

Article

Construction and Optimization Strategy of County Ecological Infrastructure Network Based on MCR and Gravity Model—A Case Study of Langzhong County in Sichuan Province

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Abstract: Against the backdrop of rapid urbanization, there is a passive adaptation state shown in urban and rural ecological spaces. Due to the shrinking of ecological patches and the fracture of corridors, problems such as the obstruction of ecological processes, the decline of ecosystem services, and the loss of biodiversity occur. Considering that county ecological space is the key level to undertake provincial ecological security patterns and implement ecological demonstration projects, the construction of a county ecological infrastructure (EI) network is beneficial to the protection of regional ecological security, the improvement of the structures and functions of farmland ecosystems, and the enhancement of the quality of human settlements. In this study, taking Langzhong County in Sichuan Province as an example, a method path for an EI network construction was explored, and an optimization strategy for ecological patterns was proposed. Firstly, morphological spatial pattern analysis (MSPA) and a patch importance index were employed to identify ecological sources. Secondly, by constructing a landscape resistance surface and adopting a minimum cumulative resistance (MCR) model, potential EI corridor paths were extracted. Thirdly, the interaction force values between ecological sources were calculated with a gravity model and important ecological corridors were identified for priority protection and restoration. Finally, an EI corridor network was optimized by combining network structure indexes (α , β , and γ) with the field situation, and stepping stone patches and ecological breakpoints were identified. Based on the analysis results, an ecological protection pattern, which involved three vertical and two horizontal ecological belts, four ecological control zones, and six clusters of EI networks in Langzhong County, was put forward, aiming at protecting 50 ecological sources, repairing 105 ecological corridors of different grades, adding 9 stepping stone patches near long-distance corridors and 15 at the intersection of ecological corridors, and repairing 18 ecological breakpoints. This study has guiding significance for the optimization of county ecological patterns, the construction of farmland forest belts, and site selection of ecological restoration projects.



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1. Introduction

With the rapid development of urbanization, there are more and more human settlement construction activities such as urban land expansion, traffic and municipal corridor construction, agricultural reclamation and planting, animal husbandry, and industrial mining. Moreover, urban and rural ecological space is in a passive adaptation state, with erosion, movement, and succession occurring constantly. Furthermore, the shrinking of ecological patches and the rupture of corridors also result in the obstruction of ecological processes, the decline of ecosystem services, and the loss of biodiversity [1,2]. The concept of ecological infrastructure (EI) was formally proposed in the Man and Biosphere Program

in 1984. Originating from a biodiversity conservation study, EI contains similar concepts, including the concepts of ecological network, green infrastructure network, and biodiversity conservation network [3]. EI focuses on building spatial patterns, thereby guaranteeing ecological processes, including two key elements: ecological sources and ecological corridors. An ecological source is the source and sink of an ecological process and serves as the habitat for organisms, while an ecological corridor is the flow path of the ecological process and serves as the channel for organisms to spread and migrate among patches in different habitats [4]. As indicated by the study, it was more conducive to the exertion of ecosystem service functions and responses to climate change to connect the discrete and isolated ecological sources functionally and maintain the integrity of the regional landscape compared to adopting an incremental approach focusing on isolated ecological patches and the expansion of natural habitat areas [5]. EI networks can maintain biodiversity, ecological processes, and the sustainability of ecological functions, thus promoting ecosystems to have stronger anti-interference abilities and resiliencies [6,7]. Moreover, the ecosystem services provided by an EI network can optimize the landscape, enrich recreational activities, and enhance aesthetic value, which is of great significance for improving the quality of human settlements [8].

In terms of EI network construction methods, scholars have conducted numerous studies on EI networks in many fields such as island ecology [9], landscape ecology [10,11], land use and planning [12], and ecosystem services [13]. Currently, by following the principle of landscape ecology, the path of “ecological source identification-corridor extraction-network optimization” is a common practice used in constructing regional EI networks [14,15]. Broadly speaking, ecological sources include the habitats of animals and plants as well as patches that provide important ecosystem services and have high ecological benefits. Moreover, the theoretical basis for ecological source selection is the “source-sink” theory in which a source area is directly proportional to the diversity of habitats. Furthermore, forests, grasslands, wetlands, and water bodies meeting a certain area threshold can all be selected as screening criteria [16] or can be identified by performing morphological spatial pattern analysis (MSPA) [17] and ecological security pattern evaluation [18]. Area identification of ecological sources do not consider the connectivity of ecological source areas, while the ecological security pattern assessment method requires a large amount of data and is more complex. MSPA has often been used because of its advantages of using small amounts of data and producing visualizations of analysis results. Because the number of identified ecological sources is often large, it has often been combined with area and connectivity analysis to screen ecological sources. Presently, there are two methods widely used for corridor extraction. One method is based on Forman’s “patch corridor” concept [19], which uses the minimum resistance model to extract potential EI corridors [20]. The other method involves introducing the connectivity model of circuit theory into ecological process simulation [21] with the low-resistance corridor used as the extraction corridor. When there are many ecological sources, the number of corridor path results is also large, so it is necessary to classify the relative importance of these corridor paths to reduce construction cost and ensure implementation. Corridor classification is mostly based on the Green Infrastructure Assessment method, but the amount of data required is large and Weight values are subjective. In addition, quantitative analysis is often applied in network optimization, and a network structure index [22] and landscape index [23] are usually employed for optimization.

Since 1992 when the Convention on Biological Diversity was adopted by the United Nations Conference on Environment and Development, China, as a contracting party, began to devote itself to strengthening the construction of ecological nature reserve systems and repairing regional ecological environments degraded by rapid urbanization. According to the exploration of many Chinese scholars on ecological network construction methods in Fujian Province [24], Taihu Lake Basin [25], Nanjing City [26], the Yangtze River Delta Integration Demonstration Zone [27], and Dianchi Lake [28], EI corridors possess a large span on the macroscale, playing a more flexible role in control and superior guidance.

Moreover, county ecological space is the key level to undertake provincial ecological security patterns and implement ecological demonstration projects [29]. In recent years, against the backdrop of giving priority to economic development, county space has often been faced with problems such as fragmentation of ecological space and the fracture of ecological corridors. How to build and screen important ecological corridors and propose feasible ecological network construction strategies in fragmented landscape patterns is crucial to county ecological restoration. Due to the redundancy of constructing ecological corridors by combining MSPA and MCR, implementation costs are too high and ecological corridors need to be screened. Considering the objectivity of screening, the availability of data, and the convenience of operation, this study introduces the gravity model to classify the importance of corridors on the basis of existing EI network planning methods and proposes to construct a quantitative method system for identifying ecological source areas based on “MSPA + connectivity evaluation”, extracting important ecological corridors based on “MCR + gravity model”, and optimizing corridors and identifying ecological strategic points based on “network structure evaluation”. Langzhong county in Sichuan province of China was taken as a case study to apply this method, and based on the spatial pattern of EI networks and the results of gravity model analysis, a progressive corridor construction scheme and a differentiated ecological zoning restoration strategy are proposed. We hope that this study can provide inspiration for the study of county ecological network construction methods and restoration strategies.

