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Simulating the Impact of Urban Expansion on Ecological Security Pattern from a Multi-Scenario Perspective: A Case Changsha–Zhuzhou–Xiangtan Urban Agglomeration, China

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Abstract: Rapid urbanization has further expanded the scale of construction land in urban agglomerations. The encroachment of urban land on ecological land has led to severe ecological problems and threatened the stability of ecological security in urban agglomerations. Analyzing the characteristics of future urban multi-scenario expansion and its impacts on ecological security patterns (ESP) can provide guidance for formulating ecologically sustainable management and control Policies. Our study focuses on Changsha-Zhuzhou-Xiangtan (CZX) urban agglomeration as the study area and establishes an ESP. Additionally, a cellular automata (CA) was used to simulate future urban expansion patterns under three scenarios (i.e., natural development scenario, urban development scenario, and ecological conservation scenario). The subsequent analysis evaluates their impact on the ESP. The simulation results indicate that from 2020 to 2030, the CZX urban agglomeration will undergo rapid urban expansion under the natural development scenario and urban development scenario, characterized by outward growth surrounding the existing construction land. In the natural development scenario, urban expansion is primarily concentrated in the northwest and south directions of construction land, the proportion of construction land increased by 2.78%; in the urban development scenario, it is concentrated in the southeast direction of construction land, the proportion of construction land increased by 3.24%. Ecological conflicts in the aforementioned development scenarios primarily arise in the southwestern region of Changsha County, as well as the southern areas of Kaifu District and Furong District. Conversely, under the ecological conservation scenario, the rate of urban expansion has significantly decreased, environmental preservation is upheld at its highest level, and the proportion of construction land only increased by 0.04%. Based on the simulation results, we present targeted recommendations for urban land planning and growth management, as well as the protection, restoration, monitoring, and development of ecological land. These suggestions provide effective guidance for improving the stability of ESP in urban agglomerations and promoting high-quality development in Chinese urban agglomerations.

Keywords: urban expansion; ecological security pattern (ESP); cellular automata (CA)

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1. Introduction

In recent decades, urban expansion has proceeded at an unprecedented rate [1]. The sustained rapid urban expansion has resulted in the encroachment of ecological land, exacerbating the severity of land use conflicts [2,3] and posing multiple obstacles to maintaining the health of ecosystems [4]. In order to strengthen resilience against environmental challenges, reduce the negative impacts of human actions, and promote sustainable development, it is essential to protect ecological well-being alongside economic growth [5].

Over the years, numerous studies have been carried out by researchers to understand the complex relationship between urban growth and ecological stability. They have examined the trends and factors driving urban expansion to pinpoint major challenges associated with rapid urbanization, including changes in land use, environmental degradation, and resource shortages. Furthermore, research has looked into how urbanization affects ecosystem services, biodiversity, air and water quality, as well as the overall health of ecosystems [6,7]. In order to address these urban ecological challenges, researchers have proposed various approaches such as ecological networks [8], green infrastructure [9,10], nature-based solutions [11], and ecological security patterns (ESP) [12,13]. Among them, ESP planning integrates landscape patterns and ecological processes; its research has evolved from solely addressing conflicts in human–land relationships to a holistic 'human-land-land-environment' approach for circular sustainable development [14]. ESP ensures the coordination between urban development and ecological environmental protection, maintaining the continuity and integrity of ecological processes and services [15].

At present, the majority of research focused on developing ESP has established fundamental procedures that include "identifying ecological source areas, constructing resistance surfaces, and extracting ecological corridors" [16]. The first step in establishing ESP involves the identification of ecological sources, such as forests, grasslands, and bodies of water with significant ecological functions and values [17]. Traditional studies often qualitatively categorize scenic areas, extensive forest regions, and nature reserves with high habitat quality as ecological source sites. This approach tends to be highly subjective and fails to accurately represent the coordination and connectivity among habitat systems [18]. In recent years, morphological spatial pattern analysis (MSPA) has been incorporated into the identification of ecological sources. To address the issue of excessive subjectivity in traditional eco-sources classification, The MSPA classifies eco-sources based on spatial form and structural connection, avoiding subjective comprehensive analysis and interpretation [19]. The next step is to construct a resistance surface. In the construction of resistance surfaces, numerous studies often compile the findings of earlier researchers and directly choose factors like land use type, distance from roads and water, elevation and slope [20]. Extracting ecological corridors is the last key step in constructing ESP. Several methods are available for extracting eco-corridors, including landscape pattern analysis, GIS spatial analysis, and the minimum cumulative resistance (MCR) model [21]. Among these models, the MCR model is regarded as the most effective in representing accessibility and connectivity among various ecological components, as it determines the route that offers the greatest potential for species dispersal at the lowest cost [22]. Numerous studies incorporate the identification and analysis of critical ecological nodes in the final step, enhancing the objectivity and comprehensiveness of ESP research and construction [23]. Generating ecological nodes involves extracting key points and intersection points [21,24]. The former identifies crucial nodes within the ESP by analyzing landscape connectivity indices, among others. The latter identifies eco-corridors via the MCR model, recognizing eco-nodes at the intersections of eco-corridors. At present, ESP is widely applied in the realms of ecosystem protection and land management. A scientifically crafted ESP can help alleviate tensions between economic growth and ecological preservation, support biodiversity stability, and foster regional sustainability [25]. By scientifically describing the temporal and spatial expansion characteristics of urban land use and its effects on ESP, it becomes feasible to implement comprehensive and sustainable urban planning, effective governance systems, and innovative strategies to reduce the negative consequences of urban expansion on ESP.

However, the majority of urban expansion studies concentrate on creating many scenarios to examine the patterns and scale of urban growth, as well as evaluate the environmental impacts that arise from anticipated urban expansion [26–29]. They pay little attention to the impact of future urban expansion under different scenarios on the current ESP. This significantly restricts our comprehension of the complex correlation between urban growth and the ecological stability of the surrounding region. Consequently, By employing simulations of future land use changes, it becomes possible to analyze the potential impact of future urbanization on ESP [30,31]. Recently, numerous scholars have carried out extensive simulations of land use and developed various models [32–34]. Currently, these models primarily consist of quantitative simulation models (e.g., logistic regression, Markov chain), spatial simulation models (e.g., CA, CLUE-S), and coupled simulation models (e.g., FLUS, PLUS) [35,36]. These models forecast the possible effects of future urban growth on ecological conflicts by simulating and modeling the patterns and processes associated with changes in land use. However, these studies often focus on one-dimensional urban spatial expansion and overlook the interactions between cities. They also fail to incorporate these interactions into CA models for simulating urban expansion in urban agglomerations. Multiple studies indicate that urban expansion is influenced by a variety of elements, including societal, economic, natural, and policy-related aspects. The accuracy of the urban expansion process depends on the selected influential factors [37]. Hence, our research examines three distinct urban expansion scenarios: Natural development scenario, urban development scenario, and ecological conservation scenario. We use the HGLM-CA [38] model to simulate the spatial expansion of urban agglomerations under the urban development scenario. The HGLM-CA model elucidates the mechanisms behind the spatial growth of urban agglomerations by examining how various levels of driving factors correlate with the spatial development of these areas. It also highlights the regulatory influence that higher-level factors exert on lower-level ones, showcasing the intricate relationships among multiple driving forces involved in the spatial expansion of urban clusters. In addition, ecological conservation measures are integrated into the ecological development scenario and other potential future scenarios are considered.

