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Optimization and Construction of Ecological Security Patterns Based on Natural and Cultivated Land Disturbance

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Abstract: In previous research on the construction of ecological security patterns (ESPs), the positioning characteristics of urban development were rarely considered, resulting in the identification of key conservation areas that are insufficient to support the ecological security of the entire region and the overall development of urban functions. Firstly, a "quality-importance-connectivity-balance" framework was created to identify ESPs and chose Liaocheng City (LC), a typical main agricultural production area, as the study site. Secondly, the ecological security level of the watershed perspective is an integrated resistance assessment method that exhibits topography, human activities, distance, and agricultural environmental impacts. Finally, the coordination pattern between agriculture and ecology was divided by the comprehensive quality of cultivated land and ESPs. A "six cores-seven belts-three zones" optimization pattern was constructed based on the components of ESPs and the distribution of cultivated land comprehensive quality. The study presents a novel approach for measuring ESPs and is an essential resource for ecological conservation and regional development planning in agroecologically complex regions.

Keywords: ecological security patterns; ecological source; ecological corridors; cultivated land quality; main agricultural production areas

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1. Introduction

China's main agricultural producing areas account for 64% of the total cultivated land area, 75% of the total grain output, and 91% of the grain output increase in the past six years [1]. The acceleration of urbanization has promoted the improvement of human life, and the expansion of cultivated land has ensured food security [2]. However, human activities and over-exploited modern agricultural bases inevitably threaten ecological security and lead to ecosystem services degradation problems such as loss of ecological species diversity, landscape fragmentation, and habitat destruction [3,4]. In China, with the implementation of the national strategy for spatial ecological restoration of the country in the new era, it is urgent to carry out ecological restoration work and protect the ecological environment [5,6]. Providing comprehensive and targeted spatial heterogeneity solutions to ensure human living standards and maintain stable social development is the key to ecological security.

The construction of ESPs is one of the most significant means of resolving the conflict between economic development and ecological conservation, as well as an essential component of the development of an ecological civilization [7–10]. The concept of ecological security is derived from landscape design planning, which is based on the theories and methods of landscape ecology to improve regional ecological security and promote the healthy and sustainable development of ecosystems by coordinating and optimizing the functional configuration relationships of patches and corridors in the ecosystem to maintain

the spatial location and composition patterns of ecological landscape elements [11–13]. The ESPs focus on the identification of essential features, such as ecological sources, ecological corridors, and ecological nodes, which compose the network and skeleton of the ecosystem [14]. From an ecological perspective, ESPs must ensure the integrity and stress resistance of the internal structure of the ecosystem within a certain spatial and temporal scale, and it is urgent to fully consider the interaction between the human social economy and the ecological environment to clarify the mechanisms and relationships between the ecological pattern and the ecological service functions, and to highlight the overall comprehensive characteristics of the ecological restoration work at the regional scale [15,16].

Sustainable agriculture management implies that farmland provides food and contributes ecological resources [17]. As the primary basis for the systematic ecological restoration of land space, the ESPs, based on the comprehensive systematicness and integrity of the region, provide layout suggestions for the ecological space of the entire municipality and promote the harmonious development of local agricultural production and ecosystem, which are of great significance in the agro-ecological complex area [18–20]. However, little research has incorporated agricultural aspects into the development of ESPs.

Since the 1970s, scholars have gradually focused on ESPs, which include methods for ecological problem identification, risk assessment, sensitivity and vulnerability assessment, and ecological security model construction and optimization. The aforementioned theories and methods can support the planning, evaluation, and monitoring of ecological restoration in national land space. ESPs have been a hot academic study path in ecological security as ecological challenges have become increasingly significant [19,21]. In recent years, "sources identification-resistance surface construction-corridor extraction" has become the fundamental paradigm of ESPs research [19,22–24], following a lengthy period of development of scholars' theoretical systems, improvement of methodological models, and implementation of ecological restoration policies in national land space.

The first stage in constructing ESPs is extracting ecological sources. The easiest approach to identifying ecological sources is to employ ecological areas such as grassland and forest, water and marsh, nature reserves and scenic spots, etc. However, the fragmented distribution of ecological sources loses the meaning of ESPs. Scholars have developed evaluation methods to determine the ecological significance of patches, including the sensitivity, functioning, landscape connectedness, and ecological risk as quantitative markers to identify ecological sources [25–27]. However, among the above indicators, the ecological sources extracted based on ecological sensitivity and ecological function may only represent a single ecological function and cannot reflect the ecological importance of a source. Indicators based on connectivity are more important indicators, and the examination of the overall connectivity index and probability of connectedness can give data to help the maintenance of ecological security at the landscape scale [28–30].

Before extracting the corridor, the migration and flow processes of ecological elements in the heterogeneous landscape of the whole region are simulated by developing the ecological resistance surface. Some researchers develop resistance surfaces based on universal land use types and adjust the surface based on nighttime lighting or impervious surface to replicate human activities [31,32]. With the advancement of research, the emerging circuit theory can better represent ecological flow, and identifying corridors and nodes based on this theory is the bulk of the existing study [33,34]. Some research has also been undertaken in mining locations to create ESPs in specific locales, with broader uses [35,36]. In addition, the ecological security prediction model is derived from the potential change in land use by simulating ESPs [8,37].

In conclusion, previous studies on ESPs have focused on methodological optimization to enhance the level of ecological protection, but this may constrain the general direction of urban growth [38]. The construction of ESPs must consider urban positioning, particularly in regions where agricultural products are the primary economic source [39]. In practice, by creating ecological protection policies, the conflict between ecological protection and

agricultural development is resolved, while the ecological and productive functions of farmed land are strengthened [40,41].

As a national agricultural production area, LC must prioritize enhacing its complete agricultural production capability, restrain large-scale and high-intensity industrialized urbanization, and coordinate the economic value of agriculture and ecological protection [42]. Several researchers have examined the effect of land use on ESPs, but our knowledge of the combined effect of agricultural land use on ecological resistance is still limited [43,44]. Few studies have developed ESPs with a balance between agro-urban growth and ecological conservation in sight.

Considering the regional specificity of LC as the main agricultural producing area of the country, we developed an agricultural-ecological combination model to construct ESPs in the entire study area. In addition to evaluating the comprehensive quality and spatial agglomeration of cultivated land, the subcategories of ESPs include cultivated land that serves a specific ecological role to assure the contribution of agriculture to the overall ESPs.

2. Materials and Methods

2.1. Study Area

LC is situated in the Shandong Province's southwest, between latitude 35°47′–37°02′ N and longitude 115°16′–116°32′ E (Figure 1). The total land area of LC is 8646.87 km^2, of which 6359.60 km^2 is cultivated land, accounting for 73.5% of the total land area. Due to its location in the alluvial plain zone of the northwest on the left bank of the downstream section of the Yellow River Basin in Shandong, it is suitable for the growth of numerous crops and vegetation and serves as a significant modern agricultural production and supply base. LC lies within the warm-temperate monsoon climatic zone, with an annual precipitation of 560.6 mm and a yearly temperature averaging 13.1 °C.