2. Materials and Methods

2.1. Study Area

Langzhong County, a county-level city north of Nanchong City, Sichuan Province, is located in the northern edge of the Sichuan Basin and the middle and upper reaches of the Jialing River. Moreover, it is between the east longitudes $105^{\circ}41'$ – $106^{\circ}24'$ and the north latitudes $31^{\circ}22'$ – $31^{\circ}51'$. Covering an area of 1878 square kilometers, Langzhong County has a resident population of 622,300. Additionally, it is dominated by low mountains and deep hills in Langzhong County. The main stream of the Jialing River and the four tributaries of Baixi, Donghe, Gouxu, and Xihe pass through Langzhong County. Due to its fertile land, mild climate, abundant rainfall, and moderate illumination, Langzhong County's main land type is cultivated land, and, as determined by the state and Sichuan Province, it focuses on commodity grain production, sericulture, and cotton production. In addition, the county is abundant in animals and plants and various natural resources, including leopards, peregrine falcons, giant salamanders, ginkgoes, red bean trees, and nanmus. The urban construction land in Langzhong County is mainly distributed along the Jialing River and the ancient city of Langzhong located in the urban area is an important tourist destination in northeast Sichuan. For the past few years, Langzhong has shown rapid economic development. Simultaneously, reclamation of cultivated land, the increase in road networks, and urban construction have all led to the reduction, disappearance, and fragmentation of natural ecological patches in Langzhong County (Figure 1). As the Prime Farmland in Langzhong County cannot be encroached upon, it is unrealistic to restore and expand the ecological space in a large area. Hence, EI network construction and landscape connectivity improvements are feasible paths to protect ecological barriers and improve ecological services.

2.2. Data Sources and Study Framework

The data employed in this study include remote sensing monitoring data of land use in Langzhong in 2020 (the accuracy is $30\text{ m} \times 30\text{ m}$), road traffic data, elevation and slope data, Urban Master Plan data, and a compilation of basic data. The land-use data comes from the website of the Resources and Environmental Science and Data Center of Chinese Academy of Sciences (<http://www.resdc.cn/Default.aspx>) (accessed on 15 August 2021), the elevation and slope data sources come from the DEM digital elevation data of Geospatial

Data Cloud (<https://www.gscloud.cn/>) (accessed on 12 July 2021), and road traffic data are obtained from Langzhong Natural Resources and Planning Bureau.

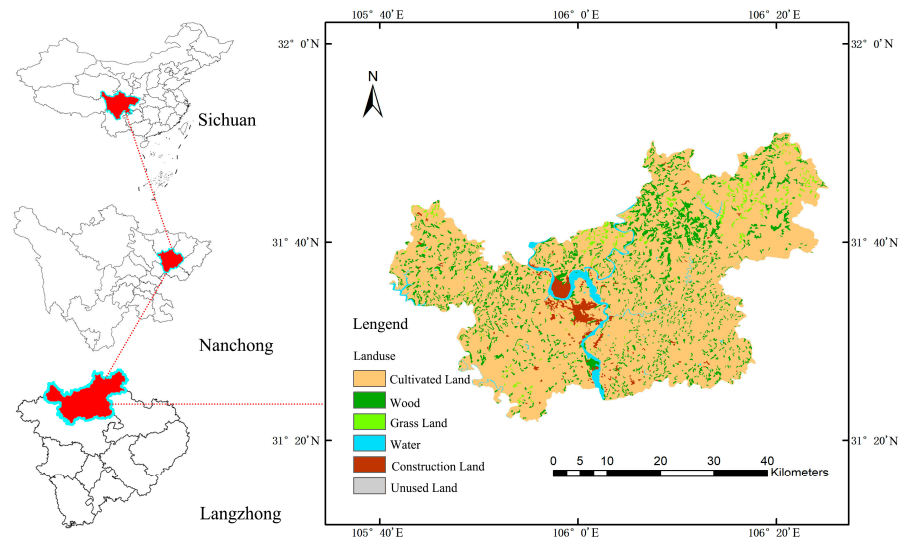


Figure 1. Study scope, location, and general situation.

Taking Langzhong County, Sichuan Province as the study area, the core patches in Langzhong County were identified with the MSPA method and the ecological sources of the study area were selected based on patch area and importance. The potential corridor path was generated by adopting the minimum cumulative resistance (MCR) model and high relative importance was selected as the EI corridor by applying the gravity model. Finally, the EI network was optimized with a network connectivity index and stepping stone patches and ecological breakpoints were identified (Figure 2). The study results provide reference for the delineation of ecological protection red lines and ecological network construction in Langzhong County, propel ecological civilization construction and biodiversity protection in this area, and also have certain reference value for EI network construction in other counties.

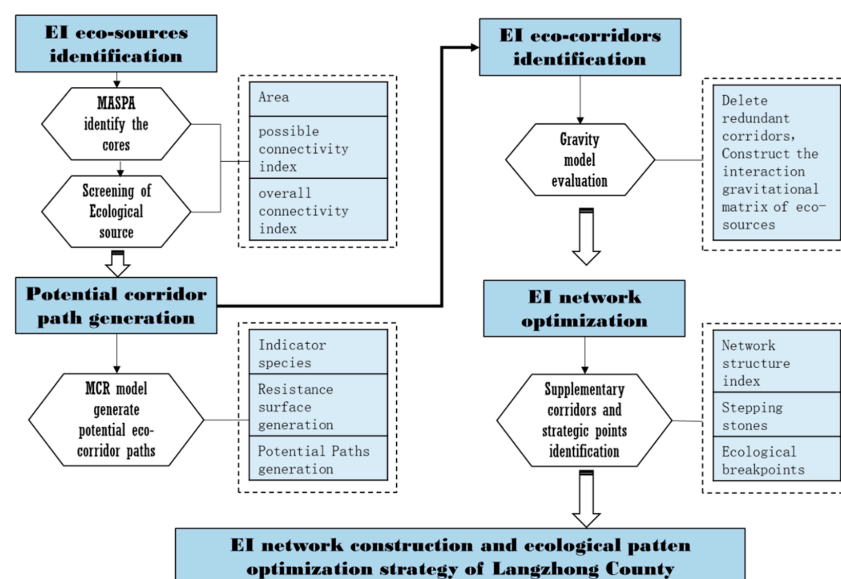


Figure 2. Research framework.

2.3. Methods

2.3.1. Ecological Source Identification Based on MSPA and Patch Importance Index

EI concentrates on ecological conservation functions such as water source regulation and purification and biodiversity protection. As cultivated land is mainly used for food supply, its ecological conservation function is limited. Hence, in GIS, forest, grass, and water were taken as the prospects with other land use types as the background, and the data grid size was 30 m × 30 m in this study. The prospects were divided into seven types using Guidos software [30]. Considering the theory of landscape ecology, there are many elements of landscape patterns that affect the processes and functions of landscape ecology, among which patch area and connectivity are the important indexes affecting ecological service ability. Conefor software was used to calculate patch landscape connectivity [30]. Based on the key species and study scale, in Conefor software, the edge width was set to 30 m, the maximum dispersal distance was determined to be 2.5 km after repeated tests [31], and the connectivity probability was set to 0.5 [32]. Ecological sources were screened and graded based on the patch area index, possible connectivity index (PC), and overall connectivity index (IIC) [32]. The calculation formulas were as follows (the larger the value, the higher the connectivity):

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}^*}{A_L^2} \quad (1)$$

where n refers to the number of patches, a_i and a_j are divided into the areas of patches i and j , respectively, A_L represents the total landscape area, and p_{ij}^* denotes the maximum probability of species dispersing in patches i and j .

