] to simulate the future land use scenarios and demarcate urban development boundaries, but the CA–Markov model is more advantageous for simulating the spatial-temporal pattern of land use changes in terms of quantity and space and for obtaining more accurate land-use-scenario simulation results.

The CA–Markov model is a predictive simulation model that integrates the Cellular Automata (CA) model and the Markov model. The CA model was firstly proposed in the 1940s, and simulates the phenomena of discrete complexity in space and time by means of simple local arithmetic operations. The model has a strong spatio-temporal processing capability and the core element is transformation rules [38]. In the model, neighborhood models and transformation rules are set up so that land cover scenarios are simulated for the desired years [39]. The formula is as follows [40]:

$$S_{(t+1)} = f\left(S_{(t)}, N\right) \tag{2}$$

where $S_{(t+1)}$ and $S_{(t)}$ are the states at times $t + 1$ and t, N is the cellular field, and f is the transition rule of cellular states in local space.

The Markov model is an effective tool for analyzing the pattern of development and predicting the future development trend [41], and can be applied in the prediction of land dynamics change in the study area. The formula is as follows [42]:

$$S_{(t+1)} = P_{ij} \times S_{(t)} \tag{3}$$

where $S_{(t+1)}$, $S_{(t)}$ are the states of land use types at time $t + 1$ and t in this study; P_{ij} is the transition probability matrix between land use type i and j, $0 \leq P_{ij} \leq 1$. P_{ij} is calculated as follows [40]:

$$P_{ij} = \frac{A_{ij}}{\sum_{j=1}^{n} A_{ij}} \times 100\% \tag{4}$$

where A_{ij} is the area or proportion of land use type i converted to j; n is the number of land use types.

Although the CA model possesses a powerful spatial simulation function, its structure is relatively simplistic and disregards external factors such as macro policies related to the real world, leading to research results that deviate from actual situations. While the Markov model can capture temporal changes in different land use types, it lacks spatial concepts and simulation capabilities. The CA–Markov model combines the advantages of spatial simulation from the CA model and temporal simulation from the Markov model, making it suitable for simulating spatio-temporal dynamics of regional land use changes.

In this study, the CA–Markov model was first applied to simulate the land use scenarios of Haikou City in 2030, 2040 and 2050 using the IDRISI selva 17.0 software, and the six driving factors and constraints of urban expansion were considered in the simulation. Then, the spatial distribution of future built-up land was extracted from the land use scenarios, and the spatial distribution of urban land was further determined, the boundaries of which were used as the future elastic urban development boundaries.

Prior to simulating future land use scenarios of Haikou City using the CA–Markov model, it is imperative to first verify its accuracy. The kappa index serves as an effective method for assessing consistency between multiple images, and can be applied to test the simulated land use scenario against actual land use data in order to validate the simulation model's accuracy. The formula is as follows [42]:

$$Kappa = \frac{P_o - P_c}{1 - P_c} \tag{5}$$

were P_o is the correct grid proportion of land use types and P_c is the proportion that simulates the correct grid in a random case. The range of index is $[-1, 1]$. If Kappa ≥ 0.75, it shows that the accuracy verification of the CA–Markov model passes. In this study, we firstly simulated the land use scenario in 2020 based on the land use remote sensing monitoring data in 2000 and 2010, and then determined its consistency with the land use remote sensing monitoring data in 2020 by calculating the kappa index. After the consistency was passed, the CA–Markov model continued to be applied to simulate the land use scenarios of Haikou City in 2030, 2040 and 2050.

3. Results

3.1. Demarcation of Rigid Development Boundary of Haikou City

3.1.1. The Source of Urban Expansion

A "source" is the initial point from which a substance spreads to its surroundings, with the ability to attract and spread being dependent on both the characteristics of the source itself and the medium through which it spreads [24]. In this study, the "source" refers to the urban land in Haikou City in 2020. Firstly, the built-up land plots (the fifth type in Level 1 of the land use classification) were extracted from the land use remote sensing monitoring data in Haikou City in 2020. Since the built-up land plots include not only urban residential plots (Number 51), but also rural residential plots (Number 52) and industrial and mining plots (Number 53), based on the Landsat remote sensing image of Haikou City in 2020, the human–computer interactive interpretation method was adopted to screen out the concentrated and continuous, adjacent, and large-area map spots from the built-up land plots of Haikou City in 2020 as urban land, and outlined the outer boundary of the urban land as the "source" of urban sprawl (Figure 4). The resulting statistics showed that the total area of urban land in Haikou City in 2020 was 261.64 km^2. The areas of urban land in Xiuying, Longhua, Qiongshan and Meilan were 90.31, 48.18, 28.14 and 95.01 km^2, respectively.

3.1.2. Urban Development Boundary of Haikou City

Figure 5 shows the spatial distribution of each resistance factor after grading. Based on the ecologically based surface-resistance evaluation system, we employed the MCR model to overlay each resistance factor and applied the natural breaks method to classify the integrated ecological resistance surface into three grades, using 4.05 and 4.96 as thresholds (Figure 6).

Subsequently, by integrating the ecologically based surface-resistance grades and the urban expansion source, employing the cost–distance tool, and utilizing the natural breaks method, we derived an integrated ESP consisting of five levels (Figure 7), namely very high ecological level, high ecological level, medium ecological level, low ecological level, and very low ecological level. The regions with higher levels of ecological security are more suitable for future urban expansion, as they represent the primary direction for development. Conversely, regions with lower levels of ecological security signify crucial thresholds, requiring meticulous protection within the city.