This study conducts multi-scenario simulations of China's urban expansion in 2030, analyzing its expansion patterns and characteristics. We also assess the impact of urban expansion on ESP. Our proposed approach involves formulating land use planning with a focus on high-risk resistance and stability, effectively planning and monitoring urban development, and evaluating and optimizing the ecological consequences of urbanization. The research findings can effectively guide the maintenance of ESP and the formulation of high-quality urban planning, providing a scientific basis for regulating and optimizing urban development modes.

This study is structured as follows: Section 2 provides an overview of the current status of Changsha-Zhuzhou-Xiangtan (CZX) urban agglomeration and presents information regarding the study data. Section 3 expounds on the method of cellular automata, the principle of simulating multi-scenario urban expansion and the method of constructing ecological security patterns. Section 4 makes quantitative and qualitative evaluations based on the simulation results and focuses on the superposition analysis of the impact of different future development scenarios on the current ecological security pattern. Section 5 puts forward planning suggestions for protecting ecological security patterns based on the analysis results.

2. Study Area and Data Processing

The Changsha-Zhuzhou-Xiangtan (CZX) urban agglomeration, comprising the cities of Changsha, Zhuzhou, and Xiangtan, is located in the middle and eastern parts of Hunan Province, as shown in Figure 1. It is a major component of the city agglomeration in the middle of the Yangtze River, with a total area of about 8604.47 km^2. The CZX urban agglomeration is strategically situated at the intersection of the Jingguang economic belt, the Pearl River Delta economic belt, and the Yangtze River economic belt, serving as the primary region for economic development in Hunan Province. The main land use types in the CZX urban agglomeration are forest, cultivated land, and construction land. The forest is dispersed throughout the periphery of the study area, while the construction land is concentrated in the central part of the study area. Furthermore, the Xiangjiang River flows in a north-south direction and is recognized as the "water ecological corridor" of the CZX urban agglomeration.

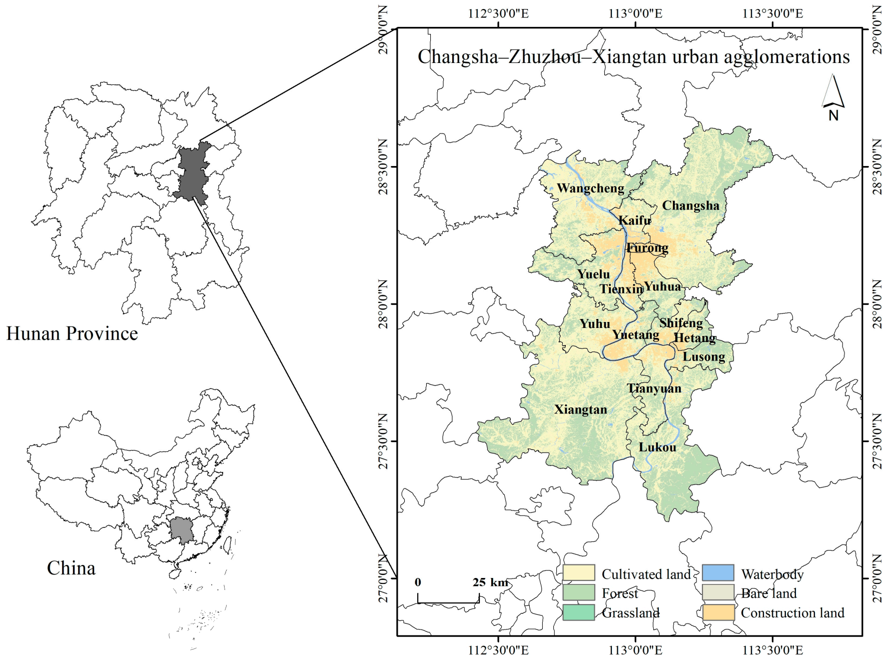

Figure 1. Location of Changsha–Zhuzhou–Xiangtan urban agglomerations, China.

Over the past few decades, the CZX urban agglomeration has experienced substantial growth in urban expansion, and this trend has continued to escalate. The expansion of urban areas resulting from urbanization has disrupted the equilibrium of ecological interactions between humans and the natural environment, leading to significant alterations in the utilization of land resources. This study incorporates several types of data, such as land use data, climate data, environmental data, and other relevant data. Table 1 displays the year, spatial scale, and data source specifics of the relevant data.

Table 1. Datasets and sources.

Data Type	Year	Spatial Scale	Data Source
Land-use pattern	2000, 2010, 2015, 2019	30 m	Derived from Yang (https://zenodo.org/record/5816591#.YvueF8iVX04 (accessed on 9 August 2022))
Population	2010	1 km	Resource and Environment Data Cloud Platform (http://www.resdc.cn/ (accessed on 2 August 2003))
GDP	2010	1 km	
Road networks	2010	1:100,000	Open-street Map (www.openstreetmap.org/ (accessed on 1 July 2004))
Evaporation (ET)	2010, 2019	1 km	National Science & Technology Infrastructure (http://www.cnern.org.cn/ (accessed on 1 July 2019))
Yearly precipitation	2010, 2019	N/A	National Meteorological Science Data Center (http://data.cma.cn/ (accessed on 29 September 2015))
Soil types	2019	1:1,000,000	Geographic Data Sharing Infrastructure, College of Urban and Environmental Science, Peking University (http://geodata.pku.edu.cn (accessed on 25 December 2018))
Digital elevation model (DEM)	2009	30 m	Geospatial Data Cloud (http://www.gscloud.cn/ (accessed on 20 December 210))
Normalized difference vegetation index (NDVI)	2010, 2019	1 km	
Net primary productivity (NPP)	2010, 2019	500 m	Derived from Google Earth Engine (GEE) (https://earthengine.google.com/ (accessed on 25 December 2017))
Soil PH	1995~2011	N/A	National Science & Technology Infrastructure (http://www.cnern.org.cn/data/meta?id=40176 (accessed on 1 July 2019))
Soil salinity	1995~2011		
Administrative boundaries	2019	1:100,000	Geospatial Data Cloud (http://www.gscloud.cn/ (accessed on 20 December 210))

3. Method

This study examines the implications of urban expansion trends under three future development scenarios on the existing ESP, with a focus on areas experiencing severe degradation. It provides an analysis of the underlying causes and proposes viable remedial measures.

Figure 2 demonstrates that the complete procedure is segmented into three distinct sections. Firstly, utilizing the CA model with the HGLM model and ecological protection area restrictions, three future development scenarios, including natural development, urban development, and ecological conservation, are formulated to simulate the spatial and temporal dynamics of urban expansion trends in the CZX urban agglomeration by 2030. Secondly, through the assessment of ecological functions and the vulnerability of the ecological environment, ecological source areas are delineated. Subsequently, ecological corridors, ecological pinch points, and ecological barrier points are identified using circuit principles, culminating in the establishment of an ESP. Finally, the existing ESP is overlaid with various scenarios of future urban expansion to provide planning recommendations for areas facing severe threats.