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i a_j}{1 + nl_{ij}}}{A_L^2} \quad (2)$$

where n refers to the total number of patches, a_i and a_j represent the areas of patches i and j , respectively, nl_{ij} denotes the number of connections between patches i and j , and A_L represents the total area of the study area.

The importance of ecological sources in the whole network connectivity, namely d_{pc} and d_{IIC} , was determined by calculating the patch importance index with the following formula:

$$d_i = \frac{I - I'}{I} \times 100\% \quad (3)$$

where I represents the index PC or IIC of patches and I' denotes the PC and IIC after removing patches. The higher the value, the higher the core position of the ecological source.

It was also necessary to include scenic spots, nature reserves, various statutory parks, and cultural landscapes in the set of ecological sources. These areas have been demonstrated to be important ecological sources.

2.3.2. Identification of Potential Ecological Corridor Paths Based on MCR Model

Ecological corridor construction aimed at strengthening the connectivity of ecological sources and reducing the influence of surface cover resistance on ecological flow movement. Ecological flow movement was affected by two factors: the natural environment and the human social environment. Different types of land use generated different topographies, different ecological suitabilities, different habitat-providing capacities, and different interference degrees, thus causing different resistances on ecological flow movement [33]. The construction of the resistance surface reflected the interference degree of human activities on species migration and ecological flow in the plane space. As for different land-use types, there were great differences in the diffusion of biology, material, energy, and information [34]. Resistance factors were divided into natural factors (including elevation and slope), human factors (including distance from various traffic roads, industrial and mining

land, and construction land), and comprehensive factors (including land-use type and vegetation-cover index). By superimposing the weights of various factors, a comprehensive resistance surface was formed [35,36] (Table 1).

Table 1. Langzhong County resistance surface assignment.

Resistance Factor	Grading Index	Evaluation
Slope (0.19)	<8°	5
	8–15°	10
	15–25°	20
	25–45°	60
	>45°	100
Land use type (0.45)	woodland	3
	farmland	100
	Grasslands/shrubs	30
	land for construction	1000
	waters	600
Distance from construction land (0.1)	0–1000 m	100
	1000–3000 m	70
	3000–5000 m	50
	>5000 m	5
Distance from road (0.16)	0–100 m	100
	100–250 m	60
	>250 m	5
Distance from water body (0.1)	>2000 m	100
	500–2000 m	50
	200–500 m	30
	0–200 m	5

Through a combination of the actual species with the geographical and geomorphological characteristics of the study area, the spatial resistance surface was constructed regarding topography (as Langzhong County is located in the upper-middle reaches of the Jialing River Basin characterized by low mountains and deep hills, and the elevation has little effect on the flow of animals, plants, and ecological processes, the slope was selected as the core factor among the natural topographic elements), landscape type, and distance from built-up areas as the factors and the basic resistance values were assigned to different factors by referring to existing studies [17,25,37] (Table 1). The weight value of the resistance factor was obtained by averaging the expert scoring method and the entropy weight method.

Night light data (NASA website, namely <http://reverb.echo.nasa.gov>) (accessed on 15 August 2021), effectively represented the regional economic development, urbanization level, and human activity interference factors [38]. To avoid excessive dependence of the resistance surface on subjective experience of the experts, the resistance surface was modified using night light data, thereby increasing its objectivity. For corridor construction, the minimum resistance model was adopted, with the formula as follows [9]:

$$MCR = Fmin \sum_{j=n}^{i=m} D_{ij} \times R_i \quad (4)$$

where F represents the functional relationship, D_{ij} denotes the distance from j ecological source to target landscape element i , and R_i means the resistance of an intermediate point i between j and target point. The potential best contact channel between sources can be simulated based on this formula, under the condition of source and resistance determination, and by employing the cost distance analysis tool in GIS.

In GIS, geometric operation was adopted to extract the geometric center of the ecological source. This geometric center was also taken as the starting point and end point of

corridor migration. Based on the comprehensive landscape resistance surface, ArcGIS's cost path analysis tool was employed to calculate the minimum resistance value between sources, thereby generating the potential corridor-connecting path between two sources. Additionally, by vectorizing the cost path, the spatial distribution of potential EI corridor paths in the study area was obtained preliminarily.

2.3.3. Identification of Important EI Corridor Based on Gravity Model

In the practical construction and protection of ecological corridors, the interconnection of two adjacent ecological sources was not necessary. Under the condition that all ecological sources were directly or indirectly connected and there was a minimum number of ecological corridors maintained, redundant corridors crossing the same habitat patches could be eliminated and then important potential corridors could be identified by applying the gravity model. The importance and effectiveness of potential corridors were characterized by the interaction strength between source areas. The gravity model was used in constructing the interaction matrix between ecological sources. By relying on interaction strength, important ecological corridors were scientifically screened for priority protection and restoration [23,39]. This also provided a more feasible scheme for GI corridor protection and construction in the study area. The formula of the gravity model is shown below:

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} \times \frac{\left[\frac{I}{P_a} \times I_n(S_a) \right] \left[\frac{I}{P_a} \times I_n(S_a) \right]}{(L_{ab}/L_{max})} = \frac{L_{max}^2 I_n(S_a) I_n(S_b)}{L_{ab}^2 P_a P_b} \quad (5)$$

where G_{ab} refers to the interaction force between sources a and b , N_a and N_b represent the weight values of the sources, D_{ab} denotes the normalized value of potential corridor resistance between patches a and b , P_a denotes the resistance value of source a , and S_a refers to the area of source a . Moreover, L_{ab} represents the accumulated resistance value of a corridor between sources a and b and L_{max} refers to the maximum resistance of all corridors in the study area.

2.3.4. Optimization of EI Network and Identification of Stepping Stone and Breaking Point

Based on the network structure analysis, the EI corridors screened with the gravity model were supplemented and optimized, thus forming a more ideal scheme. The ecological sources were deemed as nodes and the corridors carrying ecological flows were treated as a network structure with a certain connection degree. Following this, by calculating the network spatial connection degree, the functional characteristics of the network were evaluated [40], mainly including three indexes (Table 2).

Table 2. Network Connectivity Index Evaluation.

Index	Meaning	Formula	Numerical Interval	Ecological Function
α index	Network closure refers to the degree of loop in the network.	$\alpha = \frac{L-V+1}{2V-5}$	Between 0 and 1 wherein 0 means there is no loop and 1 means the loop reaches its maximum.	The loop can improve the connectivity of the landscape inside the network.
B index	Network point-line rate refers to the average number of connections of each node in the network.	$\beta = \frac{L}{V}$	Between 0 and 3 wherein the higher the value, the better the network will be from no network to tree network to grid network to the most perfect network.	Reflect the complexity of the network structure: the more complex, the stronger the stability.
Γ index	Network connectivity refers to the degree to which all nodes in the network are connected.	$\gamma = \frac{L}{3(V-2)}$	Between 0 and 1 wherein 0 means that no nodes are connected and 1 means that nodes are connected to each other.	Reflect the connectivity between nodes.

Note: In the formula, L is the number of corridors and V is the number of nodes.