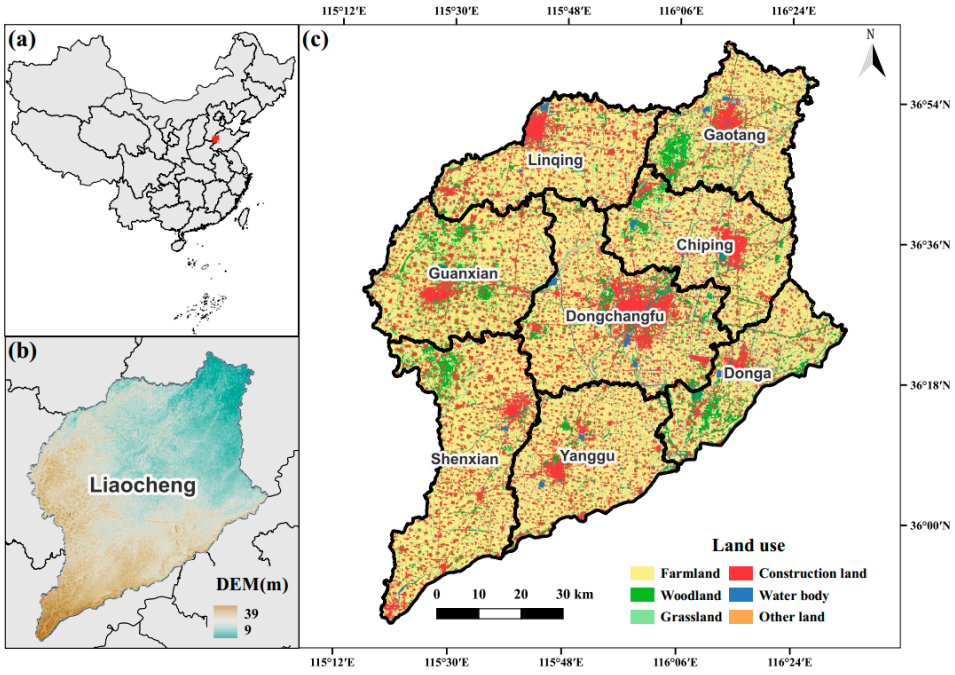


Figure 1. Study area overview of Liaocheng City (LC). (**a**) location of LC in Shangdong Province, China; (**b**) digital elevation model (DEM) of LC; (**c**) land use cover of LC.

In China's ecological function zoning, one of the country's principal agricultural production regions, LC significantly contributes to the national food supply. Due to its location in the former Yellow River region, which has been rerouted multiple times, LC has ecologically fragile characteristics such as soil erosion and landslide or sand, as well as ecological problems of cultivated land such as encroachment, declining soil fertility, and

exacerbated agricultural surface source pollution. Therefore, selecting LC to investigate the synergistic interaction between regional ecological protection and high-quality agricultural development is of practical significance.

2.2. Data Sources and Processing

The precision, time, and sources of the data are shown in Table 1. Since this paper uses the National Land Survey data with high data accuracy as the primary application land use data, the vector was transformed into a raster. All spatial data were transformed into 39 strips under the CGCS2000 coordinate system through the 3-degree split-band Gauss-Kruger projection.

Table 1. Description of the data.

Data Name	Resolution/m	Time	Data Sources
Land use	10	2017	http://data.ess.tsinghua.edu.cn/fromglc10_2017v01.html (accessed on 16 June 2021)
DEM (ALOS PALSAR)	12.5	2011	https://search.asf.alaska.edu/ (accessed on 16 June 2021)
Water Distribution	-	2018	http://www.webmap.cn/ (accessed on 16 June 2021)
NDVI (MODIS)	100	2018	http://www.resdc.cn/ (accessed on 20 August 2021)
NPP (MODIS)	1000	2018	http://www.lpadac.usgs.gov/ (accessed on 20 August 2021)
Soil	10^6	2016	westdc.westgis.ac.cn/ (accessed on 20 August 2021)
Precipitation, temperature, days with sand and wind	-	2018	http://data.cma.cn/ (accessed on 20 August 2021)
Road	-	2017	https://www.openstreetmap.org (accessed on 20 August 2021)
Nighttime light data (VIIRS/DNB)	500	2018	https://eogdata.mines.edu/products/vnl/ (accessed on 16 June 2021)
Administrative boundary	Province, city	2015	http://www.resdc.cn/ (accessed on 20 August 2021)
Third China land survey data	-	2018	Liaocheng Bureau of Natural Resources and Planning
Cultivated land quality grade	-	2019	Liaocheng Bureau of Natural Resources and Planning

2.3. Method

In principle, the construction of ESPs is the development of a model that includes patches, corridors, nodes, and other elements, and by preserving these vital ecological zones, regional ecological security can be effectively safeguarded [44]. Following a previous approach [45], this study proposed a novel "quality-importance-connectivity-balance" framework for constructing ESPs (Figure 2). There were three processes involved in the ESPs' construction. Identifying ecological sources based on habitat quality, ecological conservation importance, landscape pattern, and connectivity is the initial stage. The second phase is to build a resistance surface, taking into account ecological protection, anthropogenic activities, and agricultural development, and to demarcate ecological zones with varying levels of security. In the third step, ecological corridors are extracted and classified using minimum cumulative resistance and gravity models, and a model for ecological and agricultural coordination is developed. The methodological structure is depicted in Figure 2.

