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Research Article

Path Identification of Key Areas for the Ecological Restoration of Territory Based on Multi-method Fusion

Xuejing WEN[1], Zhi ZHOU[2,3,*], Guijun ZHANG[2,3], Siyu JING[1] and Pengtao ZHANG[2,3]

[1] College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071000, China
[2] College of Land and Resources, Hebei Agricultural University, Baoding 071000, China
[3] Key Laboratory of Farmland Ecological Environment of Hebei Province, Baoding 071000, China

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Abstract

The identification of key areas for ecological restoration is an important prerequisite for territory ecological restoration projects, and the current ecological environment restoration system established for environmental protection is imperfect. An ecological environment restoration system was proposed in this study to locate the ecological space to be restored scientifically and determine the optimal construction scale and restoration sequence to plan the ecological restoration project rationally. Taking Tang County of Hebei Province as an example, circuit theory and minimum cumulative resistance(MCR) model were used to construct the ecological network, and key areas, such as ecological pinch points, ecological obstacle points, ecological breakpoints, and low ecological quality area, were identified. The optimal construction scale, composition form, and restoration sequence of ecological key area restoration projects were further analyzed by the granularity inverse method, principal component analysis, spatial network analysis, and MCR model. Results demonstrate 28 ecological pinch points, 37 ecological barrier points, and 28 ecological breakpoints in Tang County; the low ecological quality area is 178 km^2, accounting for approximately 10% of the total area; the optimal construction granularity of Tang County's key ecological areas to be restored is 120 m, and the optimal construction scales of the pinch points, obstacle points, and breakpoints to be restored under this granularity are 39.76, 52.99, and 40 hm^2, respectively; the middle area of the long corridor, the overlap part of the ecological key area, and the concentrated distribution area should be repaired preferentially; and the other key areas should be repaired in the order of the accumulated resistance value at their locations from high to low. The proposed method provides a certain reference for ecological environmental protection and restoration.

Keywords: Ecological restoration; Ecological key areas; MCR model

1. Introduction

The industrial revolution has accelerated the process of world economic development [1], thereby increasing human income and causing ecological and environmental problems, such as global warming, species extinction, ecological and environmental problems (e.g., global warming, species extinction, and degradation of habitat quality) [2]. In the context of urbanization, human production and life have become the main driving forces that affect the ecological space [3]. Unreasonable urbanization significantly affects the urban－rural layout, thereby causing challenges, such as the contradiction between humans and land and the ecosystem's imbalance between supply and demand [4]. In recent years, ecological restoration work in small areas has mostly targeted abandoned mines, heavy mental pollution land, and waters with severe eutrophication [5-7]. It has been improved to a certain extent in local areas by setting up pilots to fix. In addition, China has carried out engineering-oriented ecological protection and restoration work in key areas, such as the Beijing-Tianjin Sandstorm Control Program and the Three-North Shelter Forest Program. The vegetation coverage rate and ecological environment in related areas have been improved [8-9].

However, the integrity of the ecosystem and the connectivity of the landscape are severely threatened because of the increasing complexity of ecological environment problems. The small-scale ecological restoration lacks systematic consideration of the entire ecological space, and the local restoration effect is significant but has minimal impact on the entire ecosystem, which further forces human beings to expand the ecological restoration's research scale to the macroscopic scope.

Based on this, scholars from China have conducted numerous studies on the ways to improve the overall integrity and connectivity of the ecosystem. The ecological restoration of the territorial focuses on the overall systemicity of the ecosystem and the sustainable use of ecological resources, thereby attracting extensive attention all over the world [10]. The study framework of "source－resistance surface－corridor" is gradually maturing [11-12]. However, the environmental restoration guidance system and scientific layout for different areas are not specific enough because of the complex human－land relationship, the large coverage area of the area to be restored, and the number of restoration objects involved. In addition, problems on how to define the key ecological areas to be restored and how to determine the ecological restoration sequence scientifically are still encountered. Therefore, the primary problems and important tasks that are currently being faced include scientifically diagnosing the key areas in

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*E-mail address: : zhouzhi797825@163.com

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the overall ecological security pattern; reasonably determining the restoration sequence; completing the integrated restoration of mountains, rivers, forests, farmlands, lakes, and grasslands; and implementing the territorial's ecological environment restoration project [13].

Therefore, based on constructing the ecological network, this study uses circuit theory to obtain the spatial distribution of key ecological areas to be restored, analyzes and calculates to obtain the optimal construction scale, determines the sequence of ecological environment restoration, and then provides references for the restoration of the ecological environment.