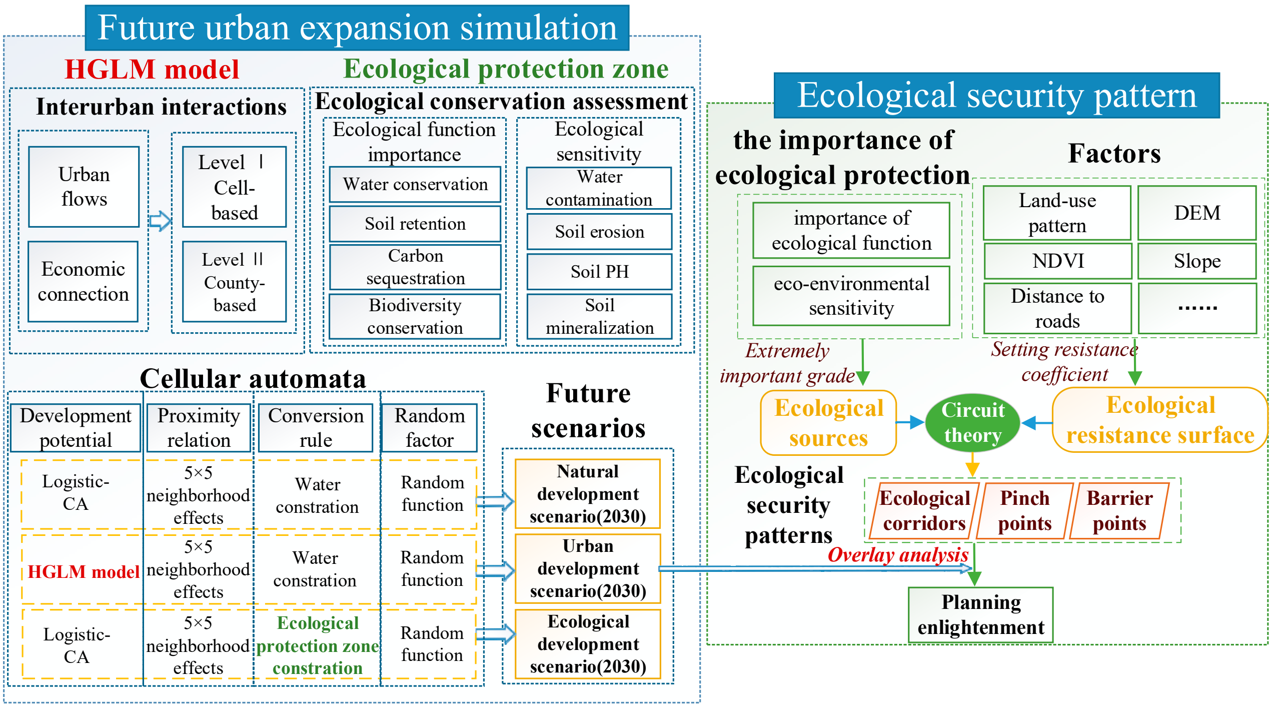

Figure 2. The methodological framework.

3.1. Cellular Automata

When utilizing Cellular Automata (CA) to simulate the spatial and temporal dynamics of land use, it is necessary to consider two distinct aspects. Firstly, "top-down" regional constraints must be considered, encompassing macroeconomic policy regulation, land planning, and management strategies aligned with social and economic development principles to predict overall demand for changes in land use structure. Secondly, a "bottom-up" perspective on geographic distribution should be considered by establishing conversion conditions within ecological protection limits and evaluating the overall probability of land development. The overall probability is determined by combining probabilities of different land types, conversion probabilities of each domain, weights assigned to each domain, adaptive inertia, and the transition matrix. By integrating these two aspects into a model for simulating urban expansion, a deeper understanding of future urban expansion trends can be gained while considering internal factors driving changes in urban growth.

3.1.1. Top-Down

When employing CA for simulating spatial land use change, it is frequently essential to forecast the overall requirement for such change and the land use configuration of the region, known as the "top-down" process. Anticipating the overall need for regional land use alteration and the arrangement of land use can act as vital factors for limiting or ending the CA model. The goal of the regional CA simulation is to guarantee that it conforms to the macro rules of socio-economic and demographic growth, serving as a "top-down" regional constraint. Various methods, including the Markov chain method, system dynamics method, and linear programming method, can be employed to achieve this forecasting process. Compared to certain intricate mathematical models, the Markov chain approach has comparatively low data needs. It has the ability to forecast outcomes with a relatively limited set of past data. In addition, the Markov chain method, which relies on state transition probability, is chosen for this study because it can forecast future states based on the current state without requiring numerous complex mathematical models and assumptions.

3.1.2. Bottom-Up

CA are characterized by their existence in a cellular space and their composition of cells that possess discrete and finite states. These systems are dynamic and change over time based on specified rules throughout distinct time intervals. CA is frequently employed for simulating the spatiotemporal changes in urban growth and land use. During the simulation process, CA typically partitions the metropolitan area into grid cells and simulates the city's evolution by considering factors such as development potential, proximity, conversion rules, and random elements [39]. The four elements are represented as follows: positional development potential (ij), proximity $(\rho_\Omega)_{ij}$, transformation rules ρ_{ij}, and random factors $(\rho_r)_{ij}$. The probability of urbanization at the point location (ij) are represented as $(p_l)_{ij}$. The precise computation involving the four components and probability is as follows:

$$p_{ij} = (p_l)_{ij} \times (\rho_\Omega)_{ij} \times \rho_{ij} \times (\rho_r)_{ij} \tag{1}$$

Development potential: $(p_l)_{ij}$ represents the potential for transformation of non-urban land into urban land, which is influenced by a range of economic, social, and environmental factors. These considerations may encompass population density, land pricing, and accessibility, among other variables. The correlation between these elements and the capacity for development can be articulated as follows:

$$(p_l)_{ij} = f(x_1, x_2, \ldots, x_n) \tag{2}$$

Multiple data mining techniques are utilized, with frequently employed methods encompassing regression analysis [40], artificial neural networks [39], and deep learning algorithms such as random forests [41,42]. The x_n in the expression indicates the initial n driver is associated with development potential. The CA model, which is based on logistic regression, has been extensively used in urban expansion simulation due to its straightforward structure and minimal data prerequisites [42]. The aforementioned equation incorporates the distance from the road, slope, DEM, and proximity factors, as determined by previous studies [39,43,44].

Proximity: The value of $(\rho_\Omega)_{ij}$ is determined by the density of community development. For our research, we established the Moore neighborhood's size as 5. In this context, N denotes the magnitude of the Moore neighborhood. The conditional function $Con(*)$ is programmed to yield a value of 1 if the next cell is classified as urban land; otherwise, it yields a value of 0. The precise formula is as follows

$$(\rho_\Omega)_{ij} = \frac{\sum_{n=1}^{N} Con(*)}{N^2 - 1} \quad (3)$$

Constraint: During the urban expansion simulation process, conversion rules are employed to maintain the original state of specific units (referred to as patches) in order to accurately depict particular locations or constraints in the real world. If a cell is located within a constraint area, denoted as $Con\left(S_{ij} = constraint\right)$, it will yield a value of 0. Otherwise, it will yield a value of 1. The precise formula is as stated below:

$$\rho_{ij} = Con(S_{ij} = constraint) \quad (4)$$

Urban expansion is typically constrained or occurs at a restricted rate and manner in certain regions. For our research, we chose water bodies and parks as restricted areas since they are widely recognized as characteristics that restrict urban planning. Therefore, designating water resources and parks as restricted zones offers a more precise representation of the urban growth process.

Stochastic factors: The urban growth simulation incorporates stochastic elements to measure uncertainty and improve the trustworthiness of the simulation results. A stochastic function [45], denoted as γ and varying between 0 and 1, is employed as a random factor of interference. In this investigation, the value of θ is specifically assigned as 3. The precise formula is as follows:

$$(\rho_r)_{ij} = 1 + (-ln\gamma)^{\theta} \quad (5)$$

3.2. Multi-Scenario Setting for Future Development

3.2.1. Natural Development Scenario

The natural development scenario takes the original CA setting and utilizes the CA model based on logistic regression to evaluate the possibility of urban development. The water limit is utilized as the rule of transformation.