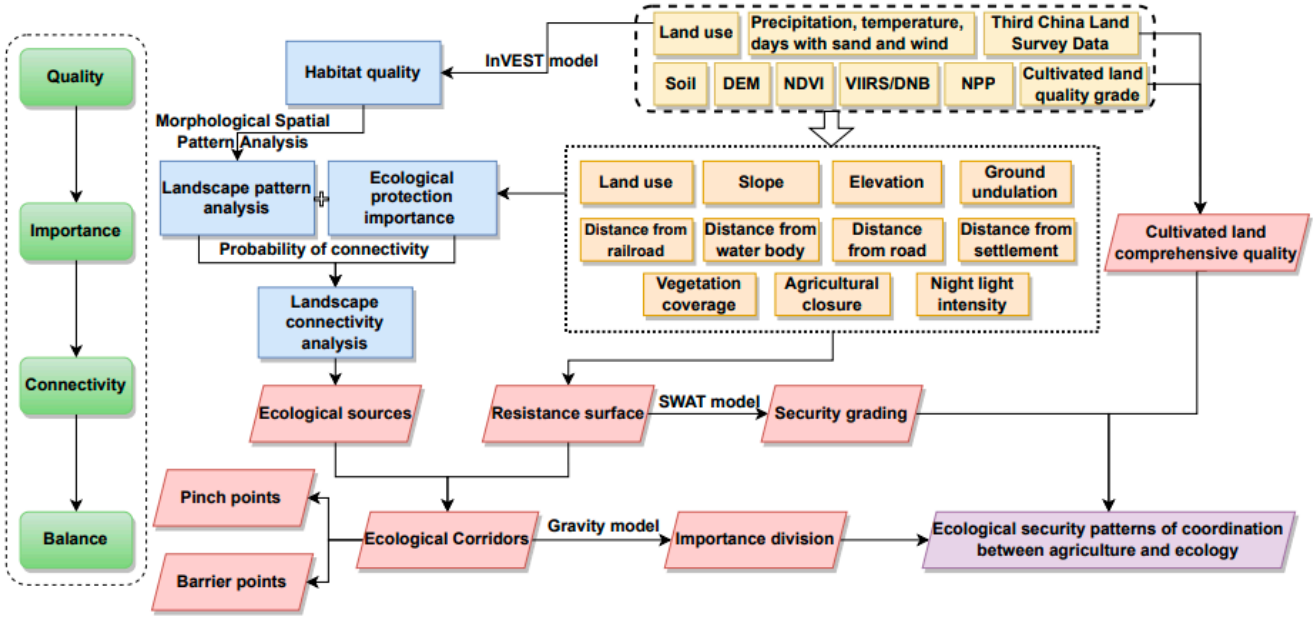


Figure 2. Research framework.

2.3.1. Identification and Evaluation of Important Ecological Sources

Habitat Quality Evaluation

The InVEST model has been widely applied to habitat quality assessment [46]. The maximum impact distance, weights, and attenuation-related types of stressors, as well as the sensitivity of different habitat types to stressors, were determined by combining the actual situation in the study area with reference to the research results of similar plain areas and consulting experts [47,48], and the specific classification criteria are shown in Tables 2 and 3. Impact distance and spatial weights were used to compute the external threat intensity, and habitat quality was evaluated based on the suitability of various land uses and the sensitivity of the corresponding threat sources [49,50]. The specific calculation process equation is as follows.

$$i_{rab} = 1 - \frac{d_{ab}}{d_{r\max}} \quad (1)$$

$$Q_{aj} = H_j \left[1 - \left(\frac{D_{aj}^2}{D_{aj}^2 + k^2} \right) \right] \quad (2)$$

where i_{rab} is the stress level of raster b to raster a, d_{ab} is the linear distance between raster a and b, $d_{r\ \max}$ is the maximum influence distance of stress factor r. Q_{aj} is the habitat quality of raster a in habitat species j; H_j is the habitat suitability of habitat species j with the value range [0, 1]; k is the half-saturation constant, always taking half of the maximum.

Table 2. Threat source influence scope and weight table.

Threat Factor	Maximum Impact Distance (km)	Weights	Decay Correlation
Urban Land	10	0.95	Index
Agricultural land	7	0.8	Linear
Industrial Land	12	1	Linear
Rural settlements	9	0.9	Index

Table 3. The sensitivity of different habitat factors to threat factors.

Habitat Type	Habitat Suitability	Sensitivity			
		Urban Land	Agricultural Land	Industrial Land	Rural Settlements
Water Field	0.35	0.55	0.35	0.60	0.44
Watered land	0.40	0.50	0.35	0.55	0.40
Dryland	0.25	0.50	0.35	0.55	0.40
Garden	0.40	0.50	0.35	0.55	0.40
Forest land	0.95	0.90	0.75	0.95	0.85
Shrubland	0.75	0.65	0.55	0.70	0.60
Thinned forest land	0.45	0.55	0.45	0.60	0.50
Low cover grass	0.35	0.30	0.20	0.35	0.25
Lakes	0.90	0.9	0.8	0.95	0.85
Rivers and canals	0.85	0.9	0.8	0.95	0.85
Reservoir	0.75	0.9	0.8	0.95	0.85
Mudflats	0.70	0.7	0.6	0.75	0.65
Unused land	0.10	0.20	0.10	0.25	0.15

Ecological Protection Importance Assessment

As study indexes, the importance of ecosystem service function and ecological sensitivity were used to determine the importance of ecological protection [51,52]. The specific calculation methods for calculating the value of ecosystem service functions are detailed in Table 4.

Table 4. Methodology for calculating the importance of ecosystem service functions.

Indicators	Methods	Parameters
Water harvesting	$WR = \sqrt[4]{NPP_{mean} \times F_{sic} \times F_{pre} \times (1 - F_{sio})}$	WR is the water harvesting capacity index; NPP_{mean} is the mean of net primary productivity of vegetation; F_{sic} is obtained by assigning equal values from 0 to 1 according to the soil texture type, 1 for sandy soils and 0.1 for heavy clay soils; F_{pre} is the average precipitation; F_{sio} is the average slope
Soil and water conservation	$S_{pro} = \sqrt[4]{NPP_{mean} \times (1 - K) \times (1 - F_{sio})}$	S_{pro} is the soil and water conservation service capacity index; K is soil erodibility
Biodiversity conservation	$S_{bio} = \sqrt[4]{NPP_{mean} \times F_{tem} \times F_{pre} \times (1 - F_{alt})}$	S_{bio} is the biodiversity maintenance service capacity index; F_{tem} is the average temperature; F_{alt} is the altitude

The evaluation method of ecological sensitivity is shown in Table 5.

Table 5. Methodology for calculating the ecological sensitivity.

Indicators	Methods	Parameters
Soil erosion	$SS_i = \sqrt[4]{R_i \times K_i \times LS_i \times C_i}$	SS_i is the soil erosion sensitivity index; R_i is the rainfall erosion force, interpolated to obtain; K_i is soil erodibility; LS_i is the terrain undulation; C_i is the vegetation cover
Land desertification	$D_i = \sqrt[4]{I_i \times W_i \times K_i \times C_i}$	D_i is the land sanding sensitivity index; I_i is the dryness; W_i is the number of wind days; K_i is the soil texture; C_i is the vegetation cover

The weights were allocated using the coefficient of variation method (Table 6) based on the evaluation results of each individual index, and the weighted arithmetic mean was then used to compute the relevance of ecosystem service function and ecological sensitivity scores.

Table 6. Weight of indicators used for evaluating the ecological conservation importance.