As a temporary habitat, the quantity, quality, and distribution of stepping stones can greatly affect the time, frequency, and success probability of species migration [41]. Long-distance corridors are not conducive to efficient migration of organisms and connectivity can be increased by adding stepping stones as temporary habitats. According to the landscape ecology theory, larger patch areas and higher proportions of forest land are the factors most conducive to improving biodiversity, so the patches with larger areas and higher proportions of forest land near the long-distance corridors were selected as stepping stones. At the same time, the intersection of EI corridors are the key strategic points of energy, material, and information sink [42]. Combining this information with the practical situation of Langzhong County, the intersection points of three or more EI corridors, as well as the intersection points of EI corridors and rivers, were identified as stepping stones (Figure 3).

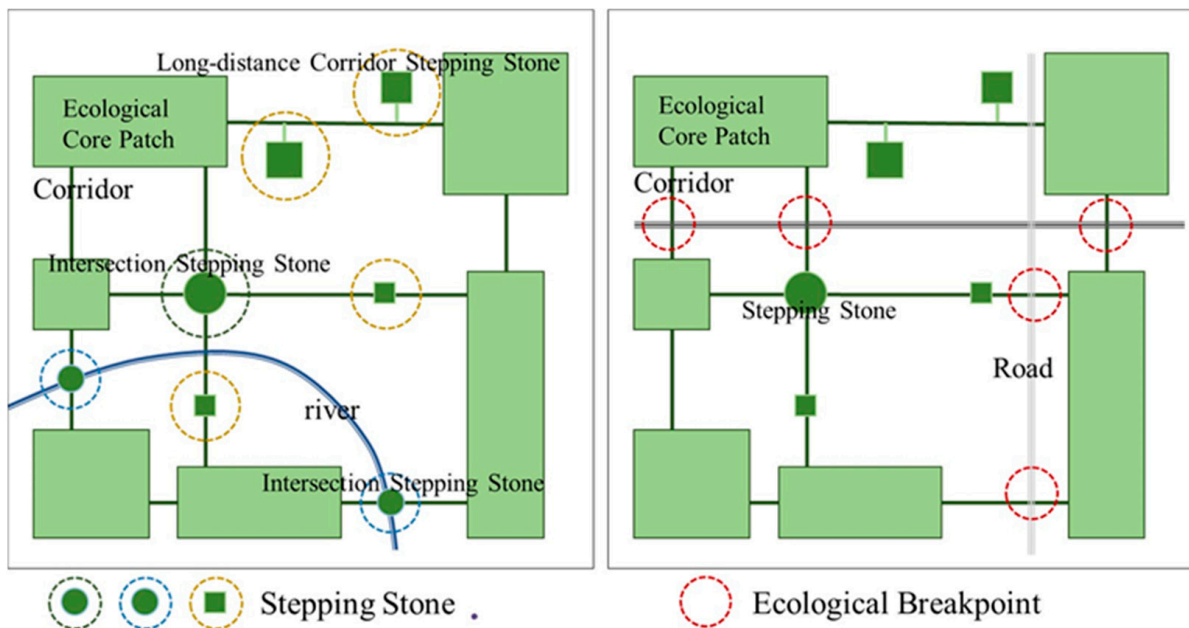


Figure 3. Identification of stepping stones and ecological breaking points.

If an EI corridor crosses with a traffic corridor, the migration of animals could be hindered in the crossing area and the animals are likely to be hit and killed by vehicles. Blocking and breaking the corridor has a negative impact on circulation of the whole ecological network and also poses hidden dangers to road safety. As a result, by using the intersect tool of GIS, the ecological breakpoints formed by the intersection of corridors and traffic lines were identified as strategic restoration points in Langzhong County (Figure 3).

3. Results

3.1. Ecological Sources Identification Results

In terms of quantity and spatial distribution, the edge of the study area was the dominant type, accounting for 36.44% of the area in the foreground (forest land, grassland, and water area). As the transition area of the core area, it mainly exhibited the edge effect. The core area was the area that provided a biological habitat and ecological services, accounting for 28.26% of the foreground, mainly distributed in the northeast of the research area and the county boundary. The bridge area accounted for 7.99% of the foreground area, and its quantity was low and mainly distributed in the north of the study area, which was not conducive to the diffusion and exchange of organisms and substances in the south. In general, the ecological landscape pattern in the study area was highly fragmented, the connectivity between patches was poor, the quantity of core and bridge areas was small,

and the distribution was significantly uneven. The south and central regions of the study area were in urgent need of ecological restoration (Table 3).

Table 3. MSPA analysis results.

Classify	Core	Bridge	Isolated Island	Ring Road	Gap	Edge	Branch
Area (km ²)	80.33	22.70	23.20	0.57	0.15	103.57	53.67
Proportion	28.26%	7.99%	8.16%	0.20%	0.05%	36.44%	18.89%
Total ratio	4.287%	1.212%	1.238%	0.031%	0.008%	5.527%	2.864%

The core patches with large areas (excluding Jialing River and its tributaries) and high dPC Values were selected as the ecological sources and 50 core patches were chosen by integrating a field land-use comparison (Table 4). When viewing the spatial distribution, the ecological sources in Langzhong County were unevenly distributed, mainly located in the northeast and southwest edge areas of Langzhong County with the main land use being forest land and water areas. Moreover, the overall layout was scattered and fragmented and there was lack of corridor connection between patches. Furthermore, it was dominated by the construction of county towns in the central part of the county and there were scarce ecological sources in the surrounding areas (Figure 4).

Table 4. The area and connectivity index of ecological sources.

Number	dPC	dIIC	dA	Number	dPC	dIIC	dA
1	12.5713	5.2359	11.8121	26	2.0150	0.7183	1.1246
2	8.7531	2.9423	8.3307	27	2.0056	0.7204	2.0174
3	7.5980	2.5233	9.2099	28	1.9864	0.8638	1.3614
4	6.6428	2.5232	6.7820	29	1.9700	0.8196	3.8400
5	6.3297	1.5917	5.8825	30	1.9672	0.6028	1.7142
6	6.0561	1.8171	5.0226	31	1.9530	0.8158	1.9638
7	4.5897	1.4830	4.7868	32	1.8782	0.5190	1.4905
8	4.4836	2.6367	4.9240	33	1.8666	0.8575	1.8111
9	4.3996	1.8048	4.6481	34	1.8640	0.5888	1.7335
10	3.9520	1.4689	3.5555	35	1.7552	0.5302	0.1934
11	3.6897	1.3324	2.4594	36	1.7478	0.6072	2.5424
12	3.3539	0.9777	3.8112	37	1.7343	0.8116	1.8047
13	3.1726	1.5922	5.3676	38	1.7280	0.4988	1.3697
14	3.1460	0.9807	2.9235	39	1.6019	0.9652	2.3552
15	3.0956	0.7555	1.7919	40	1.5908	0.3359	4.0834
16	2.8894	1.1007	4.1120	41	1.4895	0.6644	1.8990
17	2.8560	1.4604	3.6009	42	1.4800	0.5922	4.6439
18	2.7065	1.1933	0.4352	43	1.4523	0.4693	0.7600
19	2.5753	2.1142	1.2044	44	1.4222	0.8828	0.1649
20	2.5424	0.7368	2.6312	45	1.4044	0.6922	0.9445
21	2.3721	0.7168	1.6612	46	1.4043	0.5171	11.0891
22	2.3259	0.8200	1.8066	47	1.3806	0.3987	9.1626
23	2.0462	0.8586	1.5590	48	1.3768	0.3988	1.1790
24	2.0358	0.8878	2.7451	49	1.3764	0.7496	1.0543
25	2.0304	0.8240	1.5710	50	1.3757	0.3325	1.0411