2. State of the art

Under the background for an important strategy of territorial's ecological restoration, relevant studies on ecological environment restoration mostly use the method of constructing ecological networks, transforming from single element restoration to overall spatial ecological element identification and restoration, and the spatial scale of ecological restoration planning and design has also been improved to a certain extent. Ma [14-15] comprehensively considered the ecosystem as a composite system of "nature-society-economy" and constructed an ecological security pattern on this basis but failed to incorporate low-quality fragmented ecological spaces when diagnosing the research areas' ecological restoration zoning. Zhang [16-17] followed the pattern of "determining the source, constructing the resistance surface, and identifying the ecological corridors" to construct the ecological network and further explored the ecological restoration's key areas. However, determining the optimal strategic point location and scale had not been studied yet. Xu [18] used the MCR model to construct the Grand Canal's ecological network from the perspective of species migration, but did not consider functions, such as economic value and historical value, and did not build a regional composite ecological network from the perspective of balancing ecological environment protection and green infrastructure. Li [19] took the ecological protection land and large areas of forest land as the ecological source, but this method lacked objectivity and ignored the internal differences of patches. Venturini [20] identified the ecological sources by using the MSPA method, but the results of the study obtained using the method at the same research area varied with the research scale. Wu [21] comprehensively evaluated multiple indicators to identify ecological source areas, but different research areas experienced difficulty in unifying the indicator selection criteria. Yochum [22] set land-use type resistance values according to empirical values but failed to express the obstacles of different land-use types to biological flow accurately. Doetzer [23] extracted the ecological corridors through the lowest-cost path analysis. Although the obstacles of landscape heterogeneity to ecological flow were considered, the interactions between ecological sources were ignored. Urban [24] explored the importance of corridors in ecological networks through the graph theory, but the method ignored the spatial heterogeneity of landscape patches. Ravan [25-26] constructed the ecological corridors through the MCR model and circuit theory, but it only identified the corridors between narrow forest belts, thereby resulting in the lack of other corridors between important source areas. Ward [27] proposed a landscape method for the protection and restoration of river corridors, but it could not be applied to assess the ecological integrity of river corridors. Yuan [28] analyzed the potential ecological corridors in the study area through the MCR model but did not explore the interaction between ecological corridors and existing roads in depth. The ecological key areas can be divided into resource and structural types. Wang [29-30] regarded corridor intersections and weak points as key structural areas; however, such nodes were only considered independent components in the study, without considering the influence of other landscapes on them. McRac [31] combined circuit theory with landscape ecology theory to determine the structural ecological key areas that need priority restoration in the ecological network. James [32-33] identified the resource-based key areas by combining MSPA modeling with the ecological network research, but modeling led to the fragmentation of ecological networks. William [34] believes that the key ecological area is mainly the geometric center of the patch, but it ignores its strategic location in the overall landscape pattern. Sacha [35] believed that the multi-objective genetic algorithm could identify the ecological nodes in the overall landscape pattern but did not explore the restoration sequence.

The aforementioned results mainly focus on how to construct ecological networks and how to identify large-scale ecological key areas. However, studies on the optimal construction scale of key ecological areas to be restored are few and even fewer on the ecological restoration sequences. Tang County of Hebei Province is located at the eastern foot of Mount Taihang and belongs to the "three-zone coupling"areas of ecological fragile territorial, concentrated contiguous poor areas, and mineral resources storage areas. In this context, Tang County of Hebei Province is selected as the study area to identify the key ecological areas to be restored on the basis of ecological security pattern system and determine the restoration sequence. The specific steps are detailed as follows: The habitat quality, ecological service value, and spatial stability of Tang County are analyzed and evaluated comprehensively to determine the ecological source. The habitat quality, land use type, elevation, and slope are selected as the resistance factors, and the ecological resistance surface is constructed by the MCR model. Construct the ecological corridors with the Linkage Mapper tools and identify the key ecological areas to be restored with the circuit theory. The optimal construction granularity of key ecological areas is determined according to the landscape index method, granularity inversion method, and principal component analysis method. The optimal construction scale is determined through the spatial network analysis method, and the spatial distribution map of the key ecological area to be restored and the distribution map of the minimum accumulated resistance value in Tang County are superimposed and analyzed to determine the restoration sequence. It is expected to provide technical methods and references for the territorial's ecological restoration planning.

The remainder of this study is organized as follows. Section 3 describes how to construct Tang County's ecological environment restoration system. By analyzing the ecological network, the spatial location of key ecological areas to be restored and the optimal granularity, section 4 obtains the optimal construction scale and ecological environment restoration sequence. The last section summarizes the study and gives relevant conclusions.

3. Methodology

3.1 Overview of the research area

Tang County is located in the west of Baoding City, Hebei Province, at the eastern foot of Mount Taihang's northern section. It coordinates 38° 37'-39° 09'N, 114° 27'-115° 03'E, with east from Shunping County and Wangdu County, south to Dingzhou City, west to Quyang and Fuping, north to Laiyuan County. The county has a total land area of 1,417 km^2 and an altitude of 40 – 1,810 m. Tang County is located in the west of the Haihe River basin, and the terrain features high in the northwest and low in the southeast. The topography is complex, with plains, hills, mountains, and rivers. The climate features four distinct seasons, with an average annual precipitation of 508.1 mm. The soil types include brown soil, cinnamon soil, paddy soil, and meadow soil. The low mountainous soil in the northern part of Tang County is mostly gravel soil, which is thin and loose and prone to geological disasters, such as soil erosion. The water resources are abundant, and the rivers in the territory include Tang River, Tongtian River, Qingshui River, and Fangshui River. A total of 9 towns and 11 townships are under its jurisdiction with a population of approximately 605,000. The industry has distinctive characteristics, and leading industries, such as precision casting, cultural tourism, agricultural and sideline product sales, machinery processing, and building materials, have further developed and expanded, and emerging industries represented by e-commerce have developed rapidly.

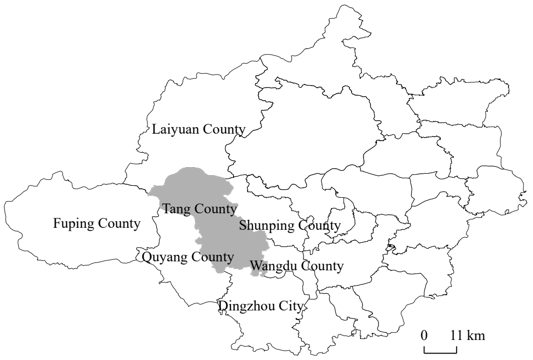

Fig. 1. Geographical Location Map of Tang County

3.2 Data sources and processing

The data used in the study include remote sensing image data (summer and autumn) of Landsat-5 in 2000 and 2010, Landsat-8 OLI in 2018, and DEM data with 30 m resolution, all of which are derived from the geospatial data cloud platform. The remote sensing images are preprocessed by radiometric calibration, atmospheric correction, and image cutting, and then the landscape types are interpreted as farmland, woodland, grassland, water area, built-up land, and unused land using supervised classification. The cloud cover of remote sensing image data is below 0.2%.