Factor Layer	Indicator Layer	Weighting
Importance of ecosystem service functions	Water harvesting	0.24
	Soil and water conservation	0.34
	Biodiversity conservation	0.42
Ecological sensitivity	Soil erosion	0.43
	Land desertification	0.57

The limit condition approach was used to calculate the ecological protection importance score, and the specific calculation formula is as follows. Three levels were classified by the natural breakpoint method: extremely important, important, and generally important.

$$ESI = \sum_{i=1}^{3} A_i \times W_i \quad (3)$$

$$ES = \sum_{j=1}^{2} C_j \times W_j \quad (4)$$

$$EI = MAX\{ESI, ES\} \quad (5)$$

where EI denotes the ecological protection importance score. ESI is the ecological service function importance score, A_i denotes the score of the i indicator, W_i denotes the weight of i. ES is the ecological sensitivity score, C_j denotes the score of the j indicator in the ecological sensitivity evaluation; W_j denotes the weight of the j.

Landscape Pattern Analysis

Morphological Spatial Pattern Analysis (MSPA) is commonly utilized for analyzing landscape patterns [33]. In this study, ecological land served as the foreground, other land types that restrict ecological circulation served as the background, and MSPA was utilized to perform eight-neighborhood opening and closing operations. According to graphical principles and mathematical procedures, landscape patches with the values 117 and 17 were obtained.

Landscape Connectivity Analysis

The probability of connectivity (PC) is used as an indicator to assess landscape connectivity [32]. In this study, dPC was categorized into high, medium, and low levels by the natural breakpoint method to distinguish the connectivity of ecological sources. PC and dPC basic formulas are as follows.

$$PC = \frac{\Sigma_{i=1}^{n}\Sigma_{j=1}^{n} a_i \times a_j \times P_{ij}}{A^2} \quad (6)$$

$$dPC = \frac{PC - PC_{remove}}{PC} \quad (7)$$

where PC is the overall probability of landscape connectivity, dPC is the possible connectivity index, A is the total landscape area, n is the number of patches, a_i and a_j are the areas of patches i and j, and P_{ij} is the maximum probability of ecological elements spreading between habitat patches i and j.

2.3.2. Ecological Resistance Surface Construction and Security Level Classification

Ecological Resistance Surface Construction

The resistance factors, which include terrain, human activity, distance, and nature, were determined from the ecological characteristics of the plain area, and the indicator's resistance values were graded as 1, 10, 50, 150, and 500 [32,53]. In addition to indicators such as slope, elevation, ground undulation degree, land use, vegetation coverage, and distance influence, the study presents the inhibition of other landscape elements, taking

into account the contribution of farmland, which is taken as a main qualitative factor in the resistance surface construction (Table 7).

Table 7. Classification and weight of resistance factors.

Resistance Factor	Indicator	Unit	Resistance Value Grading					Weights
			1	10	50	150	500	
Terrain	Slope	°	<2.5	2.5~5	5~7.5	7.5~10	≥10	0.032
	Elevation	m	<15	15~25	25~35	35~45	≥45	0.018
	Ground undulation degree	m	<1	1~4	4~7	7~10	≥13	0.050
Human activity	Land Use	-	a	b	c	d	e	0.246
Distance	Distance from road	m	≥600	450~600	300~450	150~300	<150	0.069
	Distance from railroad	m	≥800	400~800	200~400	100~200	<100	0.067
	Distance from settlement	m	≥600	450~600	300~450	150~300	<150	0.071
	Distance from water bodies	m	<50	50~100	100~500	50~1500	≥1500	0.081
Nature	vegetation coverage	-	≥0.70	0.50~0.70	0.35~0.50	0.25~0.35	<0.25	0.172
	agricultural closure	-	0.6~1	0.2~0.6	−0.2~0.2	−0.2~−0.6	−0.6~−1	0.194

In the table, a represents watershed and land for water facilities; b represents Woodland and grassland; c represents garden land and cultivated land; d represents other land, including vacant land, agricultural land for facilities, saline land, sandy land, bare land, bare rocky gravel land; e represents commercial land, industrial, mining and storage land, residential land, public administration, and public service land, special land, transportation land.

Open cultivated lands with ditches or field monopolies have a facilitative effect on the flow of ecological sources, whereas confined cultivated lands such as barns provide some resistance. Using data on farmed land quality classes, the degree of aggregation was calculated using Global Moran's I index [54], which is described as an agricultural closure index, and assigned the values −1~−0.6, −0.6~−0.2, −0.2~0.2, 0.2~0.6, and 0.6~1, respectively. In addition, the generated basic ecological resistance surface is modified based on VIIRS/DNB nighttime light data to represent the degree of human interference.

The resistance factors were categorized into five levels based on the indicator grading methods of existing studies. Using hierarchical analysis, weights were assigned to the indicators based on expert knowledge through the construction of hierarchical structures and judgment matrices, testing for consistency, and comparison of importance [55–57]. Table 7 shows the specific parameter settings. The source expansion resistance of the integrated ecosystem was computed by weighing and summing all factors as follows.

$$R_i = \Sigma_{j=1}^{n} R_{ij} \times w_j \times \frac{NL_i}{NL_{mean}} \quad (8)$$

where R_i is the patch i corrected resistance coefficient, R_{ij} is the resistance coefficient of the land type where the j indicator of i is located. w_j is the weight of the j indicator. NL_i is the nighttime lighting index of i; NL_{mean} is the average nighttime lighting index of a single landscape type.

Security Level Classification

Utilizing the quantile approach, the ecological resistance surface was reclassified into five ecological security levels: higher, higher, medium, and lower security. The watershed classification of DEM data was performed based on the SWAT model [58,59]. Under natural conditions, irrigation canals serve as water catchments due to the citywide area's small elevation variations and generally insignificant topographic relief changes, and watersheds cannot be evaluated based on watersheds. Using the Pre-defined watersheds approach and the Burn-in algorithm [60], the appropriate threshold for watershed zoning was determined to be 2500 through a step-by-step correction. The zoning statistics were used for the ecological resistance surface, and the mean ecological security level was calculated for each sub-watershed.

2.3.3. Extraction of Ecological Corridors and Key Protection Areas

Ecological Corridor Extraction

The interaction between ecological sources and resistance surface was calculated using the Minimum Cumulative Resistance (MCR) model and Cost Distance spatial analysis [61], and ecological corridors were generated based on the ecological sources with the path surface of least cumulative resistance within the study area [57,62]. The basic equation for calculating the cumulative resistance consumed by the expansion of ecological sources spreading from the ontology to the exterior is as follows.

$$MCR = f_{min} \sum_{j=n}^{i=m} (D_{ij} \times p_i) \tag{9}$$

where MCR is the cumulative resistance value of any element i to the ecological sources within the study area; f_{min} denotes the positive correlation between cumulative resistance value and ecological process; D_{ij} denotes the spatial distance from the target element i to the ecological source j; p_i denotes the resistance coefficient of the ecological source j to the movement diffusion of the target element i.