3.2.2. Urban Development Scenario

In the urban development scenario, the level of community development intimacy is evaluated by considering the proximity relationships, and the water boundary is used as the criterion for conversion. The HGLM-CA model [38] is employed to estimate the potential for urban development. This model takes into account the hierarchical nature of urban agglomerations and the interactions between cities.

The CA model is a spatial simulation technique frequently employed to simulate the expansion of metropolitan areas and changes in land usage. However, the majority of current CA models primarily concentrate on recreating the growth of metropolitan areas at a singular level, disregarding the interplay between different cities. The interconnectedness of cities is vital in shaping the socioeconomic growth framework of cities [46,47]. In addition, the movement of elements between cities has an influence on the spatial expansion and growth patterns of cities [48,49]. Hence, recognizing the importance of city contacts, this study integrates the interaction among cities while simulating the growth scenario in the urban development scenario. The degree of connection between different counties/districts in an urban agglomeration can be determined by analyzing population flow data, economic transaction data, transportation flow data, and information transmission data. The measurable data on urban flow and the economic links between different areas help to determine the level of urban interactions. The aforementioned data is incorporated into the HGLM model, along with physical characteristics such as proximity to significant traffic intersections, distance from roadways, land use, and topography. This study uses the HGLM model to assess the possibilities of urban development at both the cell and county levels.

The calculation formula based on cell level is as follows:

$$p_i(Y = urban) = 1/[1 + exp(-z_i)] \tag{6}$$

$$z_i = log\left(\frac{P_i}{1 - P_i}\right) = \beta_{oj} + \sum_{p=1}^{m} \beta_{pj} x_{pij} \tag{7}$$

The calculation formula based on the county level is as follows:

$$\beta_{oj} = \gamma_{oo} + \sum_{m=1}^{l} \gamma_{om} W_{mj} + \mu_{oj} \tag{8}$$

$$\beta_{nj} = \gamma_{no} + \sum_{m=1}^{l} \gamma_{nm} W_{mj} + \mu_{nj} \tag{9}$$

The variable $p_i(Y = urban)$ denotes the urban development potential of the ith cell. z_i represents the total score of cell i driver. At the cellular level, x_{pij} is the pth driver of the jth county on the ith cell. m represents the number of selected drivers. β_{oj} and β_{pj} represent the intercept and coefficient of the regression equation, respectively. W_{mj} represents the mth independent variable at the county level for the jth county. γ_{om} and γ_{nm} are the coefficients of the county-level regression equation. l represents the number of independent variables selected at the county level. γ_{oo} and γ_{no} are intercepts of β_{oj} and β_{pj}, respectively. μ_{oj} and μ_{nj} are also intercepts of β_{oj} and β_{pj}, respectively.

3.2.3. Ecological Conservation Scenario

The ecological conservation scenario still uses community development intimacy as a measure of proximity and utilizes the CA model based on logistic regression to assess the urban growth potential. Simultaneously, in accordance with the recommendations of the Ministry of Ecology and Environment, national regulatory policies are being implemented to underscore the imperative of ecological protection in urban development. The value of ecological functions and ecological fragility as restraints on urban growth was evaluated using various data, such as the biodiversity index, ecosystem stability index, and land cover change data. The restriction of ecological protection areas is utilized as a conversion rule for the CA model.

3.3. Identification of Ecological Security Pattern

The ESP is intricately linked to the holistic well-being and long-term viability of the ecosystem within the region. The ideal ecological services it provides are essential for attaining ecological security in the region [50] and serve as an effective method to harmonize social and economic growth with ecological protection [51].

3.3.1. Identification of Ecological Sources

Ecological sources refer to crucial ecological patches that play a vital role in facilitating ecological processes, preserving the overall health of ecosystems, and offering valuable ecosystem services [52]. Ecological source identification entails identifying and extracting areas of land that are crucial for ensuring the ecological security of the region and the watershed. Prior research has predominantly employed several methodologies, including ecosystem service valuation, ecological sensitivity analysis, granular inversion, hot spot analysis, government decision-making, residents' perspectives, or a mix of these approaches, to identify ecological sources [53,54]. In order to thoroughly evaluate the overall health of the ecosystem and its vulnerability to external disruptions, the ecological source was determined by considering the importance of ecological functions and the sensitivity of the ecological environment.

The importance of ecological functions. The ecological functions primarily refer to the ecosystems' role in maintaining the ecological balance and supporting the survival and advancement of humanity. The assessment of ecological services is based on four main indicators: water retention, soil conservation, carbon sequestration, and biodiversity conservation [55]. These indicators signify the ecosystems' capacity to maintain and support water resources, soil resources, carbon cycles, and biodiversity.

Water retention refers to the ability of soil to absorb and hold water. It measures the efficiency of the ecosystem in utilizing water resources and its contribution to the water cycle. Soil conservation refers to the ability of soil to resist natural forces such as wind erosion, water erosion, and human activities. The evaluation measures the land's capacity to resist erosion, reflecting the degree of soil resource protection provided by the ecosystem. Carbon sequestration refers to the ability of ecosystems to absorb and store carbon. It contributes to the reduction of carbon dioxide accumulation in the atmosphere, assesses the impact of ecosystems on the carbon cycle, and showcases the capacity of ecosystems to alleviate climate change. Biodiversity conservation refers to the preservation of the richness and diversity of different species within an environment. It is used to assess the variety and resilience of various organisms in the ecosystem, acting as a measure of the ecosystem's health.

Ecological and environmental sensitivity. Ecological environmental sensitivity focuses on the degree of response of ecosystems to external disturbances. The four main indicators to evaluate ecological environmental sensitivity [55] are water pollution, soil erosion, soil pH, and soil salinity. The water pollution index evaluates the magnitude of water pollution, whereas the soil erosion index quantifies the degree of erosion-induced harm to the land. In addition, the soil pH and soil salinity are indicators of the soil's acidity and salt content, respectively. These indicators offer the advantage of providing an unbiased evaluation of how ecosystems react to external disruptions and can aid in determining the environmental susceptibility of ecological resources.

3.3.2. Construct Resistance Surfaces

The resistance surface is a visual representation of the spatial distribution of resistance in various ecological processes, illustrating how landscape heterogeneity affects ecological flow. For this study, we chose a simulated land use model, slope, digital elevation model (DEM), normalized difference vegetation index (NDVI), and distance from the road as the factors that determine resistance. We determined the magnitude of each resistance factor and created the resistance surface using information from prior research [56,57].

3.3.3. Extraction of Ecological Corridors and Nodes

Ecological corridors are designated as narrow regions that link distinct ecosystems or nature reserves. Ecological corridors are established to preserve the connection of ecosystems and minimize ecosystem fragmentation. The process of identifying ecological corridors entails calculating the least-cost route between source patches, utilizing recognized ecological resources and establishing ecological resistance values. This approach is akin to electrical circuit theory, where ecological resources are treated as focal nodes in the circuit, and the surface's ecological resistance functions as the conductive medium. Assigning low resistances to certain landscapes facilitates ecosystem connectivity, while higher resistances impede it. Ecological corridors can be categorized into key and potential types. The key corridor represents the most efficient path between neighboring source patches, whereas a potential corridor indicates possible routes from each patch to nearby resource patches. Ecological corridors enhance biodiversity by allowing the migration of species and the exchange of genetic material.

