Evaluation and Construction of Regional Ecological Network Based on Multi-Objective Optimization: A Perspective of Mountains–Rivers–Forests–Farmlands–Lakes–Grasslands Life Community Concept in China

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Abstract: Landscape degradation and habitat fragmentation are some of the most urgent environmental problems associated with human development and regional integrated planning. Regional ecological network planning involves connecting high-quality habitats and reducing the negative impact of landscape fragmentation on the remaining natural patches through structural and functional connectivity. The concept of “mountains–rivers–forests–farmlands–lakes–grasslands life community”, as a system concept to solve the whole problem of regional ecological network in China, associates all natural ecological factors and ecological relations through a systematic pattern, emphasizing the systematics and integrality of ecological environment protection. This study, based on the progress of the study of “mountains–rivers–forests–farmlands–lakes–grasslands life community” and ecological network, clarifies the intrinsic connection and systemic relationship between humans and natural resources, and it clarifies the importance of multi-objective ecological network construction for the integrated development of resources in the whole region. Taking the Taishan area as the study subject, the ecological network construction approach of “risk assessment–source identification–corridor extraction–node selection” was constructed from three objectives—ecological systemic structure, ecological process integrity and ecological service efficiency—based on morphological spatial pattern analysis, minimum cumulative resistance model, gravity model and other modeling methods. The findings of this study can provide the evidence and clarification for the construction of a regional ecological network in China.

Keywords: ecological network; ecological service efficiency; landscape architecture; life community of mountains–rivers–forests–farmlands–lakes–grasslands; Taishan area

1. Introduction

Over the past ten years, the ecological and environmental issues have attracted the world’s attention [1,2]. With the rapid development of human society, the ecological space is constantly encroached upon and destroyed, which leads to the serious fragmentation of ecological patches, the reduction or even disappearance of biological habitats and then threatens the human health and survival security [3]. The connectivity and integrity of the ecosystem are constantly attacked, which seriously restricts the function of the ecosystem, thus limiting the sustainable development of the regional landscape [4]. Against the background of China’s ecological civilization construction, General Secretary Xi Jinping put forward the concept and principle of “mountains–rivers–forests–farmlands–lakes–grasslands life community” in 2013. It not only clarifies the inherent ecological relationship between the organisms and the surrounding environment in the ecosystem, but it also extends the important significance of the harmonious coexistence and common development of human
beings and nature, which is the embodiment of the systematic concept of solving the overall problem of regional ecological networks in China [5].

The concept of an ecological network is put forward against the background of protecting wildlife survival, and the area of regional ecological function is difficult to increase due to urbanization. Ecological network refers to a systematic and structural network based on the principle of landscape ecology, with the purpose of protecting biodiversity and landscape integrity. It utilizes a variety of linear ecological spaces in the open space to organically connect the resource patches to ensure the material circulation, energy flow and information transmission within the ecosystem, so as to maintain and protect its ecological, social, economic, cultural, aesthetic and other functions. The patch–corridor–matrix model, the source–sink theory and island biogeography theory are the theoretical basis for constructing ecological networks [6]. The ecological network, as an important protection structure of the ecological space, has become an important basis for ecological space management in urban green space and other ecological functional areas [7–9]. The ecological network is constructed mainly by means of the “source identification–corridor optimization–node selection” construction method and calculation model, which are mostly based on other disciplines and fields, with morphology, graph theory, mathematical models and intelligent algorithms being used more often. (Table 1) [10–13]. Among them, the ecological source is the minimum ecological land to meet the ecological needs of regional socio-economic development, and its identification is often based on the consideration of biodiversity richness and the importance of ecosystem services. There are mainly three identification methods: the empirical judgment method, the indicator factor method and the graph theory method. The ecological corridor is the carrier of regional material circulation, energy flow and information transmission, and it is an important channel to protect ecological processes. Its identification methods mainly include the traditional empirical identification method and the model simulation method. Ecological nodes are the most likely resting and staying spaces when organisms move or migrate in space. The current identification method is mainly the spatial structure analysis method, which identifies the intersection of minimum cumulative resistance paths between multiple ecological sources, and the application is mainly the intersection of potential ecological corridors.