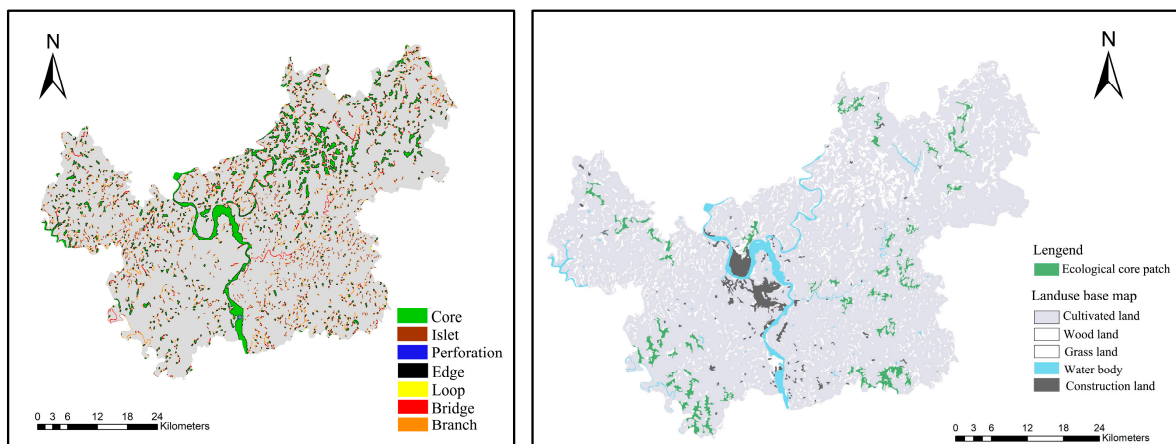


Figure 4. MSPA analysis results in Langzhong (left); screening results of ecological sources in Langzhong (right).

3.2. Construction of Comprehensive Resistance Surface and Extraction of Potential Ecological Corridors

According to the results of resistance surface construction (Figure 5), the areas with higher resistance values in the study area were distributed in the central region, showing a decreasing trend from the central region to surrounding regions. Most of the land in this area was for construction and the human disturbance factors were strong. The areas with low resistance value were mainly distributed in mountainous and hilly areas with abundant woodland and wetland resources. According to the results of the potential corridor paths analysis (Figure 6), the distribution areas of path network secrets were mainly in the southeast corner and southwest region of the county. However, the number of paths was large and too redundant to be directly applied in practice, so further classification and optimization were needed.

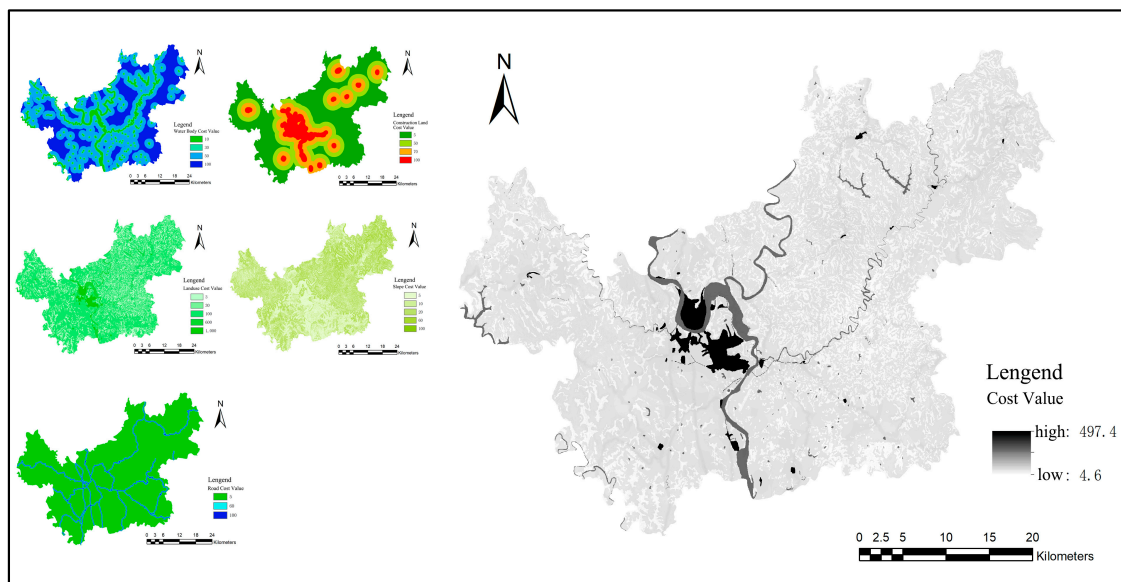


Figure 5. Comprehensive landscape resistance surface.

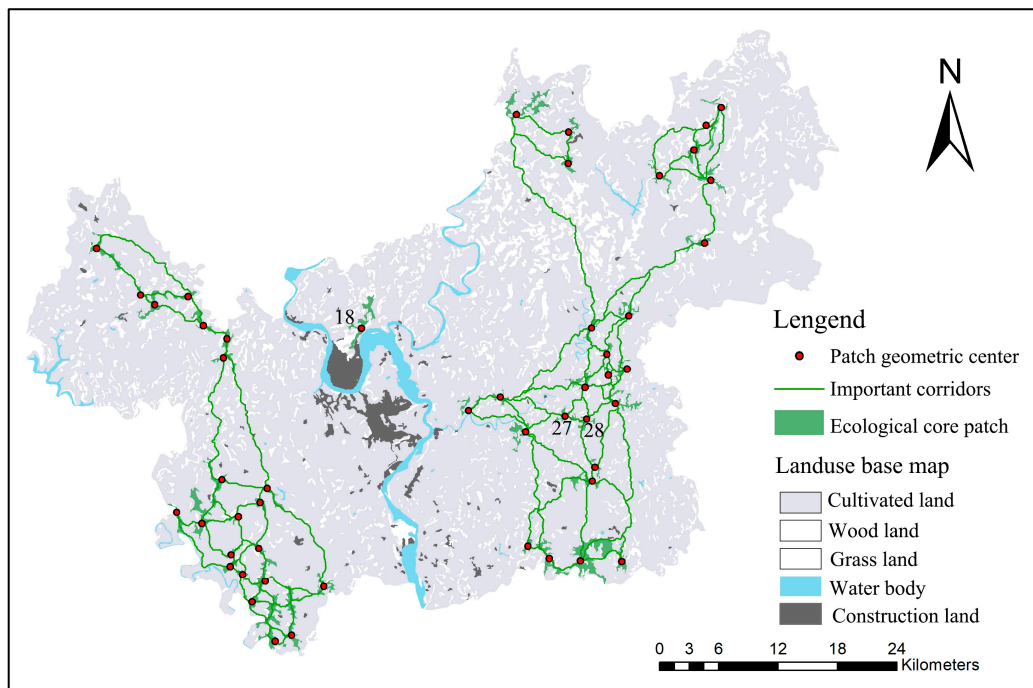


Figure 7. Screening EI corridors based on gravity model.

Table 6. Gravity values of EI corridors selected by gravity model.