Gravity models are used for corridor grading [63]. The calculation is as follows.

$$G_{ab} = \frac{W_a W_b}{{N_{ab}}^2} = \frac{\left[\frac{1}{R_a} \times ln(S_a)\right]\left[\frac{1}{R_b} \times ln(S_b)\right]}{\left(\frac{L_{ab}}{L_{max}}\right)^2} \tag{10}$$

where G_{ab} is the mutual coupling force between ecological sources a and b, W_a and W_b are the weights, N_{ab} is the normalized value of cumulative resistance, ln is the positive correlation function between patch area and resistance, R_a and R_b are the native resistance values, S_a and S_b are the areas of ecological sources a and b, L_{ab} is the cumulative resistance value between ecological sources a and b, and L_{max} is the highest cumulative resistance value of ecological corridor.

The higher the value of G_{ab}, the more important the corridor between ecological sources. The calculating results of the gravity model were categorized into three levels based on the natural breakpoint method: most important (level 1), very important (level 2) and important (level 3).

Extraction of Ecological Protection Key Areas

The circuit landscape model is used to identify ecological conservation and restoration priority regions [61]. The position of pinch points is a high-density region of surface resistance currents, which corresponds to the limited ecological material diffusion channels and the severe effects of ecological damage or degradation. The corridor width is set at 5 km, and the Pinchpoint Mapper module is used to identify pinch points in a many-to-one model.

Ecological barrier points are obstructed regions caused by the diffusion of ecological elements from the sources. The higher the cumulative current recovery value of the corridor, the greater the obstructive force of landscape interconnection and exchange. Based on the Barrier Mapper module, with 1 km as the iteration radius, the barrier points are identified using the maximum calculation mode.

2.3.4. Comprehensive Quality and Spatial Agglomeration Evaluation of Cultivated Land

On the basis of the patches and data of cultivated land quality grade, the overall quality scores of each piece of cultivated land were delineated to distinguish the construction direction of each patch on the landscape scale [64]. The comprehensive quality of farmed land was evaluated from three perspectives: natural endowment, spatial pattern, and

infrastructure level, selecting regions with the superior site, infrastructure, and location conditions [65]. The calculation is as follows.

$$K_i = \Sigma_{j=1}^{n} f_{ij} w_j \quad (11)$$

where K_i is the patch i comprehensive quality value of cultivated land; f_{ij} is the value of the indicator where the j indicator of i is located; w_j is the weight of the j indicator.

The weight of each index is determined using the entropy weight method, and the weighted total is calculated. Table 8 shows the evaluation index and weight.

Table 8. Evaluation indexes and weights of comprehensive quality of cultivated land.

Factor	Evaluation Indicators	Weights
Natural Endowment	National utilization index	0.337
Spatial Pattern	Cultivated land area (m^2)	0.385
	Shape regularity	0.236
	Farming convenience degree	0.024
Infrastructure level	Irrigation guarantee rate	0.011
	Accessibility of field roads	0.007

In the table, the national utilization index reflects the natural conditions of cultivated land, the greater the value, the better the natural quality of cultivated land; shape regularity reflects the regularity of cultivated land, the greater the value, the simpler the shape of the field; farming convenience degree the ease of operation of the settlement location where farming takes place. The above three indicators were obtained from cultivated land quality grade data. The irrigation guarantee rate and accessibility of field roads were calculated by the distance from the water source and rural road.

The cultivated land quality of a single plot needs to increase the discriminant scale to the block level to ensure a relatively concentrated contiguous area. Utilizing Getis-Ord Gi*, the local spatial autocorrelation analysis of the comprehensive quality score based on hotspot analysis is performed [66], the spatial clustering types of comprehensive quality of cultivated land were obtained, including high agglomeration (H), low agglomeration (L), and non-significant (NS).

3. Results

3.1. Spatial Distribution of Ecological Sources Identification

In terms of spatial heterogeneity, the habitat quality in the centers of several counties and districts was low, while it was higher in the north, west, and southeast. The areas of grades 1–5 were 1683.47 km^2, 1865.28 km^2, 1862.22 km^2, 1724.15 km^2, and 1499.55 km^2, with each district comprising 19.49%, 21.60%, 21.57%, 19.97%, and 17.37% of the total area (Figure 3a).

The ecological protection importance evaluation revealed that the areas of extremely important and important zones were 287.22 km^2 and 472.45 km^2, respectively, accounting for 3.33% and 5.48% of the total area. The remaining areas are generally important zones (Figure 3b).

The results demonstrate that the MSPA yields eight separated landscape types: core, islet perforation, edge, loop, bridge, branch, and background (Figure 3c). The core area distribution is concentrated in the western portion of the city, accounting for 8.72% of the study area with a distribution area of 752.69 km^2.

A total of 69 ecological source patches covering 181.16 km^2 were obtained. Landscape connectivity was weak overall, due to excessive fragmentation and discontinuous intervals across categories, with a *dPC* range of 0.025–30.158 and a mean value of 3.053. The ecological patches with low, medium and high connectivity were 81.23 km^2, 55.42 km^2, and 44.51 km^2, comprising 44.84%, 30.59%, and 24.57% of the total area (Figure 3d). Ecological sources are not distributed in the southwestern region, but they are more distributed in nature reserves, national forest parks, national wetland parks, and reservoirs in all counties

and districts, and the predominant land types provide higher ecosystem service functions: waters, woodlands, and wetlands.