After a long period of development and evolution, the ecological network has become a common method and a new policy for biodiversity conservation [14]. At present, the planning and implementation of the ecological network has gone beyond the single function of species protection and is carried out at various scales, such as international, national, regional and urban. Regional-scale ecological networks typically interconnect high-quality habitats, reducing the negative impact of landscape fragmentation on residual natural patches through structural and functional connectivity. The concept of “mountains–rivers–forests–farmlands–lakes–grasslands life community” is proposed to solve problems, such as the lack of ecosystem protection and systemic restoration. We can use systematic thinking to consider the global natural ecological elements and the ecological relationship between the elements [15]. This is consistent with the emphasis on the “pattern–process–function” relationships in landscape ecology. It is also an important development in the construction of a regional ecological network in China.

In addition, the protection of the ecosystem’s systematicness and integrality has triggered the search for a new method of protection. On the one hand, although the construction of ecological security patterns based on the theory of interaction between landscape ecology processes and patterns is a commonly used and effective way to protect ecological space and ensure the fulfillment of ecological functions, the ability to improve ecological quality and enhance ecological functions is limited due to the limited scope of the natural ecological space, and the protection of ecological functions in a single ecological space cannot further improve the ecosystem service capacity. On the other hand, the ecological network is composed of ecological source, ecological corridor and ecological node. The identification of ecological spatial elements comprises multiple identification approaches according to the different protection objectives. It is mainly divided into two
aspects, structure and function, which ensure the systematicness and functional integrity of the ecological space structure, while the combination of these two aspects is often neglected in the practical application, and the landscape ecology “process–pattern–function” research content cannot be fully expressed. In order to make the construction of the ecological network comprehensive and obtain high ecological benefits, it is necessary to achieve structural and functional integrity from multiple aspects.

Table 1. Construction methods and models of ecological network.

| Element Identification | Method                          | Theoretical Basis                                      | Normal Data                          | Calculation Model          |
|------------------------|--------------------------------|-------------------------------------------------------|--------------------------------------|---------------------------|
| ecological source      | experience method               | ecological quality                                     | relevant conservation regulation     | important ecological space|
|                        | index factor method             | ecological function                                    | ecological factors, such as soil conservation, water conservation and plant net primary productivity | factor overlapping method |
|                        | ecological sensitivity          | threat factors, such as geological disasters, flood disasters and water pollution | factor overlapping method           |                           |
|                        | ecosystem services              | value of ecosystem services                            | ecosystem service type               |                           |
|                        | landscape pattern index method  | structural integrity, systemic                         | landscape pattern index              | fragstats                 |
|                        | graph theory                    | structural integrity, systemic                         | morphological spatial pattern analysis|                           |
|                        | ecological corridor             | structural connectivity                                | landscape connectivity               |                           |
|                        | the traditional experience method| structural integrity, systemic                         | ecological linear spaces, such as rivers and windbreaks | visual observation         |
|                        | model simulation method         | ecological process (functional connectivity)           | land use status map and characteristic distribution of related ecological factors | minimum cumulative resistance model and gravity model and circuit theory |
|                        | graph theory                    | structural connectivity                                | present land use map                 |                           |
|                        | ecological node                 | structural integrity, connectivity                     | landscape centrality                 |                           |
|                        | swarm intelligence algorithm     | structural strategic point                              | ecological land                      | multi-objective genetic algorithm (mo-ga) |

“Pattern–process–function” is an important research paradigm in landscape ecology, and the three components are interactions and interdependencies that jointly contribute to human well-being and social values and have important theoretical significance. Therefore, based on the landscape ecology “pattern–process–function” research framework, and changes to the previous research, which only emphasized the single construction goal, this study aims to integrate the three objectives of ecosystem structure systematicness, ecological process integrity and ecological service efficiency, and realize the construction of an ecological network through multi-objective optimization, so as to provide spatial guidance for the implementation of overall protection, system restoration and comprehensive management.