Corridor No	Gravitational Value G	Corridor No	Gravitational Value G	Corridor No	Gravitational Value G	Corridor No	Gravitational Value G
1	1080.850	25	109.658	49	23.869	73	8.721
2	750.717	26	100.851	50	23.254	74	7.554
3	675.569	27	98.244	51	22.480	75	7.544
4	619.775	28	96.969	52	21.776	76	7.433
5	412.146	29	94.128	53	21.264	77	7.310
6	370.888	30	93.158	54	21.106	78	6.940
7	317.744	31	82.449	55	18.892	79	6.735
8	313.401	32	78.981	56	17.098	80	6.662
9	302.864	33	75.255	57	15.640	81	6.493
10	236.178	34	69.814	58	14.968	82	6.081
11	210.476	35	66.016	59	14.482	83	5.685
12	199.498	36	63.941	60	14.178	84	4.257
13	188.948	37	57.857	61	13.924	85	4.238
14	175.693	38	56.433	62	13.722	86	4.126
15	163.056	39	43.183	63	13.164	87	3.996
16	156.658	40	43.113	64	13.154	88	3.791
17	154.583	41	36.222	65	12.683	89	3.624
18	152.772	42	36.215	66	12.496	90	3.448
19	142.595	43	31.646	67	11.981	91	3.439
20	139.123	44	29.250	68	11.727	92	3.351
21	134.836	45	25.398	69	10.516	93	3.214
22	133.172	46	25.163	70	10.099	94	3.202
23	129.413	47	24.726	71	10.004		
24	120.833	48	24.545	72	9.502		

3.4. EI Network Optimization

3.4.1. Supplements to Important Ecological Corridors

To ensure the good closure and connectivity of the EI network and smooth ecological flow in the eastern and western areas of Langzhong County, 10 potential path corridors with high gravity values, including those connecting ecological source No. 18 with ecological sources No. 2, No. 20, and No. 26 and those connecting ecological source No.47 with ecological sources No. 38 and No. 29, were selected as supplements to the important corridors (Figure 8). As for the optimized EI network, the index α increased from 0.43

to 0.432, β increased from 1.709 to 1.81, and γ increased from 0.591 to 0.625. Through optimization, network connectivity was also improved. Moreover, within the network, there were more corridors connected by a single node and the flow process of material, energy, and information was more efficient and stable.

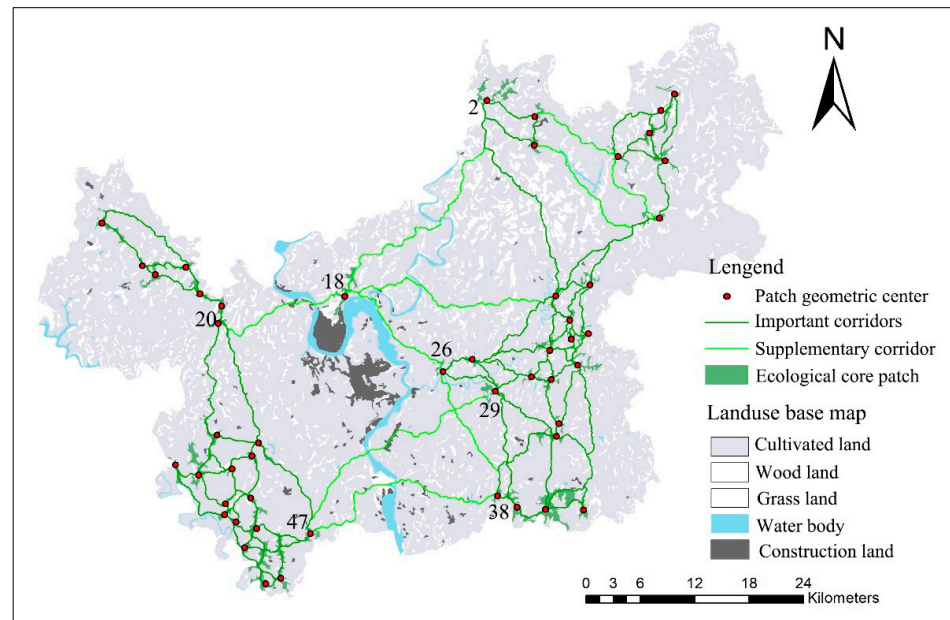


Figure 8. Optimized EI network in Langzhong.

3.4.2. Identification of Stepping Stones and Ecological Breakpoints

In order to enhance the success rate of species migration, protect biodiversity, and enhance material and energy flow, nine long-distance corridor stepping stones, nine land-based ecological corridor intersection stepping stones, and six land-based and water-based corridor intersection stepping stones were identified (Figure 9). Stepping stones were mainly distributed along the Jialing River and in the eastern part of the county where the corridor density was low, which helped to improve landscape connectivity. Eighteen ecological breakpoints were identified where the EI corridor was cut by expressways, railways, national highways, and provincial highways (Figure 9). The breakpoints were concentrated in the northern and southwestern corners of the county, mainly cut off by railways and expressways and these needed to be repaired through the construction of targeted biological bridges.

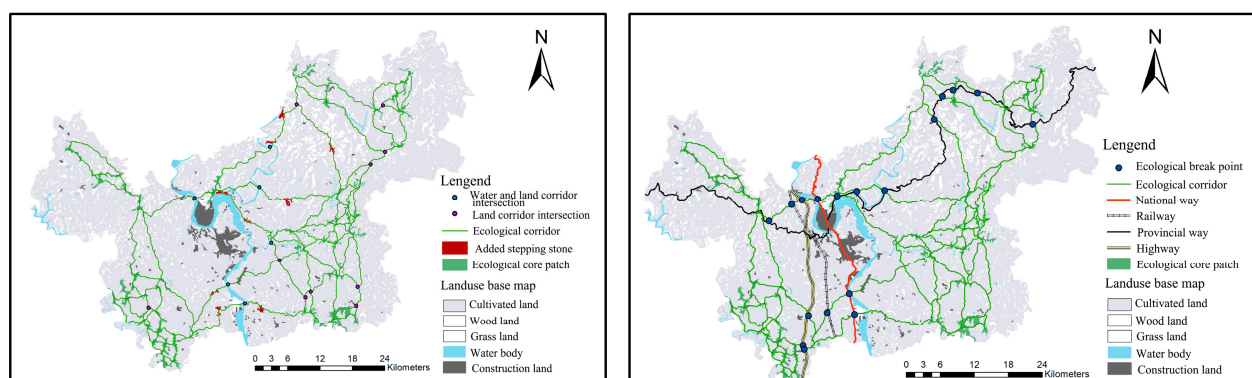


Figure 9. Patch repair of Langzhong stepping stones (left); restoration of ecological breakpoints in Langzhong (right).

4. Discussion and Suggestions for Ecological Pattern Optimization

4.1. Gradual Construction of EI Network Based on Importance

During the actual corridor restoration, prior consideration should be given to the ecological sources with larger areas and greater patch importance, namely the corridors with high gravity values and nearby stepping stones and breaking points should be repaired preferentially. According to our results, EI corridors were classified according to a gravity model. Through the quantile classification method in GIS, the ecological corridors were divided into three grades (Figure 10). The classification of EI networks in Langzhong County had Circle layer characteristics, with the primary corridors located in the area with dense ecological sources, the secondary corridors radiating outward around the primary corridors, and the third-level and fourth-level corridors mainly connecting with long-distance patches to form an outer ring. Considering the importance of the corridors, a gradual construction mode is suggested to apply to ecological restoration with corridor width considered. According to relevant studies, when the width of an ecological corridor reaches 30–120 m, the needs of animal and plant migration and species transmission can be satisfied [43]. Moreover, the width of corridor buffers should be selected based on current land-use conditions, thereby avoiding the excessive proportion of construction land and cultivated land in corridors. During the actual construction of EI networks, there may arise conflicts between land planning and utilization and the construction of potential ecological corridors, as well as other conflicts. Hence, reasonable measures should be taken to construct ecological network spaces in accordance with the practical situation.