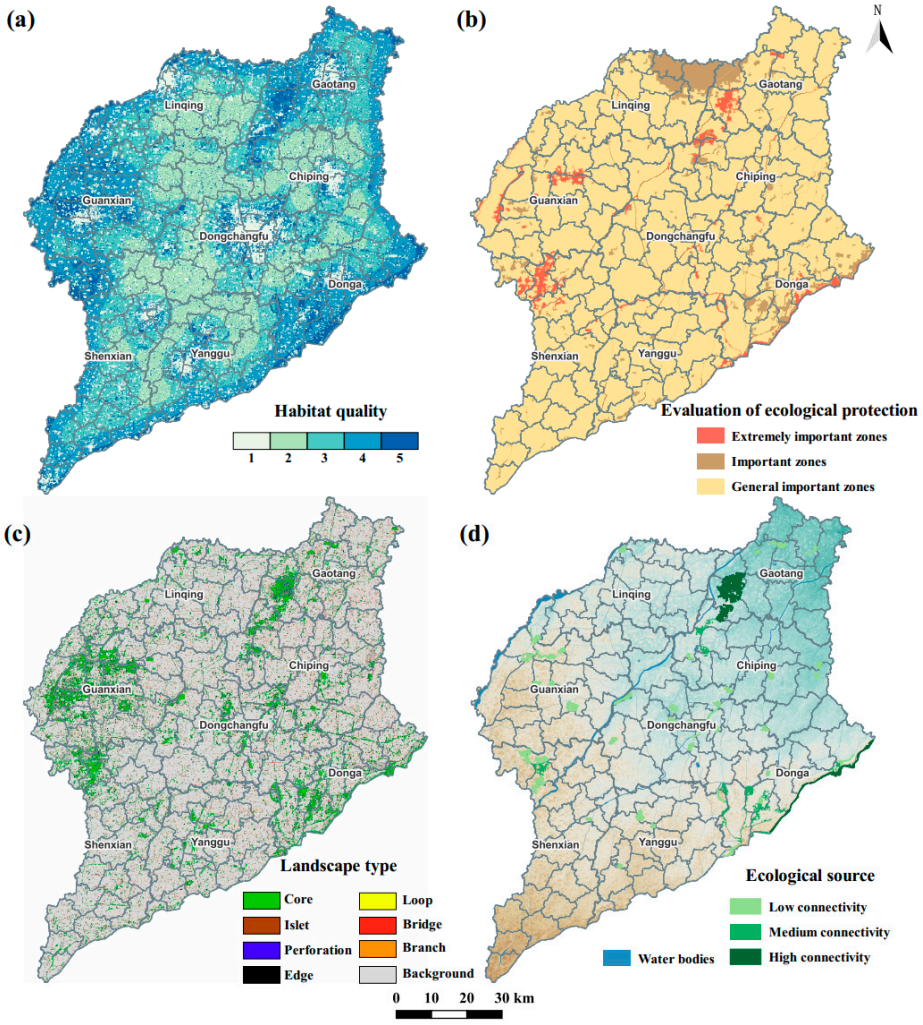


Figure 3. The process and results of ecological sources identification in LC. (**a**) habitat quality; (**b**) ecological protection importance; (**c**) landscape pattern analysis; (**d**) connectivity and ecological sources.

3.2. Ecological Resistance Surface Construction

The ecological resistance value was reasonably high overall, and the resistance value of the integrated resistance surface area spans from 1.9 to 178.6, with an average value of 39.74. The general spatial pattern was characterized by the high-resistance zone located in the central city of each county and district, which exhibited a centralized distribution pattern. The southwestern portion of the city had a higher resistance value due to the distribution of industrial and mining land and mining sites, and the low-value area was more consistent with the distribution of the river system, nature reserve, and forest park. The southern area has higher values and is significantly disturbed by human activities, while the periphery (woodlands, wetlands, and water bodies) has lower values.

The total ecological security level of LC had a strong spatial heterogeneity (Figure 4b). From the perspective of comprehensive watershed management, ecological security levels were identified using statistical analysis of watershed subdivisions (Figure 4c). The areas with varying security levels (from high to low) were 1522.11 km^2, 2353.60 km^2, 1450.86 km^2, 1528.28 km^2, and 1773.20 km^2, comprising 17.64%, 27.28%, 16.82%, 17.71%, and 20.55% of the total area, respectively. The southern and northern regions, which are primarily industrial and mining construction land and more ecologically sensitive, have the lowest

ecological security level. The low and medium security levels are dispersed across the western and central regions with high ecological security levels, which are substantially more influenced by human activity. High levels of security are more prevalent around ecological sources and ecological source expansion buffer zones, which are less susceptible to external perturbations. The majority of the regions with a high level of security are located in the central and eastern regions and are comprised of ecologically continuous land and some agricultural land with strong connectivity.

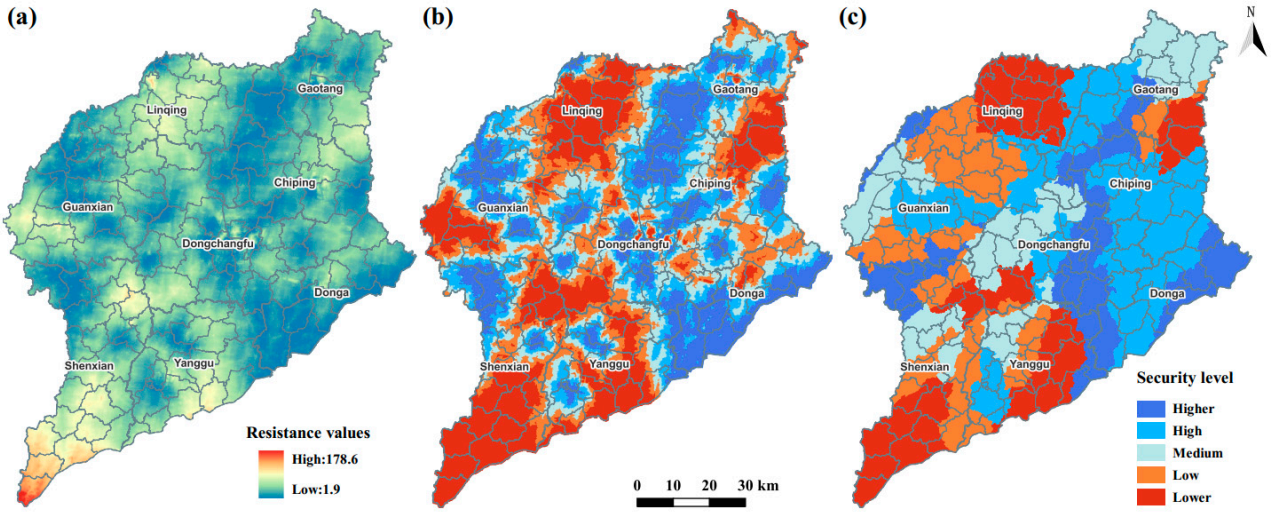


Figure 4. Spatial variation in ecological resistance of LC. (**a**) ecological resistance surface; (**b**) ecological security levels of quantile; (**c**) zones with various levels of ecological security.

3.3. Ecological Corridor Extraction and Key Areas for Ecological Restoration Results

The majority of corridors were evenly distributed, which can significantly improve the connectivity of the LC's ecosystem (Figure 5a). A total of 2446.24 km of ecological corridors were extracted, yielding 174 corridors. Among corridors, the numbers of level 1, level 2, and level 3 were 92, 56, and 26, and their lengths were 362.31 km, 1201.79 km, and 882.14 km, accounting for 14.81%, 49.13%, and 36.06% of the total corridor lengths, respectively. The level 1 corridors are primarily found in the western, northern, and southeastern regions of the study area due to the strong communicative and ecological agglomeration functions of ecological source sites, whose corridor forces are the strongest and play a crucial role in the exchange of ecological elements such as 11, 12, 14, 17, and 22. The majority of level 2 corridors are situated within the study area's inner ring. Level 3 corridors are concentrated around marginal source sites interlinked in a circle and connected to sources situated in high cumulative resistivity, with the lowest corridor pressures, higher ecological resistance to crossing, and more fragile connectivity, like sources 47, 69, and 67.