3.3 Selection of ecological sources

Tang County's ecological source areas are determined from three aspects: habitat quality, ecological service value, and spatial stability. First, four indicators, namely, greenness, humidity, dryness, and heat are selected to construct the habitat quality evaluation system. Then, the Bandmath tool of ENVI software is employed to calculate the four indicators. After normalizing the calculation results, the four indicators are merged into one image as four bands. After masking the water body, the image is imported into the PCA module of ENVI for principal component analysis, and the remote sensing ecological index RSEI is obtained to evaluate the habitat quality, which vary from 0 to 1. The higher the value, the lower the land development and utilization's degree, the higher the habitat quality. The function expression is presented as follows:

$$RSEI = f\left(Greenness, Wetness, Dryness, Heatness\right) \tag{1}$$

where $RSEI$ is the remote sensing ecological index; $Greenness$ is the green degree index; $Wetness$ is the humidity index; $Dryness$ is the dryness index; and $Heatness$ is the heat index.

Referring to the equivalent factor table of ecosystem service value established by Xie [36] and Costanza [37], the evaluation results of ecological service value are revised on the basis of the rule [38] that the economic value of ecological service value is equal to 1/7 of grain value per unit area of the year. The calculation formula is expressed as follows:

$$ESV = \sum_{i=1}^{n}\sum_{j=1}^{n} A_i \times VC_{ij}, \left(i = 1, 2, \cdots, 6; j = 1, 2, \cdots, 11\right) \tag{2}$$

where ESV is the total value of the ecosystem services in the research area, with the unit of yuan; A_i is the area of each land-use type, with the unit of hm^2 ; VC_{ij} is the ecosystem service value coefficient; i is the land use type;and j is the ecosystem service function.

The habitat quality evaluation results and the normalized ecological service value evaluation results are divided into 5 grades according to the equal space method, namely, the low grade (0-0.2), lower grade (0.2-0.4), medium grade (0.4-0.6), higher grade (0.6-0.8), and high grade (0.8-1.0). Then, the two evaluation results are overlapped with equal weight [39-40], and the patch with the highest is screened as the preliminary ecological source. Referring to relevant research [41-42], the ecological source with a patch area of more than 200 hm^2 , and the most stable ecological source in the three years is determined as the final ecological source.

3.4 Ecological resistance surface and corridor construction method

A certain amount of moving costs is consumed to communicate and move between the species in the ecological source areas. Comprehensively considering the impact of patch base and human activities on the biological flow, habitat quality, land use type, elevation, and slope considered a resistance factor according to Tang County's specific conditions and the availability of data. Referring to results of relevant study [43], a resistance coefficient of 1 – 5 is assigned to each resistance factor. The larger the resistance coefficient, the greater the resistance to the information flow between species. The weight is determined by the expert scoring method [44] (Table 1), and the ecological resistance surface is constructed by the MCR model after superposition calculation.

The MCR model can quantify the difficulty of a patch spreading from an ecological source to a certain point in the space well, and the minimum cumulative resistance path for species migration between landscape units can be obtained through model calculation. The main factors involved include spatial distance, ecological sources, and various resistance factors. The formula is expressed as follows:

$$MCR = f_{\min} \sum_{j=n}^{i=m} \left(D_{ij} \times R_i \right) \tag{3}$$

where MCR is the minimum cumulative resistance value for ecological source patch j diffusing to a certain point; D_{ij} is the spatial distance of the landscape base plane i traversed by organisms from source grid j to a certain point in space;and R_i is the basic resistance coefficient of base plane i to ecological process or species movement. The ecological corridor is the lowest resistance channel that connects two ecological patches. The Linkage Mapper tool is used to construct an ecological corridor.

Table 1. Ecological resistance surface factor weights and resistance coefficient

Resistance coefficient	Resistance factors			
	Land use type	**Habitat quality**	**Altitude (m)**	**Slope (°)**
1	Woodland and water area	0.8–1.0	40–191	0–5
2	Grassland	0.6–0.8	191–368	5–15
3	Farmland	0.4–0.6	368–565	15–25
4	Unused land	0.2–0.4	565–830	25–35
5	Built-up Land	0–0.2	830–1810	＞35
weight	0.5	0.3	0.1	0.1

3.5 Identification method of ecological key areas

According to circuit theory, the area's overall landscape is regarded as a conductive surface, and the electrons'random walk is used to simulate the organisms' flow between the source areas. Different resistance values are assigned to the landscape units according to the role in promoting or hindering the species and information exchange's flow, and the resistance value of the ecological source area for living organisms is set as zero resistance. The input current indicates the beginning of the simulation, and the current will change when the species flow. The ecological pinch points and the ecological obstacle points are identified according to the current density through the path.

(1) Identification method of ecological pinch area and ecological obstacle area

The ecological pinch area refers to the area that species must pass through during migration. The high species concentration makes it key areas characterizing the corridor connectivity, and the importance of ecological location also has the risk of the ecological environment being threatened. If the area is destroyed or disappeared, then the ecological corridor will be broken, which will further affect the ecological stability and biodiversity. Based on the ecological corridor, the Pinchpoint Mapper tool of Circuitscape 4.0.1 version was employed to distinguish the ecological pinch area according to the current density flowing through the corridor. The high current density area in the circuit indicated more species passing through the area, or the species are highly likely to pass through the area during circulation.

The ecological obstacle area has high resistance for species flowing between the source areas. Identification and restoration can improve inter-source connectivity and increase the success rate of species migration [45]. The Barrier Mapper tool was used to calculate the improved value after removing the area to identify obstacle-point areas.