In addition, the key points in the ecological corridor include ecological pinch points and barrier points. Ecological pinch points represent critical nodes with high flow, holding the utmost priority in preserving landscape connectivity and playing vital roles in biological migration and exchange functions. Ecological pinch points encompass aquatic features such as rivers and lakes, as well as forest margins. Barrier points are barriers found within ecological corridors that might hinder the movement of organisms and the exchange of genetic material. Barrier points can be found in places that have been impacted by human activities, such as highways and urban development sites. After identifying these crucial points, precise methods for conservation and management can be put into action to guarantee the proper functioning and interconnectedness of the natural corridors.

4. Results and Analysis

4.1. Analysis of Multi-Scenario Urban Expansion Simulation Results

Based on the land use matrix operation, the area of different land use types in different scenarios can be obtained for the year 2030. The specific data is shown in Table 2 and Figure 3. Analysis of Table 2 reveals that the expansion of urban construction land under natural development scenarios and urban development scenarios is mainly achieved by encroaching on farmland and forest land around urban agglomerations.

Table 2. Area of land use types in multiple scenarios.

Land Area/km^2	Cultivated Land	Forest	Grass Land	Water Body	Bare Land	Construction Land
2020	4312.790	3188.670	0.740	270.020	0.043	832.640
2030 (natural development scenario)	4141.770	3131.190	0.720	262.120	0.066	1072.600
2030 (Urban development scenario)	4097.280	3126.600	0.680	262.120	0.059	1127.730
2030 (Ecological development scenario)	4370.050	3138.400	1.160	262.120	0.160	836.580

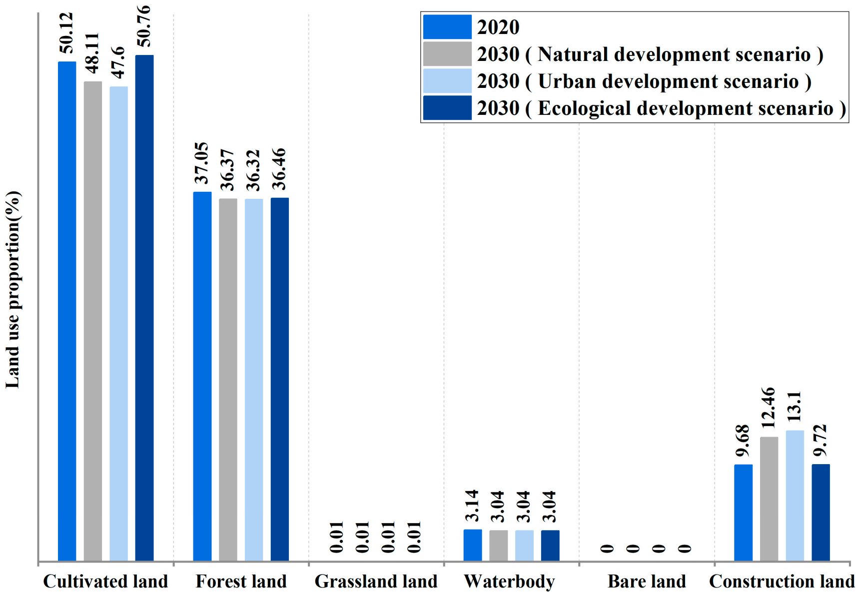

Figure 3. Proportion of land use types in multiple scenarios.

Transforming the data from Table 2 into a proportion-based bar chart enhances clarity and provides a more intuitive understanding of these trends. Under the natural development scenario, the proportion of construction land in 2030 will increase from 9.68% in 2020 to 12.46%, and the proportion of farmland will decrease from 50.12% in 2020 to 48%. Under the urban development scenario, the proportion of construction land in 2030 will increase from 9.68% in 2020 to 13.1%, and the proportion of farmland will decrease from 50.12% in 2020 to 47.6%. The encroachment of ecological land under the urban development scenario is more serious than that under the natural development scenario, and the damage to ecology is greater. Under the restrictive conditions of ecological protection, the urban construction land in 2030 will only increase by 0.04% compared with that in 2020, and the changes in agricultural land and forest land are very small.

The urban expansion under different scenarios is shown in Figure 4. In simulating the natural development scenario, urban expansion radiates outward from the original construction land, with the Furong District and Yuetang District serving as the focal points of a multipoint expansion. Compared to other development scenarios, this urban expansion is particularly pronounced in the southeastern portion of Wangcheng District, especially in the southeast of Yuhu District and the southwest of Yuetang District. The urbanization process under the natural development scenario results in the conversion of original ecological spaces into construction land and industrial zones, thereby exacerbating the negative impacts of urban expansion on the ESP. This transformation further highlights the growing conflict between urban development and ecological protection.