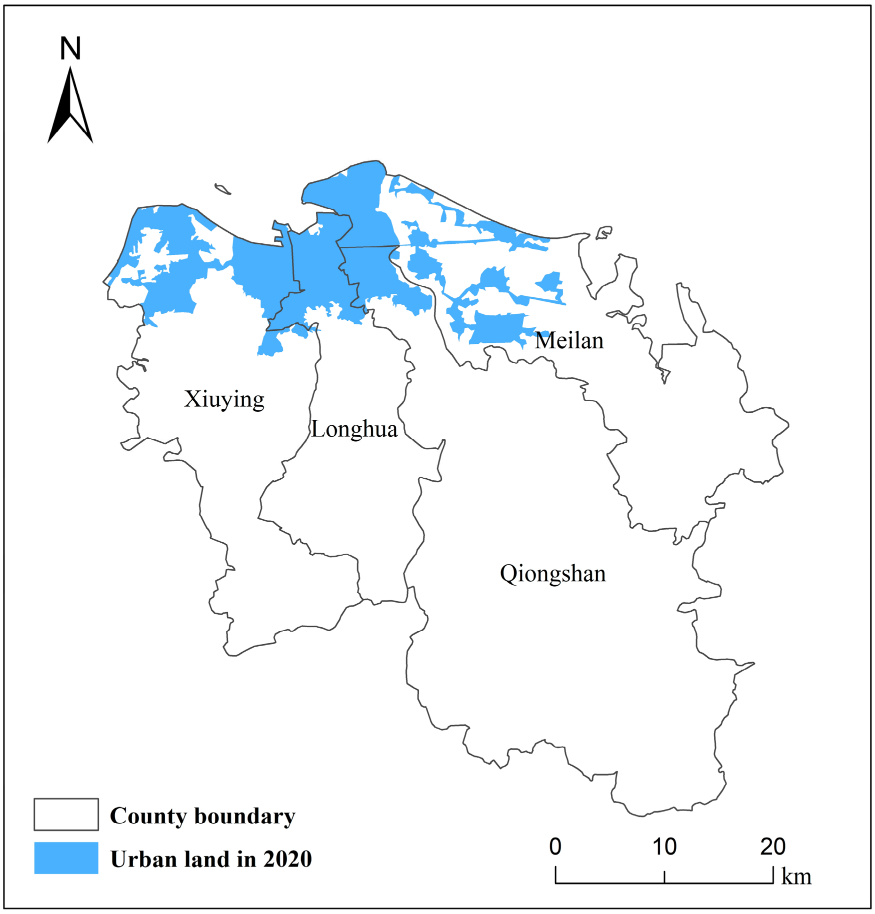

Figure 4. Spatial distribution of the urban land in Haikou City in 2020.

Finally, considering the comprehensive ESP across various ecological levels, we extracted the "very high ecological level" to define the recent rigid urban development boundary of Haikou City (Figure 8). It shows that the urban land in the rigid development boundary of Haikou City was divided into two main areas by the Nandu River. Therefore, the spatial distribution of urban land within the recent rigid development boundary in 2020 exhibits an outward expansion along the periphery, particularly in Changliu Town and Jiangdong New Area. This expansion aligns with the urban development direction outlined in Haikou City's territorial spatial planning document (2021–2035), emphasizing a "one heart and two wings" approach. The total area within the rigid development boundary was 398.37 km^2. Given that the urban land area of Haikou City in 2020 will be 261.64 km^2, it can be inferred that the potential expansion area for Haikou City in the near future would amount to approximately 136.73 km^2.

3.2. Demarcation of Elastic Development Boundaries of Haikou City

3.2.1. Simulation of Land Use Scenarios of Haikou City during 2030–2050

In this study, the land use scenarios of Haikou City in 2030, 2040, and 2050 were simulated using the CA–Markov model. Subsequently, the elastic development boundaries for Haikou City over the next 10, 20, and 30 years were demarcated.

Initially, the accuracy of the CA–Markov model need to be verified. The land use scenario of Haikou City in 2020 was simulated based on the land use remote sensing monitoring data in 2000 and 2010. The land use transfer-area matrix and probability matrix for Haikou City from 2000 to 2010 was derived (Table 3).