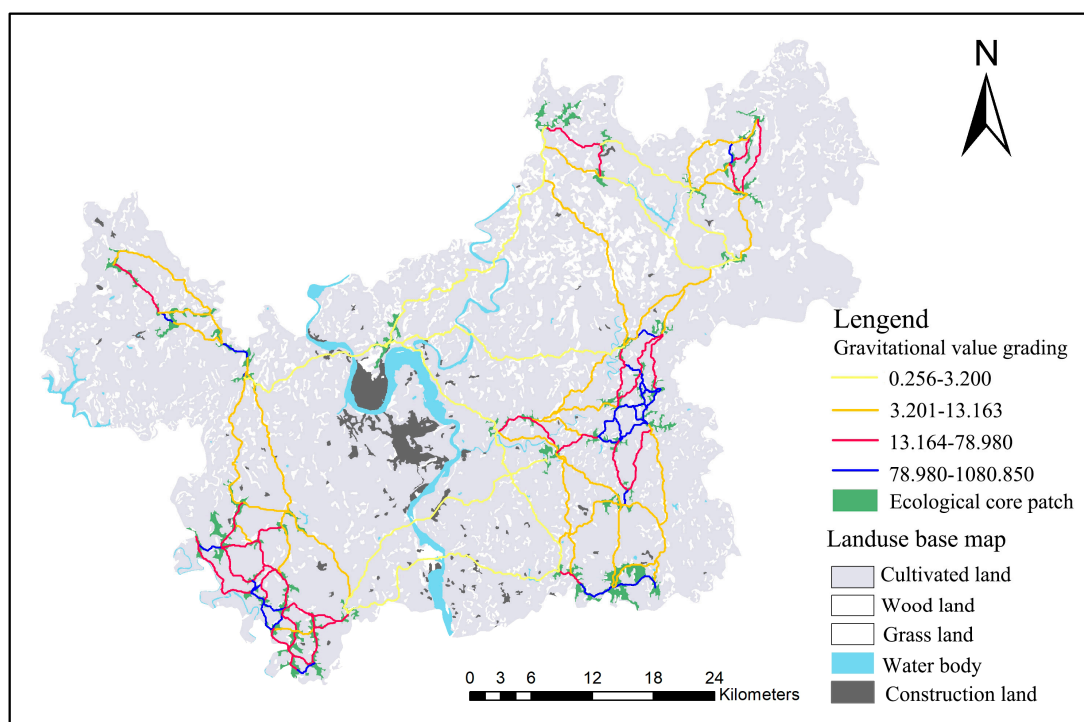


Figure 10. Importance classification of EI corridors in Langzhong County.

As for EI network planning and design, the land used is recommended to be dominated by forest land and supplemented by grassland, thus forming a three-dimensional vegetation system of forests, shrubs, and grasses. This forest network has high connectivity and is convenient for the migration and transformation of the population and nutrients in the system. Furthermore, it has greater buffering and stability characteristics in regard to changes in the external environment. Hence, the ecological function of the system is enhanced and the protection function of the forest network is promoted [44]. Moreover, the EI network embedded in the farmland matrix will not only block wind and sand and

conserve water, but also provide shade for rural recreational activities. The selection of plant types and planting modes was suggested to be determined according to the lighting, shading, and wind proofing needs of crops, forming various types of ecological corridors such as dense forest belts, sparse forest belts, shrubs, and grass belts (Figure 11).

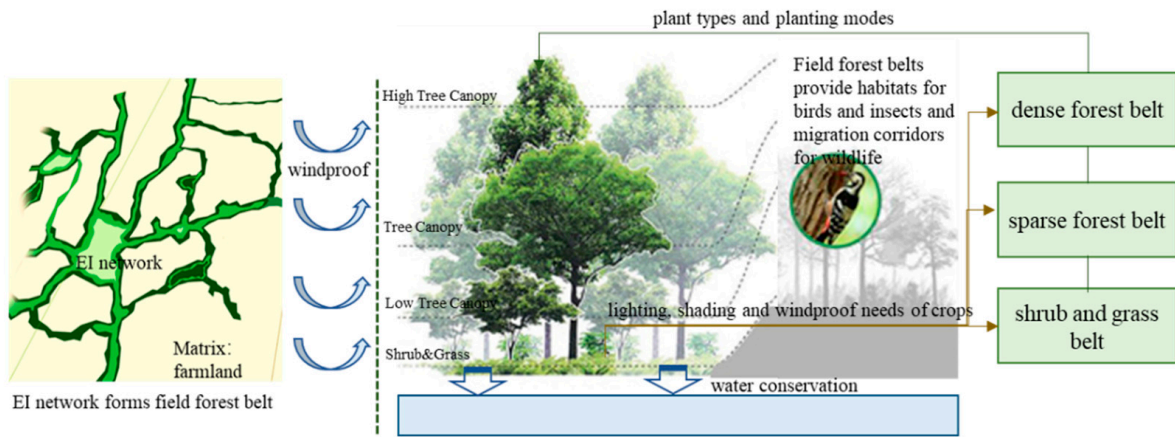


Figure 11. Field forest belt formed according to EI corridor design.

At the intersections of ecological corridors and water systems, it is necessary to strengthen wetland construction, increase the scale of green space, and design shoals and ponds. Additionally, the area of the intersection of ecological corridors and ecological corridors themselves must be expanded, thereby forming small and medium-sized habitats. As for ecological breakpoints, connectivity should be repaired by building underground passages, tunnels, flyovers, etc. (Figure 12).

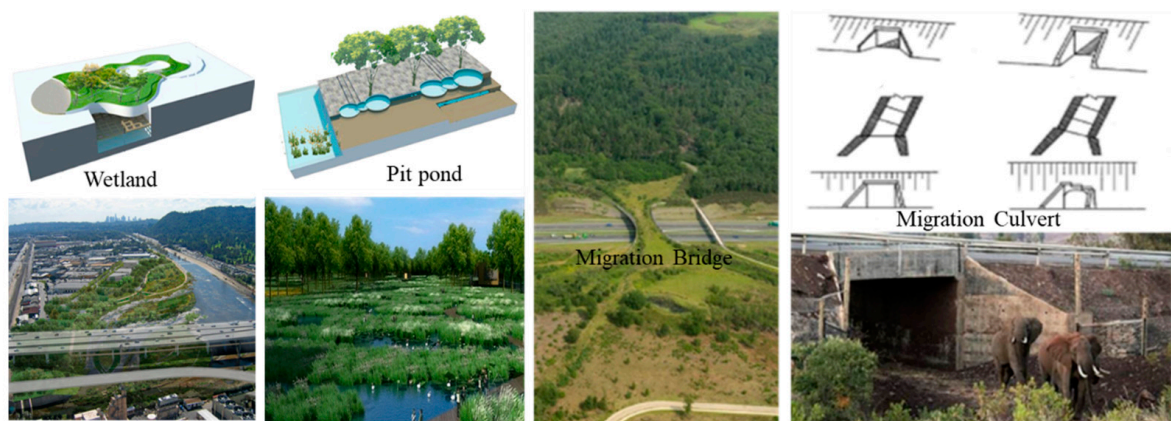


Figure 12. Design of stepping stones and ecological breaking points.