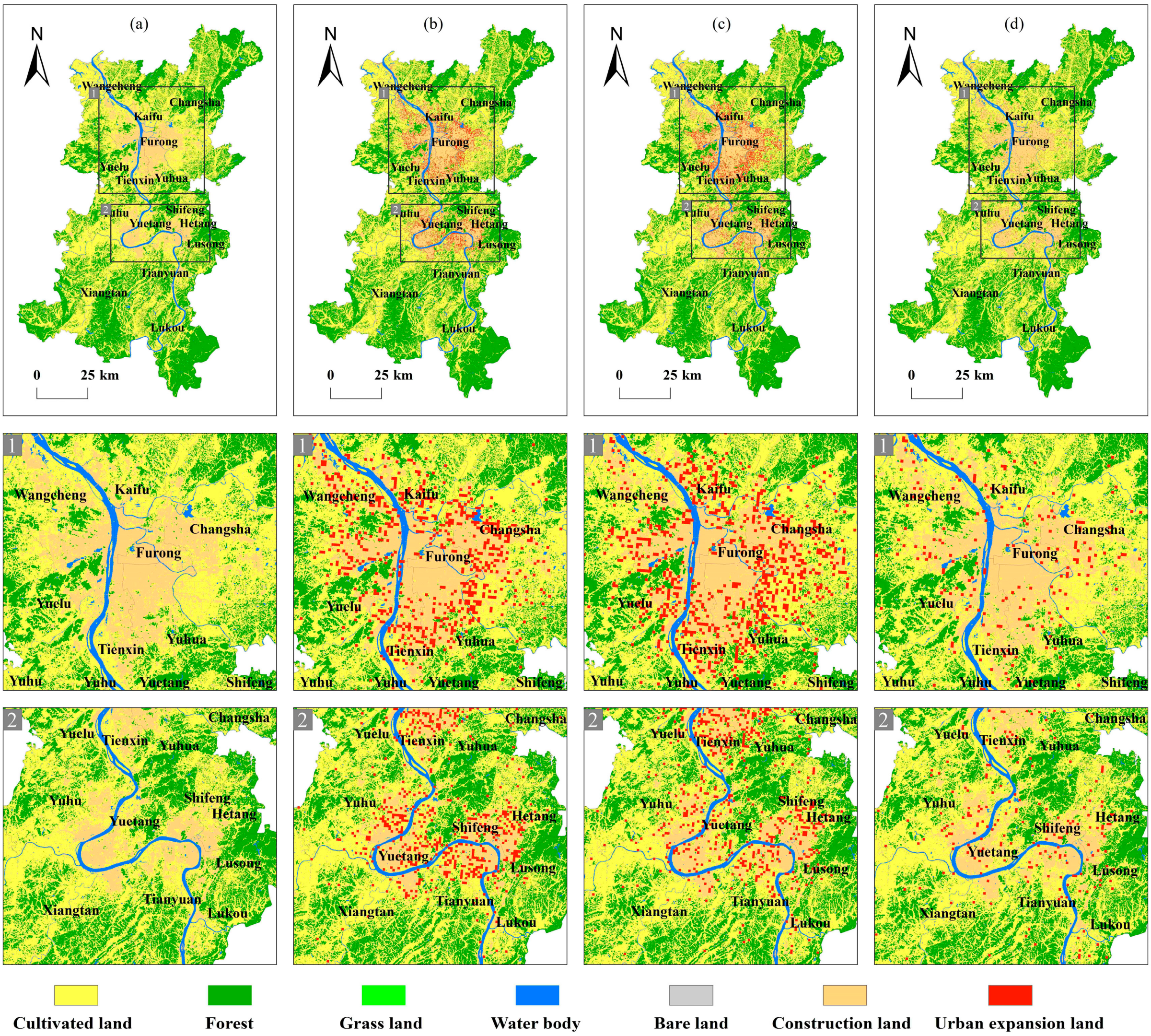

Figure 4. (**a**) Land use in 2020 (Box 1 and 2 are partially enlarged parts of (**a**). The enlarged image is directly below (**a**). (**b**–**d**) are the same as (**a**)), (**b**) Urban expansion under the natural development scenario in 2030, (**c**) Urban expansion under the urban development scenario in 2030, (**d**) Urban expansion under the ecological conservation scenario in 2030.

The HGLM-CA model was utilized to simulate the urban development scenario. This model effectively illustrates the hierarchical organization of urban agglomerations and the dynamic interactions occurring between cities, incorporating the interrelations and flow of resources among them. In contrast to the natural development scenario, the urban development scenario exhibits an accelerated rate of urban expansion, primarily driven by the regional integration efforts associated with the CZX urban agglomeration. Consequently, the focus of expansion has shifted from the northwest and southern directions of the construction areas to the southeast. Notably, the southwest region of Changsha County and the northeast region of Yuhua County, as well as central Tianxin District and the northwest portion of Kaifu District, show a concentrated high density of newly constructed land. The majority of these areas are located in proximity to rivers or at the confluence of multiple cities.

In the ecological conservation scenario simulation, ecological protection policies are predominantly viewed as restrictions on urban expansion, resulting in a significant deceleration of urban growth. In the southeastern regions of Wangcheng District, southeastern Yuhu District, southwestern Yuetang District, southwestern Changsha County, and northeastern Yuhua County, substantial amounts of new construction land were allocated under both the natural and urban development scenarios. However, the ecological conservation scenario demonstrates a remarkable reduction in new construction land within these areas. This preservation effort maximizes the safeguarding of ecological land surrounding construction sites. Thus, it is evident that the ecological conservation development scenario emphasizes high-quality development as its guiding principle, effectively alleviating land use conflicts and environmental degradation. Additionally, it protects ESP and sustains urban ecological stability by minimizing encroachment from urban expansion onto ecological lands.

4.2. Ecological Security Pattern Analysis

The distribution of ecological corridors, ecological pinch points and ecological barrier points is shown in Figure 5. In the study area, there are a total of 57 ecological corridors, comprising 36 critical ecological corridors and the remainder as potential ecological corridors. The key ecological corridors are predominantly situated in proximity to water bodies, such as the northwestern Wanzhou District and southeastern Luokou District within the study area, characterized by a high density of compactly distributed critical ecological corridors. Potential ecological corridors are located in regions with lower ecological resistance values, such as Xiangtan County and Yuhua District. These areas exhibit dispersed and distant ecological source areas, resulting in fewer but longer potential ecological corridors. The remaining potential ecological corridors extend beyond built-up areas into Changsha County, Kaifu District, Furong District, and Yuhua District, where higher ecological resistance values make them more susceptible to urban expansion. Ecological corridors play a crucial role in facilitating species migration and expanding ecological resources while serving as an important conduit for the flow of matter, energy, and information. Therefore, it is imperative to reinforce measures for their protection to ensure sustained functionality.

Ecological pinch points are primarily located in the southern Furong District, Kaifu District, and the northeastern Yuhua District, as well as along the banks of the Xiangjiang River and Liuyang River. These ecological pinch points possess significant ecological importance and sensitivity, necessitating enhanced protection measures. By fortifying these protective efforts at these pinch points, we can effectively unblock these vital pathways, thereby improving habitat quality while strengthening overall ecosystem health. Ecological barrier points are predominantly situated in the southwestern region of Changsha County, the southern area of Kaifu District, and the northeastern part of Yuelu District. These barrier points hinder the connectivity of ecological corridors and impede species movement, thereby constraining genetic exchange among different species and species migration. Consequently, this constraint results in ecological system fragmentation and biodiversity loss.

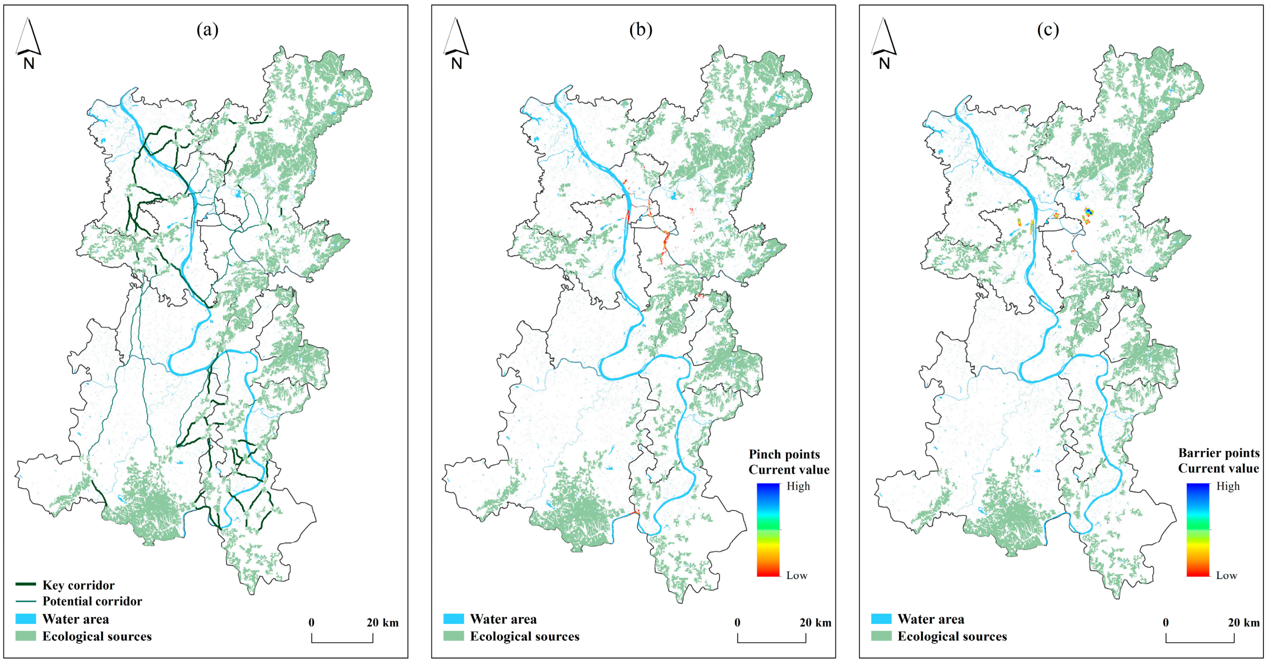

Figure 5. (**a**) Ecology Corridors in 2020, (**b**) Ecology Pinch points in 2020, (**c**) Ecology Barrier points in 2020.