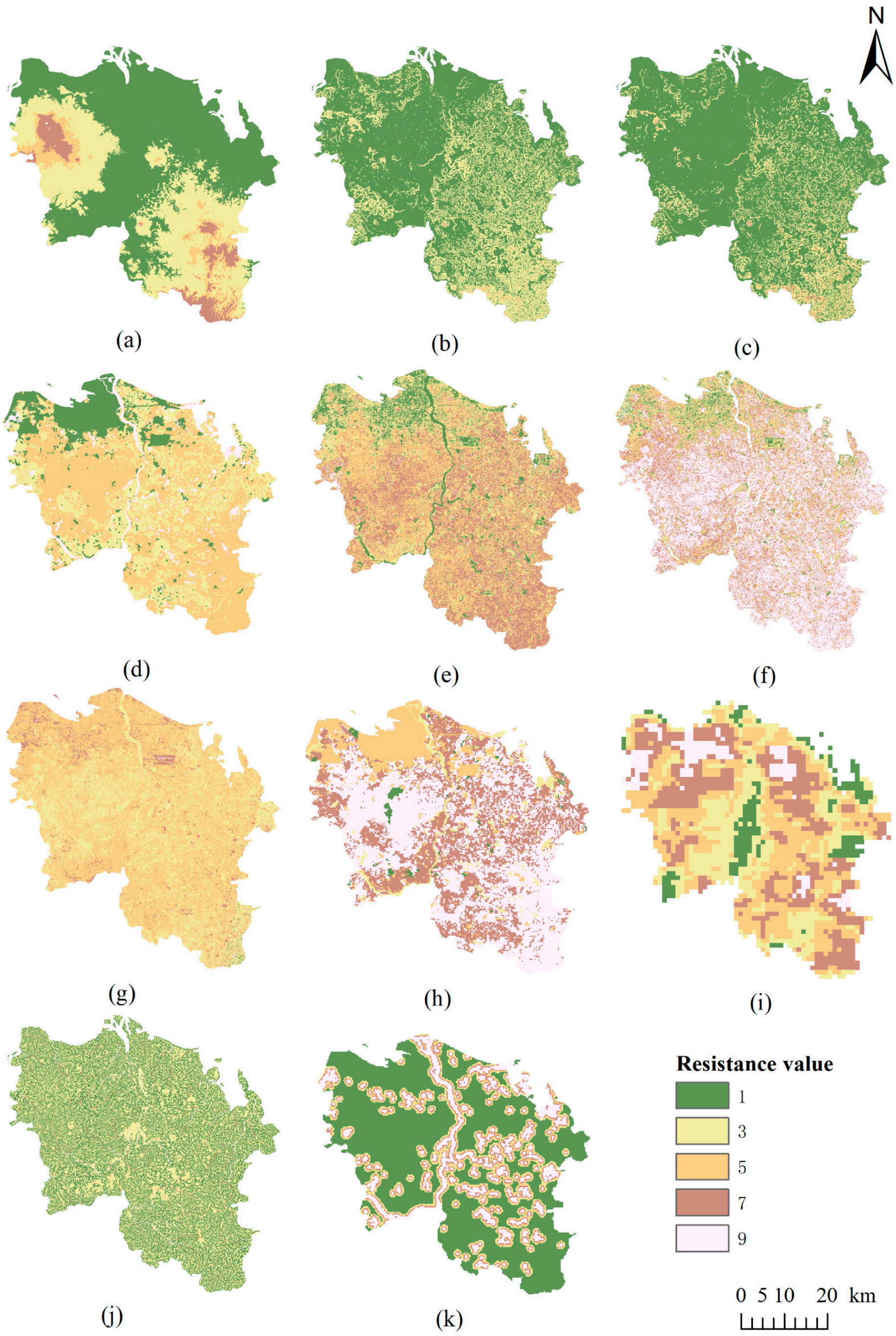

Figure 5. Spatial distribution of each graded resistance factor. (**a**) Elevation; (**b**) Slope; (**c**) Surface roughness; (**d**) Land use types; (**e**) NDVI; (**f**) SAVI; (**g**) NDSI; (**h**) Ecological risk; (**i**) Urban-heat-island-effect risk; (**j**) Low-lying and flood-prone area; (**k**) Distance from the water body.

Due to the limited accuracy of the suitability atlas obtained from the Markov module, it is imperative to consider a diverse range of driving factors and constraints in order to generate a comprehensive suitability atlas using the Decision Wizard tool. The suitability atlas encompasses distinct documents for various land use types, including cropland, woodland, grassland, water body, built-up land, and unused land. It is essential to account for driving factors and constraints when formulating suitability documents for each specific land use type. Driving factors refer to those factors that facilitate efficient conversion between different land use types within a specified timeframe, while constraints encompass factors that impede or restrict this conversion process.

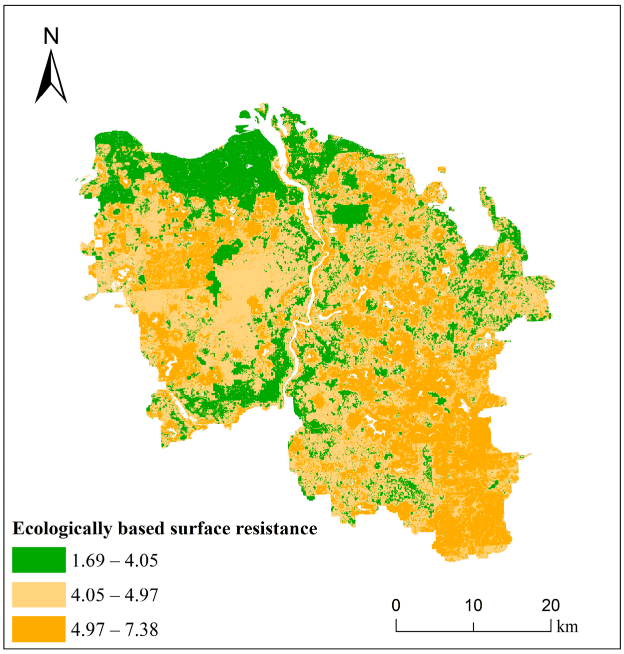

Figure 6. Elevation results of comprehensive ecologically based surface resistance.

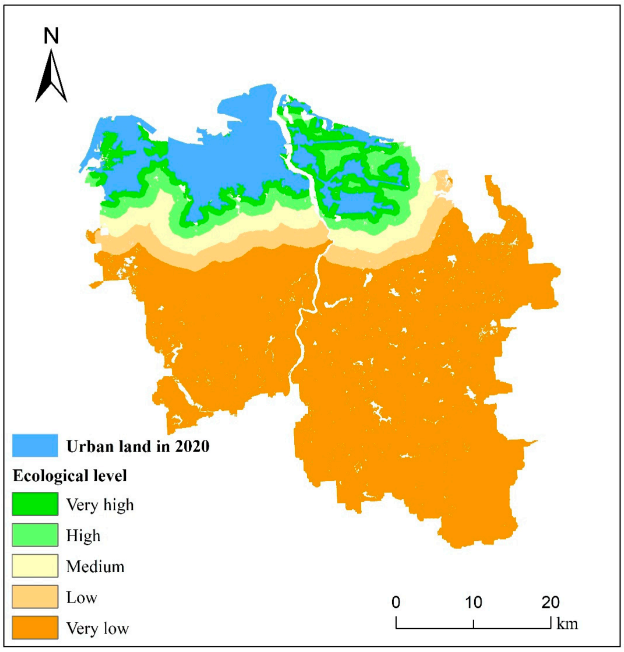

Figure 7. Distribution of the integrated ESP.

In this study, six driving factors (elevation, slope, distance from the highway and railway, population density and GDP) were selected to set rules for land-use-type conversion. Water body was used as a constraint factor for some conversions. Firstly, the characteristics of each land use type's driving factors and constraints were considered. Secondly, the function shapes (including S-type, line-type and J-type) and change trends (including increasing, decreasing, and increasing first then decreasing) of each driving factor for a particular land-use-type conversion were determined by identifying values of control points a, b, c, and d (Table 4). Since a water body is difficult to convert into other land use types in general, it was assumed that its conversion is not affected by any driving factor in this study; therefore, the suitability document of the water body was replaced using probability maps generated by the Markov module.