The majority of pinch points, with a total length of 86.64 km, are situated in ecological corridor regions with longer lengths and higher current intensities (Figure 5b). By identifying the intercepted regions when the elements of the ecological source sites extended outward, a total of 21 ecological barrier points that need to be restored were identified, most concentrated in the core of Dongchangfu District (Figure 5c).

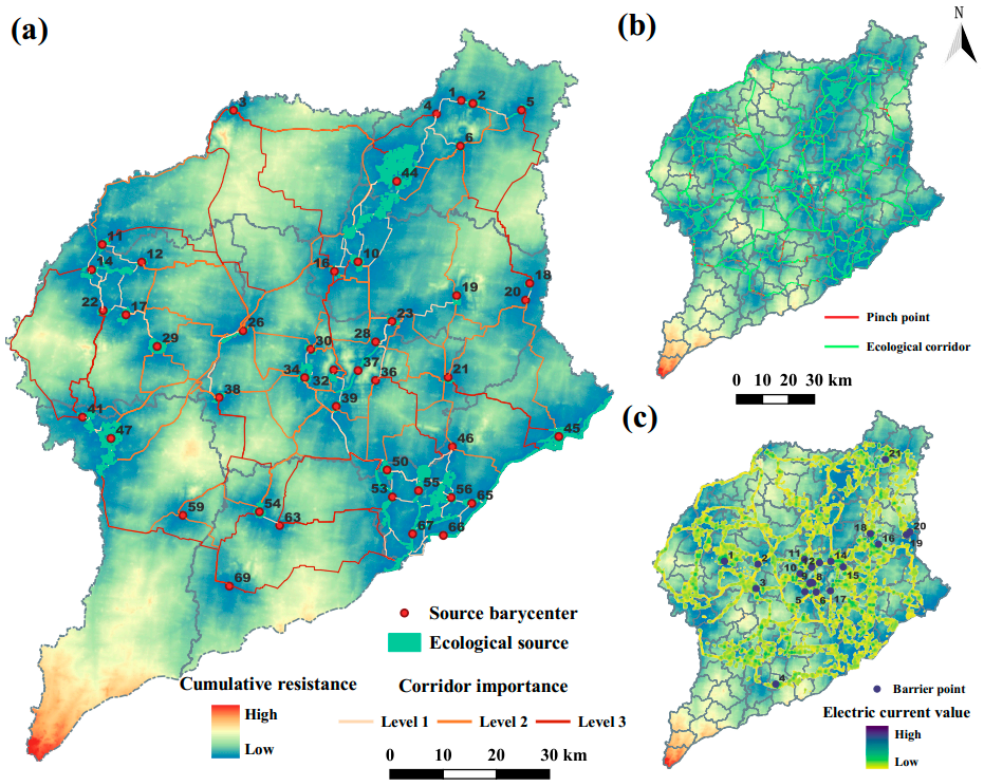


Figure 5. ESPs of LC. (**a**) ecological corridor extraction; (**b**) pinch points extraction; (**c**) barrier points extraction.

3.4. Pattern of Coordination between Agriculture and Ecology

ESPs are comprised of cultivated land zones, ecological source cores, and corridor belts based on the coordination between agriculture and ecology. According to the distribution characteristics of ecological sources, corridors, and the comprehensive quality of agriculture, this study proposes optimum ESPs of "six cores, seven belts, and three zones" from the perspective of environmental protection and agricultural development (Figure 6).

The northern, western, central, and eastern regions are the "six cores" where ecological sources are concentrated. In the western and eastern regions, there are two cores, respectively. The western and eastern cores, along with the northern core, have the distributional features of a pentagonal star's apex, and the central core is the ecological heart of the entire city.

The "seven belts" are corridor belts that transmit ecological elements. Belts on the east and west sides are each firmly connected to three cores, and each triangle forms a stable ecological space structure. The main urban area is the macro pattern's center, with the other five cores extending inward to form the pattern's periphery.

"Three zones" refers to three sorts of spatial agglomeration types of cultivated land comprehensive quality: high aggregation type, low aggregation type, and non-significant type. The construction of high-standard cultivated land in the three zones should be bolstered to develop high-quality cultivated land that is concentrated and connected, to offer critical security for food and ecology, and to increase the degree of landscape connectivity.

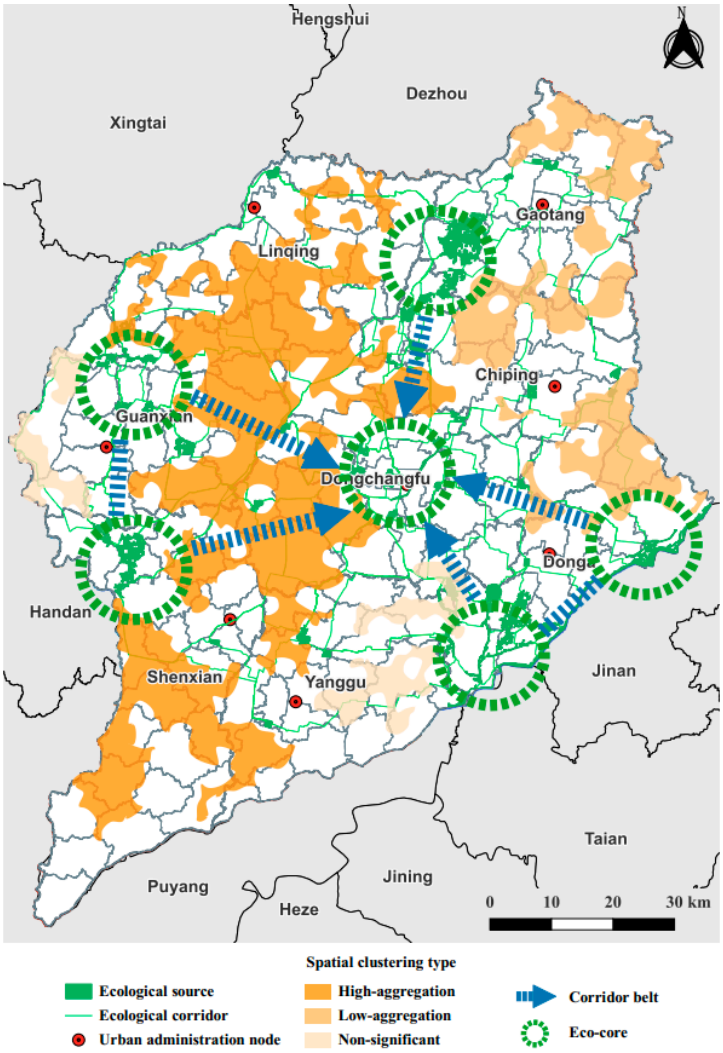


Figure 6. Optimization framework for balancing ecological security and agricultural production of main agricultural production regions, LC.