4.3. Change Analysis

The impact of urban expansion on ecological security pattern under different scenarios is shown in Figure 6. In the southeastern and southwestern regions of the study area, there was no discernible urban expansion under all three scenarios, resulting in minimal impact on the key and potential ecological corridors located in these areas. In the northwestern part of the study area, there is a high concentration of key ecological corridors. Under the natural development scenario, urban expansion in this region is significantly intensifying, leading to an increased risk of ecological corridor destruction. Under the urban development scenario, rapid acceleration of urban expansion occurred in the northern and eastern areas of built-up land with a substantial rise in new construction density at county boundaries. Consequently, multiple potential ecological corridors situated outside these peripheries are likely to face significant degradation and destruction. Furthermore, under the urban development scenario, continued outward expansion of built-up land was observed in the southwestern area, leading to an increased likelihood of significant damage to two key ecological corridors within this vicinity. The analysis indicates that in the scenario of urban development, there is an increase in interconnectivity between cities and a further enhancement of synergy between districts. Consequently, this will result in a heightened density of new construction land between districts in urban development scenarios, potentially leading to greater ecological corridor damage.

The ecological pinch point is situated at the interface between existing and new construction land, primarily concentrated in the junction of Furong District, Changsha County, and Yuhua District. It also encompasses the southwest basin of the Xiangjiang River basin near Kaifu District. Under the natural development scenario, the ecological pinch points will suffer damage and erosion to some extent. However, under the urban development scenario, there is a significant increase in the density of new construction land at connection points between various districts and counties, such as the southeast of Furong District and the north of Yuhua District, as well as the northeast of Yuhua District and the southwest of Changsha County. These areas closely align with the distribution of ecological pinch points. Thus, it is probable that the ecological functions of this area will be compromised under the urban development scenario, leading to a substantial adverse impact on the ecological pinch points, pivotal nodes connecting ecological corridors.

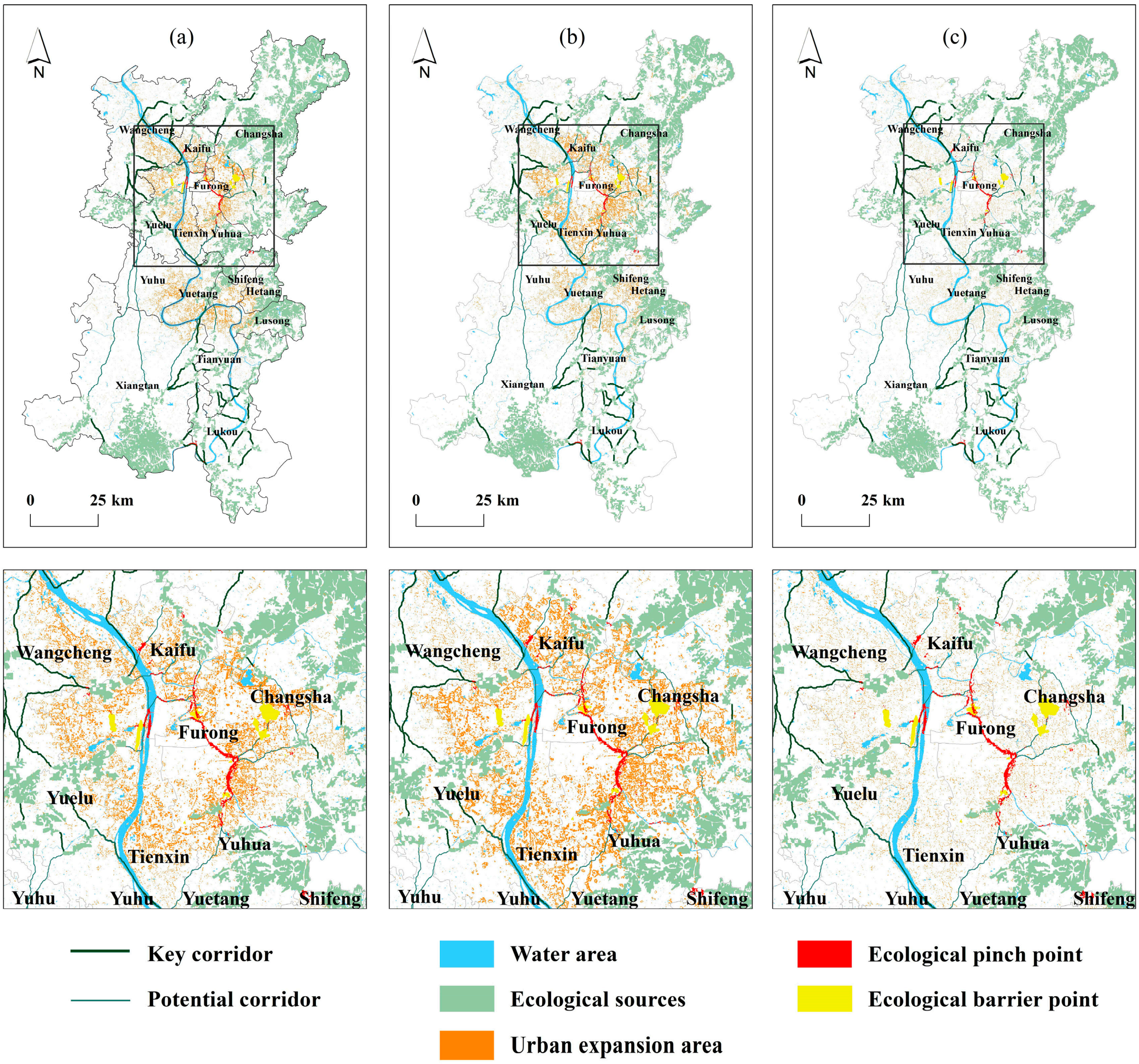

Figure 6. Ecological security pattern analysis map ((**a**): natural development scenario, (**b**): urban development scenario, (**c**): ecological conservation scenario).

The ecological barrier points are primarily located in the southwestern region of Changsha County and the southern area of Kaifu District, which are both near Furong District and the northeastern part of Yuelu District near the Xiangjiang and Jinjiang rivers. The largest concentration of ecological barrier points is found in the southwestern region of Changsha County, which has experienced rapid urban expansion under both natural development and urban development scenarios. In the context of urban development, this area has witnessed the most accelerated pace of urban expansion and a significant increase in new construction land. This trend will undoubtedly further expand the scope of ecological barrier points in this region, consequently impacting species dispersion and rendering the ecological environment more susceptible to disruption. In addition, there are ecological barrier points located at the peripheries of urbanized areas. Further urban expansion within these areas will present a significant challenge to maintaining the species cycle of the ecological environment surrounding urban agglomerations.

5. Discussion

The identification of key ecological corridors and pinch points that are at risk of destruction due to urban expansion highlights the need for targeted conservation efforts.

For instance, the ecological corridors in the southeast region, although relatively safe, require continued monitoring. In contrast, the concentrated distribution of corridors in the southwest necessitates urgent measures to mitigate the risk of destruction. The potential loss of ecological functions in these areas could have significant negative impacts, further affecting species distribution and making the ecological environment more fragile. These findings underscore the importance of incorporating ecological considerations into urban planning and decision-making processes.

5.1. Implications for Urban Planning

The expansion of urban construction land reflects a significant aspect of China's ongoing socio-economic development and is expected to persist for the foreseeable future. As a result, trends such as urban landscape fragmentation, loss of ESP functions, and complex interactions between urban growth and ecosystems seem to be enduring. Nevertheless, these trends are not set in stone [58,59]. Strategies that focus on urban land management and ecological resilience may provide more immediate and practical solutions, to some degree, when compared to restoration efforts based on Nature-based Solutions (NbS) [60].