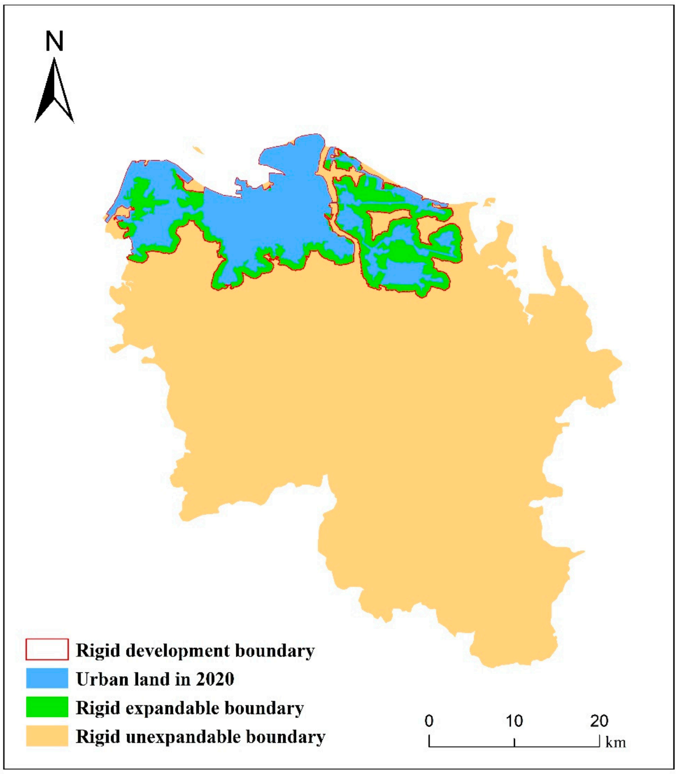

Figure 8. Demarcation of recent rigid urban development boundary of Haikou City.

Table 3. Land-use-transfer probability matrix during 2000–2010.

		2010						**Sum**
		Cropland	**Woodland**	**Grassland**	**Water Body**	**Built-Up Land**	**Unused Land**	
2000	Cropland	0.8108	0.0009	0.0000	0.0438	0.1445	0.0000	1
	Woodland	0.0192	0.8192	0.0000	0.0497	0.1119	0.0000	1
	Grassland	0.0109	0.0000	0.7638	0.1482	0.0771	0.0000	1
	Water body	0.1578	0.0031	0.0000	0.8076	0.0220	0.0095	1
	Built-up land	0.1055	0.0414	0.0000	0.0581	0.7950	0.0000	1
	Unused land	0.6902	0.0000	0.0000	0.0448	0.0000	0.2650	1
Sum		1.7944	0.8646	0.7638	1.1522	1.1505	0.2745	6

Subsequently, the analytical hierarchy process (AHP) method was employed to determine the weights of the driving factors based on their influence on land-use-type conversion (Table 5). Additionally, the MCE module was utilized to generate a suitability atlas for land-use-type conversion excluding the water body.

Next, the Markov module was employed to generate the transferred area matrix of Haikou City during 2000–2010, which was combined with the suitability atlas generated by the MCE module to simulate the land use scenario of Haikou City in 2020 using the CA–Markov module. The simulated 2020 land use scenario underwent coefficient testing against the land use remote sensing monitoring data, resulting in a kappa index of 0.87. This indicates a high level of consistency between the simulated land use scenario and actual land use data, demonstrating that the CA–Markov model possesses sufficient accuracy for future simulations of land use scenarios in Haikou City. Consequently, based on the land use remote sensing monitoring data in 2010 and 2020, we utilized the CA–Markov model to further simulate the land use scenarios of Haikou City in 2023, 2040, and 2050.

Table 4. Driving factors and constraints for land-use-type conversion.

Land Use Types	Driving Factors						Constraint
Cropland	Elevation (m) (decreasing, c = 150, d = 199)	Slope (°) (decreasing, c = 5, d = 15)	Population density (people/km^2) (increasing, a = 100, b = 2500)	GDP (10^4 CNY/km^2) (increasing, a = 200, b = 5000)	Distance from the highway (m) (decreasing, c = 500, d = 20,000)	Distance from the railway (m) (decreasing, c = 2000, d = 40,000)	Water body in 2010
Woodland	Elevation (m) (increasing, a = 10, b = 199)	Slope (°) (increasing, a = 2, b = 25)	Population density (people/km^2) (decreasing, a = 500, b = 3000)	GDP (10^4 CNY/km^2) (decreasing, a = 500, b = 5000)	Distance from the highway (m) (decreasing, c = 500, d = 25,000)	Distance from the railway (m) (decreasing, c = 1000, d = 45,000)	Water body in 2010
Grassland	Elevation (m) (decreasing, c = 150, d = 199)	Slope (°) (decreasing, c = 10, d = 30)	Population density (people/km^2) (decreasing, a = 500, b = 3000)	GDP (10^4 CNY/km^2) (decreasing, a = 1000, b = 6000)	Distance from the highway (m) (decreasing, c = 500, d = 20,000)	Distance from the railway (m) (increasing, a = 1000, b = 40,000)	Water body in 2010
Water body	——	——	——	——	——	——	——
Built-up land	Elevation (m) (decreasing, c = 50, d = 199)	Slope (°) (decreasing, c = 2, d = 15)	Population density (people/km^2) (increasing, a = 100, b = 3000)	GDP (10^4 CNY/km^2) (increasing, a = 100, b = 5000)	Distance from the highway (m) (decreasing, c = 200, d = 20,000)	Distance from the railway (m) (decreasing, c = 1000, d = 40,000)	Water body in 2010
Unused land	Elevation (m) (decreasing, c = 50, d = 199)	Slope (°) (decreasing, c = 5, d = 15)	Population density (people/km^2) (decreasing, a = 1000, b = 3000)	GDP (10^4CNY/km^2) (decreasing, a = 1000, b = 5000)	Distance from the highway (m) (decreasing, c = 500, d = 20,000)	Distance from the railway (m) (decreasing, c = 2000, d = 40,000)	——

Table 5. The weights of driving factors of each land-use-type conversion.