4.2. Proposal of the Management and Control Strategy of Regional Ecological Patterns

Based on the results of EI network analysis and by integrating the county development pattern, it is proposed to construct Langzhong County’s regional ecological pattern with three vertical and two horizontal ecological belts, four ecological control districts, and six clusters of EI networks (Figure 13). Furthermore, different ecological management and control measures should be taken at the four districts as follows.

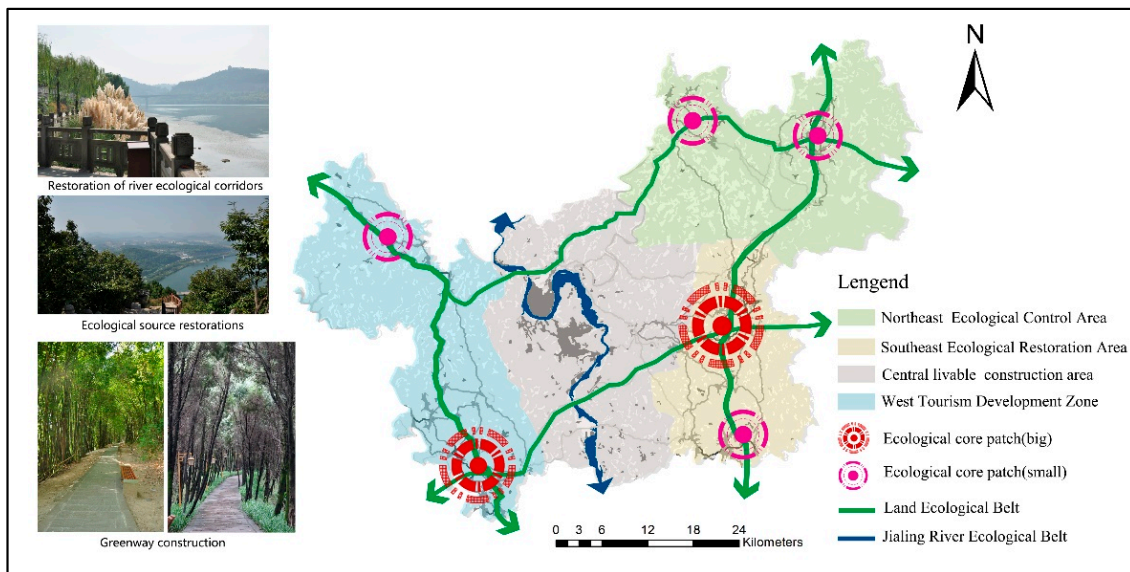


Figure 13. EI network and ecological pattern optimization strategy in Langzhong.

(1) Livable town construction area: Attention should be paid to the correlation between the ecological patches inside and outside construction lands, and the urban green space system should be integrated with the county's ecological structure. Furthermore, the utilization rate of land in built-up areas needs to be improved scientifically. Additionally, the living environment and land-use efficiency need to be optimized. (2) Western eco-tourism development area: The development of afforestation, artificial grasslands, and grassland improvement should be encouraged actively. As for existing sloping farmlands, positive measures should be taken to encourage the gradual transformation from farmland to forests and grasslands or to stimulate the building of terraces. Moreover, natural scenery resources with cultural heritage resources (including some ancient villages, religious deposits, ancient buildings, etc.) should be combined in the region. The cultural heritage and its surrounding scenery form a unique landscape. It is necessary to preserve and integrate the cultural landscape in the EI network construction. On this basis, the slow-moving greenway can be designed to connect the cultural heritage sites in series to form eco-tourism routes. (3) Northeastern ecological protection area: It is necessary to focus on ecological environment protection, maintain the relative stability of habitats, and repair the long-span corridor fault zone. (4) Southeastern ecological restoration area: It is necessary to concentrate on the restoration of EI corridor networks separated by patches of agricultural land, attach importance to the remediation and restoration of cross-ecological nodes between cultivated land and forest land, and maintain the quantity of farmland and basic soil fertility. Moreover, it is forbidden to cultivate crops on steep slopes with a slope greater than 25° . Furthermore, it is advocated to prepare land for afforestation on slopes, nurture young forests, and reclaim economic trees such as *camellia oleifera* and tung trees. In addition, soil and water conservation measures must be taken to prevent soil erosion and ecological rural tourism should be developed by combining ancient towns and temples.

5. Conclusions

In view of ecological space optimization and control, there is a relatively clear pattern and framework in top-level design (including double evaluation of provincial land space and delineation of an ecological red line) and bottom-level implementation (involving land remediation measures and key ecological restoration projects). Nevertheless, identification of ecological restoration units, spatial layout of ecological facilities, and control methods in the middle level are still under discussion. By constructing the county EI network, better guidance can be provided to site selection, implementation, and construction of ecological restoration projects. To reduce subjective interference in ecological source selection and de-

termine the optimal path and spatial position of ecological corridors, this paper considered Langzhong County, Sichuan Province as the study area, used MSPA and the MCR-Gravity Model in building the EI network of Langzhong County, and proposed strategies for ecological source protection, corridors, and stepping-stone construction as well as regional ecological pattern restoration in Langzhong County. This paper has the objectives of optimizing the ecological background of Langzhong County, protecting the biodiversity of the county, and enhancing the ecosystem services, which has direct significance to ecological security of the middle and upper reaches of the southwest river basin.

The study conclusions are as follows:

This study recommends plans to protect 50 ecological sources, mainly located in the northeast and southwest marginal areas of Langzhong County. The land-use types give priority to woodland supplemented by grassland and cultivated land. A total of 105 ecological corridors are proposed to be constructed, classified into three grades based on gravity values. The primary corridors are located in areas with dense ecological sources, the secondary corridors radiate outward around the primary corridors, and the third-level and fourth-level corridors mainly connect with long-distance patches to form an outer ring. Moreover, this study recommends plans to construct nine stepping-stone patches in long-distance corridors, nine stepping stones at the intersections of land ecological corridors, and six stepping stones at the intersections of land and water corridors (by planting wetlands and designing shoals and deep ponds for upgrading), thereby improving the success rate of species migration, protecting biodiversity, and enhancing the smoothness of material and energy flow. Additionally, this study recommends plans to repair 18 ecological breakpoints of EI corridors cut off by highways, railways, national highways, and provincial highways and restore connectivity by constructing underground passages, tunnels, and flyovers. Generally, it proposes protective countermeasures according to a regional ecological pattern with three vertical and two horizontal ecological belts, four ecological control districts, and six clusters of EI networks.

As for this study, there are still several aspects for further discussion as follows: (1) Different study scales have different influences on the results. To maintain small patches with good connectivity, this study adopts a study granularity of 30×30 m based on the related literature [45], and future studies at different scales and granularities need to be conducted. (2) This study focuses on the spatial distribution of an EI network. Corridor width should be considered in future planning and design. A buffer zone with an appropriate width should be built according to corridor route selection. Additionally, the current ecological space can be fully utilized, thus improving construction efficiency. (3) The study on the analysis and evaluation of farmland quality and supply service capacity is still shallow. Hence, it is necessary to further explore the action mechanism and coping strategies of each ecological function of GI at the city level.

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