We simulated the impact of future urban expansion on ESP under multiple scenarios. Continuous urban expansion under natural development scenarios and urban development scenarios will inevitably affect ESP and further threaten the realization of sustainable development goals. This encourages us to reevaluate China's policies regarding land use and ecological conservation [61]. In the last ten years, the Chinese government has enacted a range of policies aimed at strategically managing the spatial layout of urban growth while protecting ecosystems. This includes defining an ecological protection red line, launching the Yangtze River Protection Plan, promoting reforms in spatial planning systems, and setting a "dual-carbon" target [62–64]. Nonetheless, the impact of urban expansion on ecosystems is primarily seen in the encroachment of urban development onto ecological lands such as forests, agricultural land, and water sources, which disrupts the balance between the supply and demand for ecosystem services [65]. Thus, addressing the impacts of urban expansion on ESP necessitates the incorporation of various contributing elements into a holistic and interconnected ecological governance framework, promoting the sustainable development of ESP [66,67].

5.1.1. Construction Land Growth Control

Regulating the amount of urban land is an effective approach to safeguarding valuable ecological areas like forests, agricultural land, and wetlands. To lessen the impacts of future urban growth, it is essential to slow down urban expansion, manage the size of construction land, and optimize existing resources, thereby reducing the ecosystem service deficit to some degree [65,68].

In the context of urban development, areas with ecological pinch points are also undergoing high-density urban expansion, potentially leading to significant ecological repercussions. Hence, it is worthwhile to contemplate the adoption of urban growth borders surrounding current cities as a means to limit urban expansion. The urban growth boundary serves as a regional planning tool that can predict the scope of urban expansion and aid in the logical planning of urban development inside the border. When used in conjunction with suitable land use rules, this technique successfully reduces the expansion of urban areas into valuable cultivated land and ecologically important areas. At the same time, the China Construction Bureau should enhance its oversight of cropland conversion, rigorously implement minimum standards for arable land, ensure the safeguarding of essential farmland, and concurrently prioritize the protection of natural habitats during the process of replacing agricultural land [68,69].

Controlling the extent of urban land satisfies the spatial demands for production, everyday activities, and ecological endeavors, while simultaneously maximizing resource distribution, improving land utilization efficiency, and promoting a balanced interaction between humans and the environment. As a result, the newly developed land will be converted into urban land that combines spatial intensity, functional intensity, and resource intensity.

5.1.2. Set Up Ecological Protection Zoning

In order to preserve the ecological functions of important places that are essential for maintaining ecosystem stability, it is necessary to construct protected ecological areas. These places should be protected from the harmful impacts of urban expansion by establishing a strict land management system. Efforts in spatial planning should give priority to implementing strategies that focus on conserving and protecting these environmentally delicate areas.

It is imperative to prioritize the preservation of critical ecological corridors and areas of ecological significance, as they play a pivotal role in upholding the existing pattern of ecological security. In Wangcheng District and Lukou District, there exist significant ecological corridors, whereas crucial ecological pinch points are situated in the southern part of Fuzhou District and the northeastern part of Yuhua District. During the process of urban expansion, it is imperative to ensure maximum protection for these regions. Simultaneously, safeguarding and managing the Xiangjiang River basin holds paramount importance, with a key focus on strengthening water supply protection in pivotal ecological preservation zones to guarantee production and domestic water safety.

5.1.3. Ecological Restoration and Restoration

The ecological compensation mechanism should be introduced in urban expansion to make reasonable compensation for the areas whose ecosystems are damaged by development activities so as to ensure the overall balance of the ecosystem. Given the future urban expansion, it is crucial to temporarily slow down the pace in the local distribution areas where ecological barrier points have emerged. Simultaneously, it is imperative to execute ecological restoration initiatives that focus on revitalizing the impaired ecosystems, augmenting their ecological capabilities and resilience while ensuring that there are no adverse effects on urban development. Moreover, ecological restoration and conservation endeavors, such as afforestation, wetland restoration, and habitat enhancement, can be implemented to reinstate the ecological functioning of ecosystems. Ecological restoration work must be vigorously conducted in the northern and northeastern regions of Yuelu District, including in areas along the Xiangjiang River, the Jinjiang River, and the intersection of Kaifu District and Furong District near the Liuyang River.

5.1.4. Conduct Environmental Monitoring and Assessment

Efforts should be intensified to enhance environmental monitoring and evaluation in order to promptly identify ecological harm and erosion and implement suitable actions. Develop and enhance the information database that tracks land inventory and changes in land use, with a specific focus on monitoring the expansion of future construction sites and designated ecological reserves. This will allow for timely assessment of changes and implementation of appropriate measures.

5.1.5. Carry Out the Construction of Ecological Channels

Urban design can incorporate the establishment of new ecological corridors and ecological pinch points to compensate for the decline in ecological services caused by urban expansion. Ecological pathways can be created by implementing green belts, ecological corridors, and connectivity projects. The main areas where prospective ecological corridors are found include Xiangtan County and Yuhu District in Xiangtan City, as well as the southwestern region of Changsha County and Kaifu District in Changsha City. In order to optimize the efficiency of these corridors, it is imperative to enhance the ecological integrity and apply strategies such as reforestation. This will enable them to effectively leverage their strengths as central pathways.

5.2. Limitations and Future Research Directions

The study identified the impact of future urban expansion on ESP under different scenarios and proposed corresponding urban planning strategies and governance systems to mitigate the adverse effects of urban growth on ESP. This includes exploring environmental management practices and integrating ecological factors into urban planning and decision-making processes.

However, this study has several limitations. Firstly, the simulation of future urban expansion primarily focused on planning and policy constraints while ignoring future climate and meteorological changes. Subsequent investigations should include supplementary factors such as temperature and precipitation to enhance the precision of the forecast. Moreover, in the CZX urban agglomeration, where human activities are prevalent and the industrial structure is intricate, relying on a single set of socio-economic and natural factors may not adequately capture the underlying dynamics. Thus, gathering extensive socio-economic and environmental data along with employing appropriate methodologies can enable a thorough examination of Ecological Security Patterns (ESP) and urban expansion trends within the CZX urban agglomeration.

Our future research should adopt more precise multi-scenario simulation schemes with more detailed spatial divisions to enhance the simulation accuracy of the study area's future spatial conditions. This will enhance the scientificity and logicality of the simulation. This research also does not provide concrete strategies to reduce negative impacts. Future research can further study the environmental management practices proposed in this study, such as sustainable infrastructure design and specific forms of green space enhancement. The socio-economic effects of urban expansion need to be explored in greater depth. Gaining insights into how it affects local communities, livelihoods, and economic development will aid in creating inclusive and fair urban growth strategies.

6. Conclusions

This study focused on the CZX urban agglomeration and used the CA model to simulate urban expansion under different scenarios. The potential risk of destruction and erosion of the current ESP was discovered through multi-scenario simulation and superposition analysis. Key findings include the identification of ecological corridors and pinch points at risk of destruction due to urban expansion. The study simulates the potential impacts and proposes planning recommendations, such as controlling construction land growth, delineating ecological protection areas, carrying out ecological restoration, strengthening environmental monitoring, and constructing ecological channels. This study aims to provide guidance for the systematic expansion of the CZX urban agglomeration and offer policy recommendations for safeguarding the ESP, thereby promoting sustainable development and ecological civilization construction.

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