(2) Regional identification method of ecological breakpoint areas

Ecological breakpoints' occurrence is mainly related to the cutting of large-scale transportation roads. In recent years, the problem of landscape fragmentation has gradually emerged with convenient transportation. The partial fracture of the ecological corridor directly affects the movement of species, not only increasing the difficulty of migration, but also increasing the mortality of species during migration, and causing varying degrees of damage to ecological security. The transportation map is superimposed on the ecological corridors' distribution map, and the intersection of the corridor and road is the ecological breakpoint area.

(3) Identification method of low-ecological-quality areas

Low ecological quality areas' emergence is closely related to human occupation of lands for farming or the sharp increase in the rural settlements and construction lands. Its scale and distribution directly affect the landscape fragmentation's degree and the ecosystem's stability and becomes one of the main reasons for the regional habitat's overall quality degradation. The study regards patches of the lowest grade generated by the superimposed evaluation results of the habitat quality and the ecological service value as low-ecological-quality areas.

3.6 Determination method of the optimal construction granularity in key ecological areas

First, grids of different granularity levels are generated on the basis of the original land use data to represent different landscape component structures. Then, starting from the landscape pattern's overall connectivity, the landscape pattern index is selected to calculate the indices of different granularity levels separately. According to the characteristic that the inflection point is the data curve's characteristic point, each granularity's connectivity is analyzed comprehensively, and the optimal construction granularity is selected through the granularity inverse method. ArcGIS is used to extract three land-use types of woodland, grassland, and water area as ecological lands, and 26 landscape components were constructed under 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 160, 180, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 800, 900, and 1,000 m.

Calculations are performed using Fragstas software, the landscape pattern indices, such as the average proximity distance (PROX_MN), the contagion index (CONTAG), adjacent ratio (PLADJ), cohesion (COHESION), sub-dimension (DIVISION), and aggregation index (AI) at the landscape level under different granularities. Following the criteria of cumulative contribution rate greater than 80% and a characteristic value greater than 1, the principal components of the landscape pattern's overall connectivity are determined. The overall comprehensive scores under different granularities are obtained through a series of calculations, and the key area's optimal construction granularity is determined accordingly.

3.7 Method of determining the optimal construction scale and time sequence for key ecological areas

The spatial network analysis method is used to calculate the key areas' scale with the optimal construction granularity determined. Each key area's reachable range under the optimal granularity is calculated on the basis of the ecological network, and the covered area is the key area's optimal construction scale. The study mainly relies on the service area analysis module of ArcGIS, which could generate the polygons that exist in the ecological network based on the analysis of the ecological network's specific spatial location. Therefore, the dependence between the ecological network and the generated polygons could be established. The idea of this study could fit the key ecological area's scale. The restoration sequence is determined by superimposing the MCR map and the key ecological area distribution map and considering the ecological network's distribution.

4 Result Analysis and Discussion

4.1 Identification results and analysis of ecological-source areas

As an important habitat for species and an important source of information flow, ecological source areas are characterized by good ecological quality and high ecological service value. Based on the characteristics and the impact of ecological source's stability on the ecosystem's stability, 10 Tang County's ecological-source areas (see Fig.2) of 91.22 km^2 accounting for 6.4% of the total area were finally determined. Most of the ecological sources were located in Shimen Township and Daomaguan Township in the northern part of Tang County. The southern part of Tang County was a plain, and human activities were concentrated here for the low and flat terrain. Hence, no ecological source distribution is observed in this area. The direct distance between the ecological source areas in the north and southwest was far apart, and the ecological sources' number in the southwest was relatively small.

4.2 Results and analysis of ecological resistance surface and corridor construction

The minimum cumulative resistance surface (Fig. 3) in the study area was constructed on the basis of the MCR model, showing that the minimum cumulative resistance value of the entire Tang County was between 0 and 66,670. The figure shows that the values in the southeast and the north－central regions were high and low, respectively. The high resistance areas mainly covered Tang County's southeast areas, which were far away from the ecological source area and greatly influenced by local human activities. A large number of rural residential areas were concentrated on these areas because of the relatively flat terrain, and the surrounding cultivated land, green space, and other ecological patches were isolated. The vegetation coverage in the north and southwest was higher, and human activities were less. Thus, the resistance value was relatively low.

The Linkage Mapper plug-in of ArcGIS was used to extract the least resistant cost path that connects the two ecological sources as the ecological corridor (Fig. 4). A total of 20 key and potential corridors were constructed with a total length of 240.66 km. The longest corridor was 39 km, and the shortest was 0.36 km. The ecological corridor began from the ecological source and radiated outward along the low-resistance channel. The distribution of the northern ecological corridors was dense, and the ecological network was relatively complete. The passage between the northern source and the two ecological sources in the middle and southwest was relatively long. Hence, the resistance to be overcome to keep the corridors intact and unobstructed was relatively large, and the ecological network's stability was far behind that of the northern part. The Xidayang Reservoir in Luozhuang Township was the main support for the interconnection between the southwest source and the northern source, and the waters' ecological security here was of great significance to the ecological network's stability and ecological security in the southwest of Tang County.