Driving Factors	Elevation	Slope	Population Density	GDP	Distance from the Highway	Distance from the Railway
Cropland	0.3125	0.0879	0.1874	0.1444	0.0732	0.1946
Woodland	0.1932	0.3372	0.1948	0.0940	0.1012	0.0796
Grassland	0.2371	0.3895	0.1362	0.0539	0.1065	0.0768
Built-up land	0.0838	0.1049	0.1766	0.3244	0.1955	0.1127
Unused land	0.2687	0.2153	0.1448	0.1288	0.1272	0.1152

3.2.2. Elastic Urban Development Boundaries of Haikou City

We extracted the built-up land plots from the simulated land use scenarios of Haikou City in 2030, 2040 and 2050, and then eliminated broken and scattered plots and retained those with a higher degree of aggregation, such as the urban land in 2030, 2040 and 2050. The outer envelope of the urban land was then plotted as the elastic development boundaries of Haikou City in these three years (Figure 9). It can be shown that the urban land will continue to expand beyond the existing urban land in the next 10, 20, and 30 years. The area within these boundaries were calculated to be 451.80, 489.46 and 523.37 km^2, respectively, representing an increase of 190.16, 227.82 and 261.73 km^2 compared to that of 2020. Therefore, compared with 2020, in the next three decades the urban land expansion rate will be 19.02, 3.77 and 3.39 km^2/a, respectively, indicating that the urban expansion rate will gradually slow down, which is conducive to promoting the intensive and economical use of urban land and realizing smart urban growth. Furthermore, the results exceeded the recent rigid development boundary by an additional area of 53.43, 91.09 and 125.00 km^2, respectively.

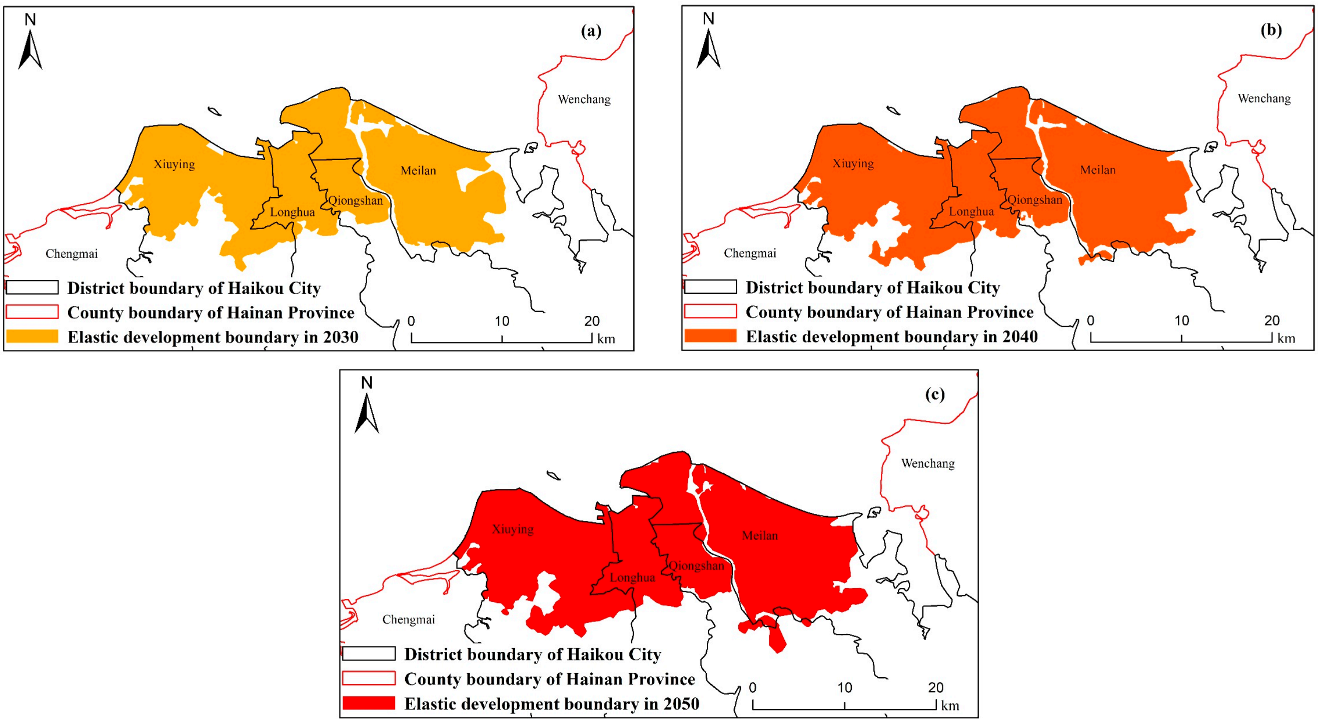

Figure 9. Demarcation of elastic urban development boundaries of Haikou City in (**a**) 2030, (**b**) 2040 and (**c**) 2050.

Therefore, the demarcation of urban development boundaries can not only ensure ecological security and demarcate the rigid urban development boundary in the near future, but also take into account the internal urban development demand and demarcate the elastic development boundaries in the future.

3.3. Suggestions for Implementing the Demarcation of Urban Development Boundaries

This study proposes some suggestions for implementing the demarcation of urban development boundaries in Haikou City. Firstly, the implementation of demarcation of urban development boundaries necessitates the establishment of a comprehensive technical system. It is imperative to establish an integrated management platform under the leadership of the Department of Natural Resources Management, ensuring the harmonization of land use planning, urban and rural planning, main functional area planning, and various types of ecological planning, in accordance with unified technical standards. Additionally, it is crucial to develop a unified map of the information technology system. Secondly, the successful implementation of urban development boundaries necessitates robust policy support and legal protection. This entails adherence to various laws and regulations, including the Urban and Rural Planning Law of the People's Republic of China, the Land Management Law of the People's Republic of China, and the Environmental Protection Law of the People's Republic of China. Moreover, it is imperative to enhance the ecological compensation mechanism during this process by adequately addressing damage and pollution caused by human socio-economic activities on natural resources and ecosystems. Finally, a strict responsibility management system comprising a province- and prefecture-level city—county—township system will be established, with targeted monitoring measures within rigid and elastic boundaries, along with implemented control and protection strategies.