4. Discussion

4.1. ESPs Fit with Urban Development Direction

Current research on ESPs is based on the theory of landscape ecology, which provides an important spatial approach to the construction of ESPs, the core of which is the interaction between landscape patterns and ecological processes and the effective protection of ecological security through the enhancement of indicators [36].

Ecological sources consist of landscape patches with higher relevance of ecological services, more sensitive habitat quality, and better inter-patch connectivity, which play a vital role in preserving and promoting ecosystem stability [67]. For the identification of ecological sources in this study, three characteristics should be met: first, the value of ecosystem services must be high; second, the habitat quality must be sensitive; and third, the structure arrangement must be cohesive [34].

In identifying ecological sources, the significance of ecological functions such as water containment, biodiversity, and ecological sensitivity is considered the fundamental basis for defining sources [45]. The dPC index describes the ecological structure between patches based on internal penetration and patch connectivity. It also describes the mutual continuity of landscape elements in adjacent ecological spaces, the degree of efficiency of diffusion and migration of ecological elements between sources, and the flow of plant dispersal and animal migration [68,69]. Nevertheless, there is no standardized procedure

for identifying ecological sources. Experiments have shown that reversing the priority of ecological sensitivity and ecological service functions might lead to the absence of certain essential sources.

Considering the quantitative landscape connectivity and high habitat quality attributes could assure the accuracy of extraction results. The landscape-based ecological resistance surface characterizes the influence distance of the difficulty of propagating the flow of ecological elements between heterogeneous landscapes and consists of various resistances to the outward expansion of ecological sources to their destinations [70,71]. The higher the security level by resistance surface, the more stable the ecological security, the stronger the ecosystem's resistance to the outside world, and the more adequate the flow exchange. When establishing the resistance surface, the landscape variability of regional differences and the bearing function of multiple ecological processes were taken into account to provide simulation results that are more realistic and practicable [70].

In addition to identifying ecological sources through quantitative landscape connectivity and high habitat quality traits, the study also incorporates agricultural land use factors into the ecological resistance surface, emphasizing the trade-off of urban development orientation on ESPs. On the basis of the variability of urban ecological circumstances, regional development orientation, and the influence of the intensity of human activity on ecological processes, ESPs were constructed comprehensively to assure the synergistic growth of agriculture and ecological service values.

4.2. Application of ESPs for Agricultural Cities

The major causes of biodiversity and ecological reduction in terrestrial ecosystems are land use fragmentation, degradation, and habitat destruction caused by urban and agricultural expansion [8]. Nonetheless, cultivated lands provide humans with food, fruits, and other goods, as well as a biological survival habitat for population structures and food chains while providing functions such as water retention and biodiversity maintenance to a certain extent. Agricultural land is included in the category of semi-artificial ecological land classification based on the concept and connotation of ecological land and the relevant classification studies, as summarized by relevant research [35,36].

Comprehensive quality and spatial agglomeration evaluation revealed cultivated land with concentrated contiguous plots, level field surface, deep soil layer, and tillage layer, no apparent obstruction factors, standard soil environmental quality, and ideal field irrigation facilities [72]. Combining ESPs to meet the requirements of ecological agriculture in urban modernization, this index steered the development of cultivated land toward high yield, high aggregation, security, and environmental preservation [73].

ESPs provide new methods for ecologically conserving agricultural land. The increase of cultivated land results in the severance of ecological element exchange links, while the fragmentation of landscape patterns impedes regional ecological service functions and high-quality agricultural growth [74]. ESPs and the basic cultivated land protection red line coordinate and complement one another to safeguard ecological source land and agricultural land. Meanwhile, ecological corridors provide connectivity across regional landscapes and cyclically transform energy and material between patches [75].

The study has relevance and practical value in the municipal ecological security governance strategy, and to a certain extent, it resolves the conflict between the ecological environment and green agricultural economy in developing countries and plain areas. Based on the construction of ESPs, this study combines comprehensive quality and spatial agglomeration evaluation, proposes agricultural and ecological spatial optimization strategies for LC, provides a reference for resolving the contradiction between agricultural production and ecosystem protection, and is significant for optimizing the pattern of territorial development and promoting the construction of ecological civilization.

4.3. Limitations and Future Research

Despite the fact that the majority of research has explored the relationship between various types of ESPs and ecological elements [67,76,77], these studies are often undertaken in the context of the entire regional ecosystem, neglecting the baseline features and development goals of urban areas. Therefore, there is a need to construct a variety of ecological security theoretical systems in a targeted manner. The study evaluates the adequate ecosystem services offered by agricultural land, although the ESPs analysis might be optimized in several aspects.

First, the ecological red line specifies the minimal ecological land area range necessary to preserve ecosystem functions [78]. Policymakers must consider in greater depth how to protect ecological security while effectively assuring the economic benefits of developing the area protected by high-standard cultivated land and balancing the ESPs and ecological red line.

Second, detailed geographic information data based on the spatial landscape can assist in all aspects of ecological security protection; however, this study only selects spatial data of cultivated land and has not yet explored the method of constructing ESPs based on agricultural economic production data.

Third, since the flow of ecological factors is not bounded by administrative areas, the influence of ecosystems in the surrounding areas on the overall ESPs cannot be ignored, and whether expanding the boundaries of the study area to construct relatively complete ESPs is an issue to be considered in future research.

Future research must investigate establishing a common threshold determination methodology for the real scenario, such as the region, to provide universal standards and practical applications for the ecological restoration of national space.

5. Conclusions

In this study, a "quality-importance-connectivity-balance" framework was developed to identify ecological sources based on habitat quality, ecological protection importance, landscape pattern, and landscape connectivity; utilize natural and agricultural components to determine resistance surface, and extract ecological corridors by using the MCR model; based on the SWAT model, the ecological restoration and pattern optimization of LC was carried out through ecological security zoning; and diagnose important ecological nodes based on circuit density theory. Finally, the comprehensive quality and spatial agglomeration of cultivated land were categorized, and the ESPs of LC were perfectly constructed.

The results of the study indicate that the ecological sources are primarily distributed in national wetland parks, natural forestry reserves, national forest parks, and national wetland parks, with a total area of 1811.58 km^2 and a total of 69 patches and 2567.07 km of ecological corridors were extracted, for a total of 174. The length of pinch points with a 5 km breadth was established for a total of 86.64 km; a total of 21 barrier points with a 1 km search radius were found, the majority of which were mainly distributed in the central district. The paper presents a comprehensive ecological restoration and pattern optimization strategy based on three types of ecological security zones and urban planning recommendations for decision-makers in similar regions.

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