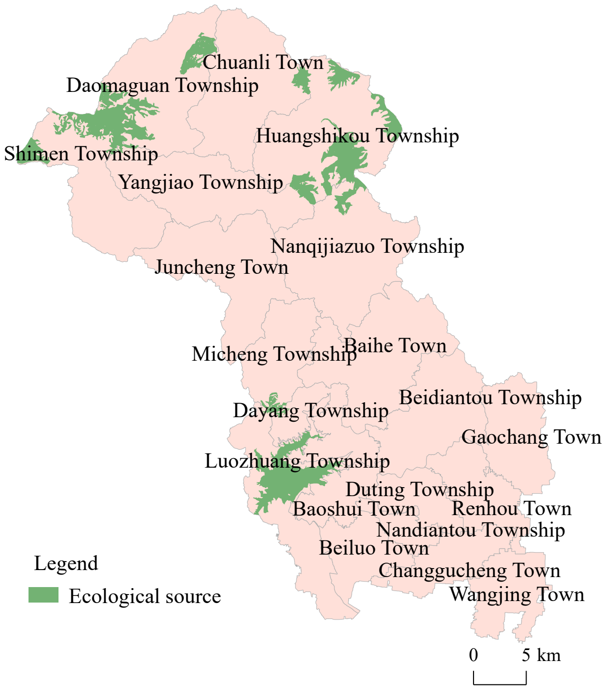

Fig. 2. Selection of ecological sources

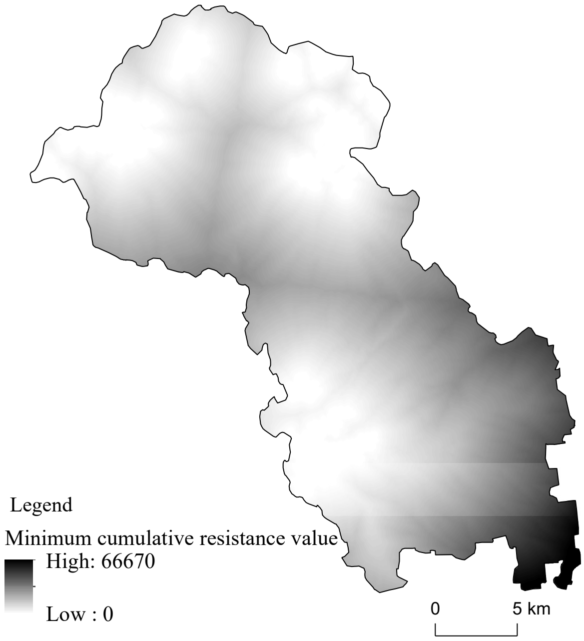

Fig. 3. Distribution of minimum cumulative resistance value

4.3 Diagnosis results and related analysis of key ecological areas

4.3.1 Diagnosis results of key ecological areas' spatial location

(1) Ecological pinch point area and ecological obstacle point area

Fig. 5 showed the spatial distribution of the ecological pinch points, the blue area with high current intensity was the ecological pinch area. A total of 28 ecological pinch points to be restored were finally determined, and they are mainly located at the center or top of the ecological corridor. The land-use types were mostly high and medium-covered grassland, and a few were woodland and low-covered grassland.

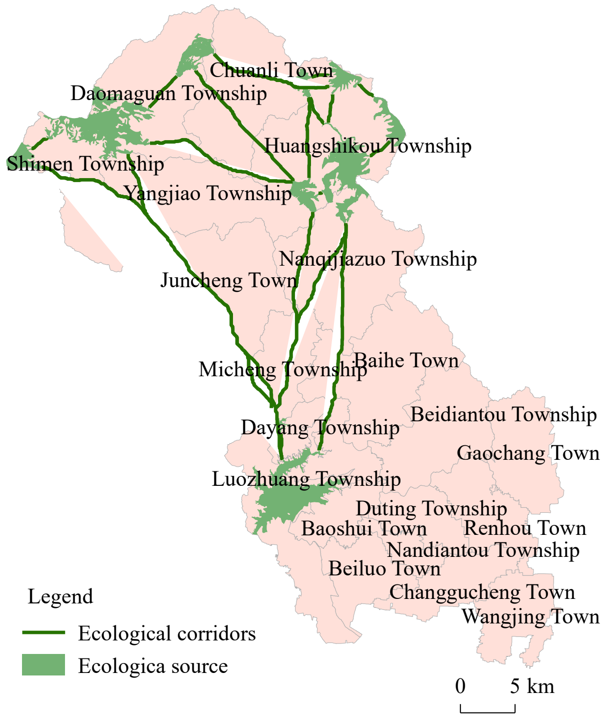

Fig. 4. Spatial distribution map of ecological corridors

Using the natural breakpoint method, the area above 1.35 was regarded as the obstacle point area, and 37 areas were identified. The analysis in Fig. 6 showed that the ecological obstacle point areas were mainly distributed in the center or both ends of the corridor. The number of obstacles in the southeast and southwest of the study area was large and densely distributed, accounting for more than 50% of the total number.

(2) Identification of ecological breakpoints

Fig. 7 showed the distribution of such 28 areas—8 areas were located on the towns and villages' road land; 3 areas located on the Junbai line's county road; 14 areas located on the S322, S335, and S241 provincial roads; 3 areas located on S52 Baofu Expressway. None of the roads passed through the ecological source area, so the source patch's integrity was guaranteed to a certain extent.

(3) Identification of areas with low ecological quality

After extracting the lowest grade patches in the results of comprehensive evaluation in 2000, 2010, and 2018, and the areas were selected as key areas of low ecological quality in addition to rural residential areas and construction lands (Fig. 8). The key areas covered a total of 178 km^2, accounting for approximately 10% of Tang County's total area. The key areas were scattered throughout the whole region, especially in the central and southern parts, and the land-use types were mainly dry land and grassland.

4.3.2 Determination and analysis of key ecological areas' construction scale

Based on the research method in Section 3.4, the Fragstats software was used to measure the index values under different particle sizes (Table. 2) and analyze the changes. Finding shows that PLADJ, COHESION, CONTAG, and PROX_MN changed significantly at 120 m. SPSS 22.0 software was used to analyze each landscape index's principal component and determine the principal component according to the variance contribution rate.

The correlation coefficient matrix (Table 3) showed that the cumulative contribution rate of the two principal components was 88.464%, thereby satisfying the principle that the cumulative contribution rate was greater than 80%, and the eigenvalue was greater than 1. The component matrix (Table 4) showed that the sprawl index, adjacency ratio, cohesion, and agglomeration index of principal component 1, which represented the landscape components' aggregation degree, were relatively high. Thus, it can be regarded as the landscape's overall connectivity index. The sub-dimension load of principal component 2 was relatively high, thereby representing the regional landscape components' separation degree. Thus, it can be regarded as the landscape fragmentation index. The overall connectivity had a greater impact on the ecosystem's stability according to the cumulative contribution rate.