4. Discussion

4.1. The Rationality Analysis of the Research Results

The urban development boundary includes the rigid development boundary that restrains the urban sprawl under the constraint of ecological resistance, and the elastic development boundaries that take into account the future internal development demand of the city. Scientific and reasonable demarcation of urban development boundaries can effectively stimulate the intensive use of urban land and realize the urban smart growth [43]. Next, the rationality of the research results of this study will be analyzed from the two aspects of the scale and layout of urban development boundaries.

In 2000, 2010 and 2020, the urbanization rate of Haikou City was 28.40%, 49.81% and 82.61%, respectively, with an annual growth rate of 2.14% and 3.28% before and after 2010. As for the built-up area of the city, the annual growth of the urban land area of Haikou City in the two decades before and after 2010 was 6.44 km^2/a and 10.60 km^2/a, respectively, indicating that the urbanization process of Haikou City is gradually accelerating. The simulated annual urban-space growth of Haikou city from 2020 to 2050 was 8.72 km^2/a, indicating that the urban-space expansion rate of Haikou City will gradually slow down after 2020. This is conducive to promoting the intensive economic development of Haikou City and meeting the requirements of sustainable urban development in the future [44].

In addition, the Master Plan for Haikou City's Territorial Space (2020–2050) mentions that Haikou City will take the principle of "Dongjin, Xiti, Nanyu, Beilian, and Zhongyou" for overall development, leading the integrated development of "Haikou—Chengmai—Wenchang—Ding'an". This means that by 2035, the development direction of urban land in Haikou City will be centered on the city center, promoting the development and construction of Jiangdong New Area to the east, and strengthening the functional connection with Wenchang City. To the west, it will promote the development and construction of Changliu town. To the south, it will focus on the development and construction of the southern suburbs. To the north, it will link the northern mainland, and construct the transportation routes across the Qiongzhou Strait. At the same time, in terms of regional coordinated development, it will promote the integrated development of Haikou—Chengmai—Wenchang—Ding'an. In this study, the layout of urban development and construction in the demarcation results of the elastic urban development boundaries of Haikou City in 2030, 2040, and 2050 conforms to the layout scheme of the overall territorial space plan.

Therefore, from the perspective of scale and layout, the demarcation results of urban development boundaries in this study are reasonable.

4.2. Limitations of Demarcating Rigid and Elastic Urban Development Boundaries

Although this study has successfully established recent rigid urban and future elastic development boundaries in Haikou City, further exploration is necessary to address existing limitations.

4.2.1. Limitations of Demarcating Rigid Urban Development Boundary

When using the MCR model for constructing an urban ecologically based surface-resistance evaluation system, this study selected 5 Level 1 and 11 Level 2 ecological resistance factors as evaluation indicators to characterize the resistance against urban expansion, referring to relevant research [24,45]. Data on these ecological resistance factors were readily available. However, these evaluation indicators may not fully summarize all the ecological resistance faced by the tropical coastal city Haikou in the process of urban expansion. For example, due to the difficulty of data acquisition, the resistance of some important terrestrial and nearshore ecological functional areas to urban expansion has not been taken into account. Therefore, future research should aim to include more diversified and comprehensive evaluation indicators to build a more comprehensive evaluation system.

In addition, the urban ecologically based resistance evaluation system should include two parts: ecological resistance and ecological construction prohibition. In this study, only 5 Level 1 and 11 Level 2 ecological resistance factors were considered to construct the urban ecologically based resistance evaluation system. For Haikou City, some ecological construction prohibition areas should also be taken into account, such as a permanent basic-farmland protection area, an ecologically sensitive and fragile coastal zone, a coastal zone nature reserve, a first-class water source, a historical and cultural reserve, and so on. These ecological-construction prohibition areas refer to the areas where urban expansion and encroachment are prohibited. However, because the spatial distribution data of the above regions are difficult to obtain, they were not applied in this study, which may affect the accuracy of the results of the ecological security pattern construction.

4.2.2. Limitations of Demarcating Elastic Urban Development Boundaries

In this study, there are also certain limitations in demarcating the future elastic urban development boundaries of Haikou City using the CA–Markov model. Aiming at the urban internal development demand, this study selected six kinds of natural and socio-economic driving factors and one constraint (water body in 2020), to simulate the future land use scenarios of Haikou City, and then demarcated the future elastic urban development boundaries of Haikou City, but did not deeply consider the impact of future land use and urban planning policies on land use pattern and urban development. Future urban expansion may be affected by various policies related to cropland protection, socio-economic development and ecological conservation. Therefore, in future research, we can set up a variety of schemes to simulate future land use scenarios to match possible future land-use and urban-development policies. With reference to the studies of Zhou et al. [45], Feng [6], and Tang et al. [46], three kinds of scenarios can be set: urban development type, cropland protection type and ecological protection type. The simulation results of the three types of land use scenarios can provide a reference for the future policy formulation of land use and urban development. The details of the three types are as follows:

The urban development type means that when the CA–Markov model is used to simulate future land use scenarios, the importance of population and economic growth for urban development is emphasized in the setting of built-up-land-conversion rules. Therefore, population density and GDP are given higher weights in the built-up-land adaptation map. This can ensure the expansion of built-up land to meet the needs of rapid social and economic development;

The cropland protection type means that when the CA–Markov model is used to simulate future land use scenarios, we can refer to the Overall Territorial Space Plan of Haikou City (2020–2035) (public version), in which the cultivated land is planned to be 628 km^2 by 2035. So the conversion of cultivated land to other land types is restricted in the setting of land-use-change conversion rules, which can ensure that the scale of agricultural land is increased, together with the food supply in Haikou City;

The ecological protection type means that when CA–Markov model is used to simulate future land use scenarios, we will strictly implement the policy of balancing the appropriation and compensation of cropland, and prohibit the development of construction land to occupy woodland, water and other types of land of high ecological value.