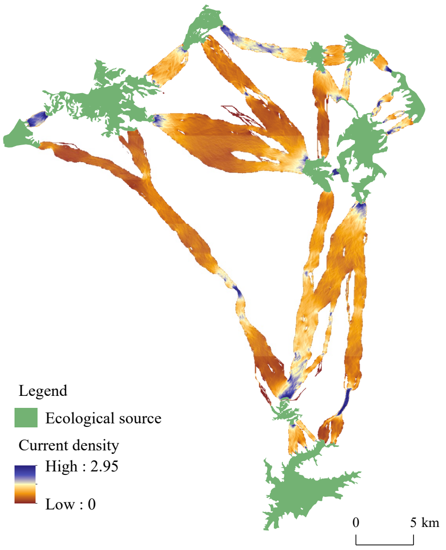

Fig. 5. Distribution of ecological pinch point area.

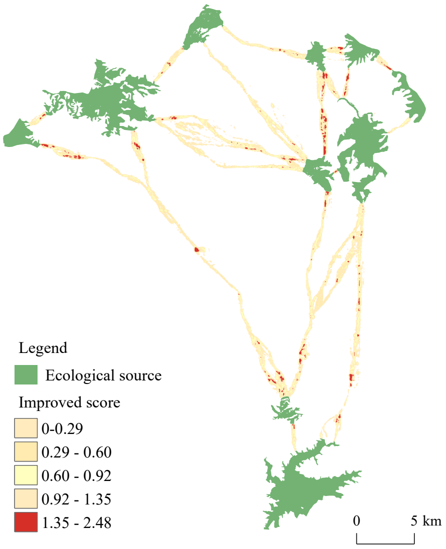

Fig. 6. Distribution of ecological obstacle.

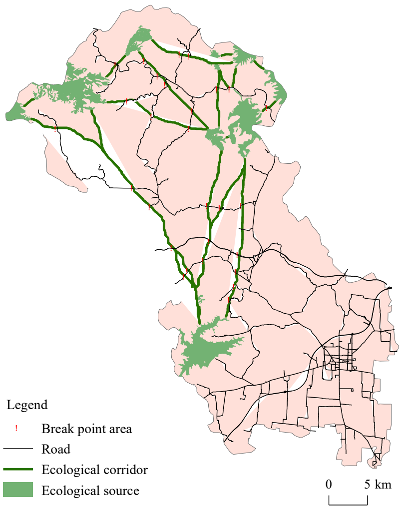

Fig. 7. Distribution of ecological breakpoints.

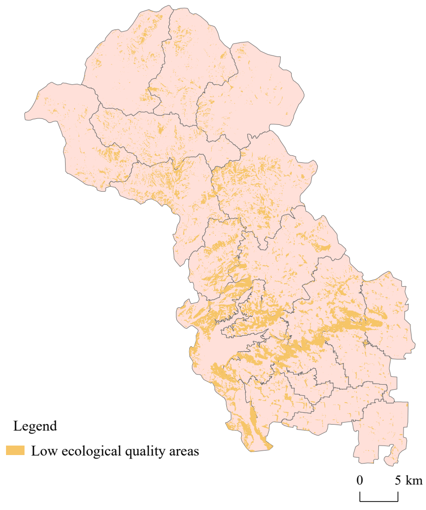

Fig. 8. Distribution map of low ecological quality areas.

The basic data were standardized through SPSS 22.0 and were then substituted into the function expression to calculate the overall connectivity score (Figure 9). The trend of the overall score was that the overall comprehensive score gradually decreased as the particle size increased, and several fluctuations occurred in the process. The change was mainly due to the increased granularity, and the smaller and more independent patches were removed or merged into the corresponding ones. Therefore, the landscape components' fragmentation degree became larger, and the aggregation degree decreased accordingly, thereby reducing the ecosystem's stability. However, when the ecological node was introduced, the overall score would fluctuate greatly. The turning point's position at the time indicated that the landscape component structure under this granularity was in the optimal state, and the ecosystem under this granularity was also the most stable. Combined with Fig. 9, the landscape component structure in the study area was the most stable at the granularity of 120 m, and it was a significant inflection point for the landscape components' structural changes. Considering that the landscape stability under the granularity was much greater than the others, the granularity of 120 m was the optimal one for the construction of key areas.

Since the circle has the optimal convergence, the polygon construction principle of service area analysis in spatial network analysis is similar to the circle calculation principle. Thus, the circle's calculation formula is used to calculate the key ecological area's scale. When the area of the ecological landscape patch was larger than one-half of the granularity of 120 m, the optimal construction radius of the key ecological area in Tang County, Baoding City was approximately 48 m.

Table 2. Measured index values under different particle sizes

Granularity	PROX_MN	CONTAG	PLADJ	COHESION	DIVISION	AI
50	9.1264	63.6274	92.2017	98.8271	0.968	94.1721
60	4.2791	63.7776	90.7958	98.6201	0.9666	93.1095
70	1.9148	64.0693	89.6464	98.2112	0.9695	92.6341
80	0.6249	64.4496	88.3588	97.8995	0.9694	91.9403
90	0.5572	64.2584	87.346	97.4968	0.9724	91.5381
100	0.484	64.2818	86.2173	97.2016	0.9705	90.9398
110	0.4167	63.9042	84.7667	96.5948	0.9744	90.0513
120	0.1465	65.9307	90.9323	97.3148	0.9653	89.6363
……	……	……	……	……	……	……
1000	0.1019	54.7736	55.7518	81.4708	0.9701	74.551

Table 3. Correlation coefficient matrix

Element	Starting eigenvalue			Extract the sum of squares and load		
	Total	Contribution rate	Cumulative contribution rate	Total	Contribution rate	Cumulative contribution rate
1	4.225	70.409	70.409	4.225	70.409	70.409
2	1.083	18.055	88.464	1.083	18.055	88.464
3	0.653	10.888	99.351			
4	0.023	0.390	99.742			
5	0.013	0.213	99.955			
6	0.003	0.045	100.000			

Table 4. Component Matrix

Index	Element	
	1	2
PROX_MN	0.572	-0.453
CONTAG	0.971	0.077
PLADJ	0.996	0.035
COHESION	0.987	0.064
DIVISION	0.064	0.931
AI	0.992	0.027

$$\begin{aligned} Y1 &= 0.278X_1 + 0.473X_2 + 0.485X_3 + 0.480X_4 + 0.031X_5 + 0.483X_6 \\ Y2 &= -0.435X_1 + 0.074X_2 + 0.034X_3 + 0.062X_4 + 0.894X_5 + 0.026X_6 \end{aligned} \tag{4}$$

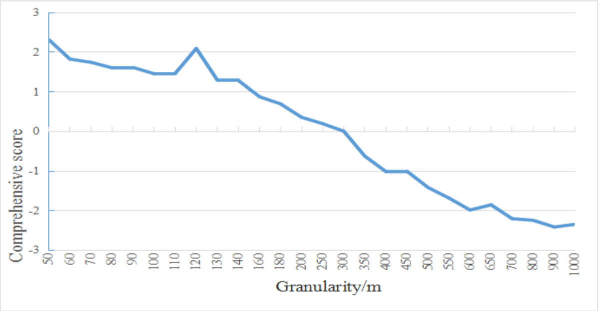

Fig. 9. Overall connectivity score of the landscape under each granularity

A total of 28 ecological pinch areas, 37 ecological obstacle points areas, and 28 ecological breakpoint areas were identified, with a total area of 126.08 hm^2. The pinch point area was 39.76 hm^2 with the obstacle-point area of 52.99 hm^2, and the breakpoint area of 40 hm^2 with an overlap area of 6.67 hm^2.

4.3.3 Analysis of the composition of key ecological areas

Based on the scale map of each key area, the land use-type map was superimposed to obtain each key area's current land use status (Figs. 10, 11, and 12). The ecological pinch area was 39.76 hm^2, and the land-use types included woodland, grassland, arable land, and water area. Woodland area was 6.04 hm^2, accounting for 15.19%; grassland area was 29.28 hm^2, accounting for 73.64%; the cultivated land area was 2.73 hm^2, accounting for 6.87%; and the water area was 1.41 hm^2, accounting for 3.55%.

The ecological obstacle area was 52.99 hm^2, and the land use types included grassland, woodland, unused land, and construction land. Grassland area was 15.56 hm^2, accounting for 29.36%; the woodland area was 5.61 hm^2, accounting for 10.59%; the unused land area was 21.76 hm^2, accounting for 41.06 %; and the construction land area was 8.53 hm^2, accounting for 16.1%.

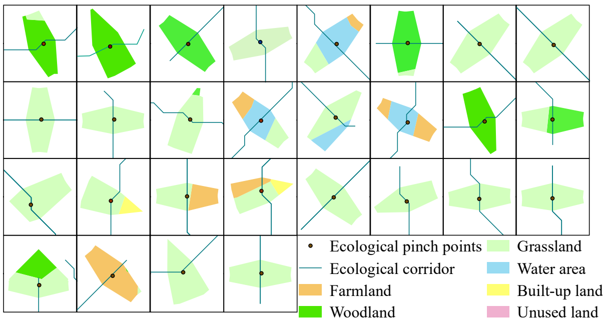

Fig. 10. Form of the composition of the ecological pinch points in Tang County

The ecological breakpoint area was 40 hm^2, and the land-use types included woodland, grassland, water area, and built-land. The woodland area was 1.41 hm^2, accounting for 3.53%; the grassland area was 9.84 hm^2, accounting for 24.6%; the water area was 4.83 hm^2, accounting for 12.08%; and the construction land area was 23.91 hm^2, accounting for 59.78%. Among them, construction land accounted for the largest proportion, most of which was the land for transportation in reality, which proved that roads had a great effect on cutting the ecological network to a certain extent.

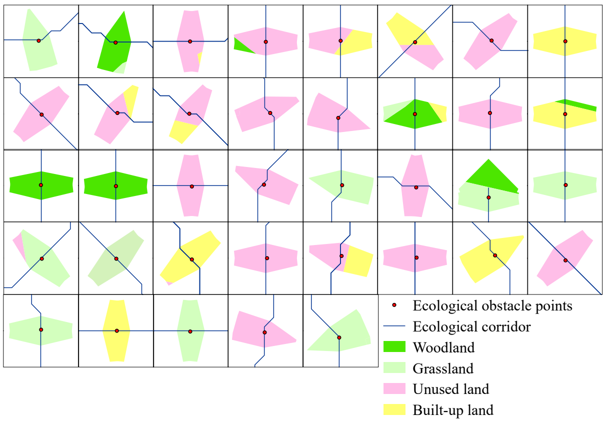

Fig. 11. Form of the composition of ecological obstacle points in Tang County

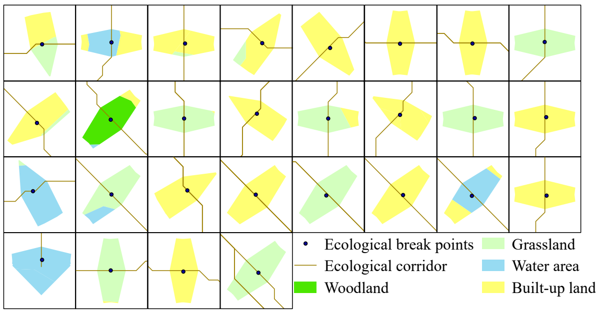

Fig. 12. Form of the composition of ecological break points in Tang County

4.3.4 Determination of key ecological areas' restoration sequence

In the ecological security pattern, the larger the cumulative resistance value of the patch location is, the greater the resistance will be for the species to spread out. Furthermore, ecological restoration could greatly improve the landscape connectivity and stability of the ecological network. The minimum accumulated resistance value calculated on the basis of MCR model was divided into four categories according to the natural breakpoint method, and the resistance values of Tang County, which were used as the basis for determining the restoration sequence, were graded (Table 5).