5. Conclusions

The demarcation of urban development boundaries should not only consider the recent rigid constraint of the ecological bottom line, but also the future elastic space of internal urban development demand. Therefore, the urban ESP was constructed and the recent rigid development boundary were demarcated using the MCR model, and the elastic development boundaries in 2030, 2040 and 2050 were demarcated using the CA–Markov model. The conclusions were as follows:

(1) By identifying the current urban land boundary of Haikou City, the area of urban land in 2020 was 261.64 km^2. Xiuying, Longhua, Qiongshan and Meilan accounted for 90.31, 48.18, 28.14 and 95.01 km^2, respectively;
(2) The MCR model was used to construct a comprehensive urban ESP and to demarcate the rigid development boundary of Haikou City in the near future. The total area within the rigid development boundary was 398.37 km^2, so the maximum growth area of urban expansion in the near future was 136.73 km^2;
(3) By using the CA–Markov model and considering a variety of natural and socio-economic driving factors and constraints, the elastic urban development boundaries of Haikou City in 2030, 2040 and 2050 were demarcated. The internal area within the boundaries in the three years was 451.80, 489.46 and 523.37 km^2, respectively. Compared with 2020, it increased by 190.16, 227.82 and 261.73 km^2, respectively. The internal area within the elastic boundaries was 53.43, 91.09 and 125.00 km^2 more than the recent rigid boundary, representing the increased elastic expansion space of urban development in the next three decades, while meeting the rigid constraint conditions.

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References

1. Liu, R. *Study on Urban Growth Management in China*; Science Press: Beijing, China, 2016.
2. Zhang, L. *Demarcation and Management of Urban Growth Boundary in Combination with Ecological Security Patterns*; Zhejiang University: Hangzhou, China, 2018.
3. Ni, W.; Liu, Z. Green belt policy in England and its revelation. *City Plan. Rev.* **2006**, *2*, 64–67.
4. Ding, C.; Knaap, G.J.; Hopkins, L.D. Managing urban growth with urban growth boundaries: A theoretical analysis. *J. Urban Econ.* **1999**, *46*, 53–68. [CrossRef]
5. Zang, S.; Ni, H.; Li, Y. Response of land utilization in Resource-rich cities to wetland ecology safety: A case study of Daqing in Heilongjiang Province. *Press Geogr.* **2004**, *23*, 33–42+109.
6. Feng, Y. *Urban Growth Boundary Delineation Method Based on Ecological Security Pattern—A Case Study of Hohhot City, Inner Mongolia*; Inner Mongolia Normal University: Hohhot, China, 2019.
7. Yang, Y. Strategy of defining boundary of development in small mountainous cities—A Practice in Shaowu City, Fujian Province. *Fujian Archit. Constr.* **2018**, *7*, 8–12.
8. Harig, O.; Hecht, R.; Burghardt, D.; Meinel, G. Automatic Delineation of Urban Growth Boundaries Based on Topographic Data Using Germany as a Case Study. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 353. [CrossRef]
9. Tayyebi, A.; Perry, P.C.; Tayyebi, A.H. Predicting the Expansion of an Urban Boundary Using Spatial Logistic Regression and Hybrid Raster-Vector Routines with Remote Sensing and GIS. *Int. J. Geogr. Inf. Sci.* **2014**, *28*, 639–659. [CrossRef]
10. Zhuang, Z.; Li, K.; Liu, J.; Cheng, Q.; Gao, Y.; Shan, J.; Cai, L.; Huang, Q.; Chen, Y.; Chen, D. China's New Urban Space Regulation Policies: A Study of Urban Development Boundary Delineations. *Sustainability* **2017**, *9*, 45. [CrossRef]
11. Liang, X.; Liu, X.; Li, X.; Chen, Y.; Tian, H.; Yao, Y. Delineating Multi-Scenario Urban Growth Boundaries with a CA-Based FLUS Model and Morphological Method. *Landsc. Urban Plan.* **2018**, *177*, 47–63. [CrossRef]
12. Yi, D.; Guo, X.; Han, Y.; Guo, J.; Ou, M.; Zhao, X. Coupling Ecological Security Pattern Establishment and Construction Land Expansion Simulation for Urban Growth Boundary Delineation: Framework and Application. *Land* **2022**, *11*, 359. [CrossRef]
13. Dai, X.; Xu, Y. Research Progress of China's Urban Growth Boundary from Perspective of Ecological Security Pattern. *J. Hunan Ecol. Sci.* **2021**, *8*, 82–88.
14. Song, X. *Defining of Urban Growth Boundaries Under the Constraints of Ecological and Food Safety Bottom-Lines—A Case Study of Wuhan, China*; Wuhan University of Science and Technology: Wuhan, China, 2022.
15. Yu, K. Security patterns and surface model in landscape ecological planning. *Landsc. Urban Plan.* **1996**, *36*, 1–17. [CrossRef]