Table 5. Resistance level table in Tang County

Resistance level	Minimum cumulative resistance value range	Grid proportion
Grade I	(0, 7,844]	11.76%
Grade II	(7844, 20393]	18.83%
Grade III	(20393, 36603]	24.31%
Grade IV	(36603, 66670]	45.1%

The key ecological area distribution map (Fig. 13) was superimposed on the MCR map based on the study method in Section 3.5. The analysis showed that three obstacle points were overlapping with the pinch point area; two obstacle points overlapped with the breakpoint; and the pinch points, obstacle points, and breakpoints were relatively close within one area. Three obstacle points were located in the center of the long-distance ecological corridor, which was at an important turning point. Most of them were important habitats for organisms during the migration process. Once destroyed, the ecological corridor would be cut off, and the materials would experience difficulty in flowing, thereby requiring key protection and restoration. Therefore, the seven aforementioned areas should be restored, and the other key areas were repaired in sequence according to the area's cumulative resistance values in the order of levels IV, III, II, and I.

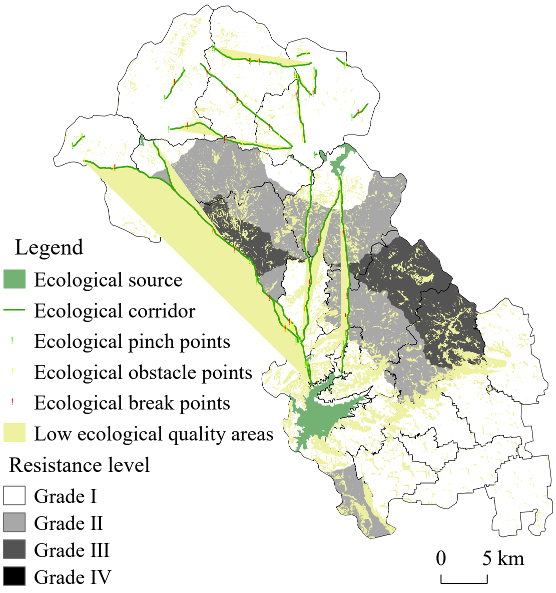

Fig. 13. Remediation resistance grade map of key ecological areas

5. Conclusions

The study took Tang County, Hebei Province as the research area to establish an ecological environment restoration system and provided a theoretical basis for the rational planning on environmental protection and restoration projects. The MCR model, circuit theory, landscape index method, granularity inversion method, principal component analysis method, and the spatial network analysis method were used to study Tang County's ecological security pattern, the spatial location of key ecological areas to be restored, the optimal construction scale, the composition form, and the restoration sequence. The following conclusions could be drawn:

(1) A total of 10 ecological sources in Tang County were identified, mainly distributed in the northern part of Tang County, a few in the southwest, and none in the southeast. It was mainly related to more forest and grassland and high vegetation coverage in the north, large-scale waters in the southwest, and more human activities in the southeast plain area. A total of 20 ecological corridors were constructed to connect the ecological source areas, with a total length of 240.66 km. Its number and density were closely related to the distribution in the ecological source areas.

(2) Under the optimal construction granularity of 120 m, the number of ecological pinch points, ecological obstacle points, and ecological breakpoints to be repaired was 28, 37, and 28, respectively. The optimal construction areas were 39.76, 52.99, and 40 hm^2. The low ecological quality area was 178 km^2, which account to approximately 10% of the total area. More than 70% of the ecological pinch areas were grassland, nearly 50% of the obstacle point area was unused land, and about 30% was grassland. More than 50% of the breakpoint area was the construction land, and about 30% was grassland. Low ecological quality areas were mostly cultivated land and grassland, and the surface oil in research areas was mostly gravel soil, which is suitable for grass or other drought-tolerant plants. The construction of green land could be strengthened by artificial grass planting. Thus, it could be restored to grassland ecological protection area and landscaped grass area, thereby reducing the species circulation's resistance in this area and the occurrence of ecological problems, such as soil erosion.

(3) The middle area of the long corridor, the overlapping part of the key area, and the concentrated distribution area were regarded as the highest priority protection and restoration area. Next, the key areas distributed within the minimum cumulative resistance value of level IV were repaired in the second order. Then, the key areas distributed in areas of resistance levels III, II, and I were repaired successively.

An ecological security pattern should be constructed from an overall perspective with the key area's identification, protection, and restoration completed because the habitat quality's degradation and ecological spaces' fragmentation caused by the rapid development of urbanization need to be solved urgently. The study explored the optimal construction scale of the key ecological areas to be restored based on the optimal granularity and extended from the identification of key points to the exploration and restoration of the key aspects. In addition, the restoration sequence of ecological corridors and the identified key ecological areas to be restored were observed.

The study could provide ideas and references for improving the stability of ecological network and the landscape connectivity as a whole, as well as a theoretical basis for the ecological restoration projects of territorial. However, the following shortcomings are noted. First, the width of the ecological corridors had not been studied and evaluated. Second, the width of the corridors had a certain degree of influence on the establishment and stability of the ecological network, which need to be determined according to existing methods and the specific actual conditions of the study area in the future research and practice. Moreover, the resistance factors related to human activities involve a wider range of research and only consider the land-use type during the construction of the ecological resistance surface. The selection system of the ecological resistance factors should be improved gradually in the future.

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