16. Yu, K. Landscape ecological security patterns in biological conservation. *Acta Ecol. Sin.* **1999**, *19*, 10–17.
17. Liu, Y.; Meng, J.; Zhu, K. Progress in the research on regional ecological security pattern. *Acta Ecol. Sin.* **2010**, *30*, 6980–6989.
18. Ren, X.; Ren, S. Study on planning principle and method of urban pattern for ecological security. *Chin. Landsc. Archit.* **2009**, *25*, 73–77.
19. Yu, K.; Wang, S.; Li, D.; Li, C. The function of ecological security patterns as an urban growth framework in Beijing. *Acta Ecol. Sin.* **2009**, *29*, 1189–1204.
20. Zhou, R.; Wang, X.; Su, H.; Qian, X.; Sun, B. Delimitation of urban growth boundary based on ecological security pattern. *Urban Plan. Forum* **2014**, *4*, 57–63.
21. Zhuo, F. *Study on Service Efficiency of Park Green Space Based on Accessibility in Haikou City*; Hainan Normal University: Haikou, China, 2019.
22. Chen, Y.; Wu, G.; Ge, Y.; Xu, Z. Mapping gridded gross domestic product distribution of China using deep learning with multiple geospatial big data. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2022**, *15*, 1791–1802. [CrossRef]
23. Xu, Z.; Wang, Y.; Sun, G.; Chen, Y.; Ma, Q.; Zhang, X. Generating gridded gross domestic product data for China using geographically weighted ensemble learning. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 123. [CrossRef]
24. Ye, Y.; Su, Y.; Zhang, H.; Wu, Q.; Liu, K. Ecological resistance surface model and its application in urban expansion simulations. *Acta Ecol. Sin.* **2014**, *69*, 485–496. [CrossRef]
25. Zhang, J.; Qiao, Q.; Liu, C.; Wang, H.; Pei, X. Ecological land use planning for Beijing City based on the minimum cumulative resistance model. *Acta Ecol. Sin.* **2017**, *37*, 6313–6321.
26. Wei, W. *Land Use Optimal Allocation Based on CLUE-S and MCR Model in Shiyang River Basin*; Lanzhou University: Lanzhou, China, 2018.
27. Knaapen, J.; Scheffer, M.; Harms, B. Estimating habitat isolation in landscape planning. *Landsc. Urban Plan.* **1992**, *23*, 1–16. [CrossRef]
28. Dai, L.; Liu, Y.; Luo, X. Integrating the MCR and DOI Models to Construct an Ecological Security Network for the Urban Agglomeration around Poyang Lake, China. *Sci. Total Environ.* **2021**, *754*, 141868. [CrossRef] [PubMed]
29. Li, H.; Peng, J.; Yanxu, L.; Yi'na, H. Urbanization Impact on Landscape Patterns in Beijing City, China: A Spatial Heterogeneity Perspective. *Ecol. Indic.* **2017**, *82*, 50–60. [CrossRef]
30. Zhang, Y.; Xu, H. Research on suitability subareas of rural residential distribution based on MCR model and optimization model: A case study of Jinniuhu Street in Nanjing, Liuhe District. *Resour. Environ. Yangtze Basin* **2014**, *23*, 1485–1492.
31. Xiao, Z.; Wei, X.; Wen, Y.; Zhao, Y.; Chen, Z. Zone control and regulation of rural residential areas in Liaoning Province based on MCR and multi-factor comprehensive evaluation. *Areal Res. Dev.* **2018**, *37*, 121–127.
32. Pan, J.; Liu, X. Assessment of landscape ecological security and optimization of landscape pattern based on spatial principal component analysis and resistance model in arid inland area: A case study of Ganzhou District, Zhangye City, Northwest China. *Chin. J. Appl. Ecol.* **2015**, *26*, 3126–3136.
33. Tian, Y.; Zhang, M.; Xu, D.; Zhang, S. Landscape ecological security patterns in an ecological city, based on source-sink theory. *Acta Ecol. Sin.* **2019**, *39*, 2311–2321.
34. Pu, L. Demarcation of future urban rigid and elastic development boundaries of the City of Haikou. *Sustainability* **2022**, *14*, 2874. [CrossRef]
35. Ren, J.; Liu, X.; Yue, J.; Wang, Y.; Zhang, T. Delimiting the urban development boundary of Jiayuguan City based on MCE-CA model. *Arid. Land Geogr.* **2016**, *39*, 1111–1119.
36. Cai, Z.; Deng, M. Delimitation method of urban development boundary in Pinghe County, based on "Double-Evaluations" and FLUS model. *Yunnan Geogr. Environ. Res.* **2020**, *32*, 23–29+2+77.
37. Jin, Y. *Research on Urban Development Boundary Demarcation of Large and Medium-Sized Cities in Jilin Province Based on GIS and Geo-CA*; Jilin Jianzhu University: Changchun, China, 2020.
38. Yang, Q.; Li, X. Integration of multi-agent systems with Cellular Automata for simulating urban land expansion. *Sci. Geogr. Sin.* **2007**, *4*, 542–548.
39. Li, L.; Kong, X. A scientometric analysis on the agent-based modelling of cities as complex systems. *Sci. Geogr. Sin.* **2021**, *41*, 797–803.
40. Hou, X.; Chang, B.; Yu, X. Land use change in Hexi corridor based on CA-Markov methods. *Trans. CSAE* **2004**, *20*, 286–291.
41. Jiang, G.; Zhang, F.; Kong, X. Determining conversion direction of the rural residential land consolidation in Beijing mountainous areas. *Trans. CSAE* **2009**, *25*, 214–221.
42. Zhang, J.; Li, J. Prediction and Analysis of Land Use Change Based on CA-Markov Model in Ganzhou District. *Chin. Agric. Sci. Bull.* **2017**, *33*, 105–110.
43. Peng, C.; Song, M.; Han, F. Urban Economic Structure, Technological Externalities, and Intensive Land Use in China. *J. Clean. Prod.* **2017**, *152*, 47–62. [CrossRef]
44. Fu, J.; Xiao, G.; Wu, C. Urban Green Transformation in Northeast China: A Comparative Study with Jiangsu, Zhejiang and Guangdong Provinces. *J. Clean. Prod.* **2020**, *273*, 122551. [CrossRef]

45. Zhou, L.; Dang, X.; Sun, Q.; Wang, S. Multi-scenario simulation of urban land change in Shanghai by random forest and CA-Markov model. *Sustain. Cities Soc.* **2020**, *55*, 102045. [CrossRef]
46. Tang, J.; Zhou, L.; Dang, X.; Hu, F.; Yuan, B.; Yuan, Z.; Wei, L. Impacts and predictions of urban expansion on habitat quality in the densely populated areas: A case study of the Yellow River Basin, China. *Ecol. Indic.* **2023**, *151*, 110320. [CrossRef]