2. Materials and Methods

2.1. Study Area

The life community of mountains–rivers–forests–farmlands–lakes–grasslands in the Taishan area (hereinafter referred to as “Taishan area”) is located along the Yellow River in western Shandong Province, with a total area of about 13,578.81 km². The administrative area includes most of Jinan City and all of Taian City, accounting for about 8.6% of the land area of Shandong Province. The Taishan area is located in the west along the Yellow River, east to the middle of the Taishan Mountains. The Dawn River and the Xiaoqing River are located on the south and north sides of the Taishan Mountains, respectively. The Taishan area is not only an important ecological functional area in the lower Yellow River but also an important ecological barrier in the North China Plain (Figure 1). The Taishan area
is divided into three ecological areas—Taishan ecological area, Dawen River–Dongping Lake ecological area and Xiaoqinghe ecological area—according to the characteristics of ecological background, which mainly comprise ecological environmental problems, such as mine goaf collapse, serious water pollution, high water resources development rate, vegetation degradation, biodiversity reduction and unreasonable land use. The ecological protection and restoration project of mountains–rivers–forests–farmlands–lakes–grasslands in the Taishan area encompass five major types of projects, including geological environment, land consolidation, water environment, biodiversity and regulatory capacity building [16]. At present, the projects are mainly divided into planning assessment and engineering practice. Planning evaluation projects mainly evaluate the ecological functions of important ecological function areas, such as the ecological evaluation of the Taishan Mountains, the southern mountains, the Dawen River and the Dongping Lake. Engineering practice projects mainly carry out ecological restoration projects according to the ecological environment problems in each ecological region.

2.2. Data Sources

The Landsat 8 OLI_TIRS 30 m digital satellite image from 11 May 2019 was selected as the data source. Based on the ENVI software platform, we used high-resolution (15 m) single-band image and low-resolution (30 m) multi-spectral image band fusion to obtain a 15 m resolution satellite image, through the combination of 30 m DEM digital elevation data and related survey data; then, we classified the remote-sensing image into five types of land use: forest land, waters, grassland, cultivated land and construction land. Finally, we established the land use status in the Taishan area (Table 2, Figure 2). Additionally, through on-the-spot investigation, we learned about the restoration project pilot sites of various ecological restoration types in the Taishan area, such as the Ningyang County coal mining subsidence treatment projects, the damaged mountain restoration on both sides of the Taifei First-Level Road and Provincial Road 330 Line, the mine ecological environment restoration in Ningyang County, the trilateral greening of the Dongping County section of the Dawen River, the construction of the Wenhe National Wetland Park and the construction of ecological protection forests in the old lake town of Dongping Lake.
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Table 2. Statistics of land use status of the life community of mountains–rivers–forests–farmlands–lakes–grasslands in Taishan area.

| Land Use Type (km²) | Ecological Region                  | Taishan Ecological Area | Dawen River–Dongping Lake Ecological Zone | Xiaoqing River Ecological Area | Taishan Area   |
|--------------------|-----------------------------------|-------------------------|-------------------------------------------|-------------------------------|----------------|
| forest land        | 654.83                            | 1658.66                 | 673.49                                    | 2986.98                      |
| grass land         | 147.57                            | 964.79                  | 427.88                                    | 1540.24                      |
| water              | 16.61                             | 417.16                  | 42.49                                     | 476.26                       |
| cultivated land    | 174.38                            | 4938.54                 | 869.77                                    | 5982.69                      |
| construction land  | 84.16                             | 1767.91                 | 740.57                                    | 2592.64                      |
| total              | 1077.55                           | 9747.06                 | 2754.20                                   | 13,578.81                    |

2.3. Methods

Based on the research framework of “pattern–process–function” in landscape ecology, this study integrated the three objectives of ecological structure systematicness, ecological process integrity and ecological function stability. On the basis of ecological risk assessment, the construction approach and construction method of “source identification–corridor optimization–node selection–network construction” were coupled to achieve the efficiency of ecological network ecosystem services (Figure 3).
2.3.1. Ecological Risk Assessment Based on Landscape Pattern Index

The landscape pattern index representing landscape fragmentation was selected to construct the ecological risk assessment system of the Taishan area, and the ecological risk assessment of the landscape pattern was carried out with four types of ecological function land use patches of forest land, water, grassland and cultivated land. In order to ensure the spatial homogeneity and interval heterogeneity in the region, the ecological risk assessment units of 3 km × 3 km were used as the analysis samples, and broken plots with an area less than 1.8 km$^2$ were eliminated. Finally, a total of 1570 analysis units were obtained. In order to ensure the contribution of different importance indices, the principal component analysis method was used to calculate the weight of the pattern index, and the principal component factors that have a greater impact on ecological risk were selected to complete the ecological risk assessment and ecological risk analysis of the Taishan area [17]. SPSSAU was used to carry out the negative indicator positivization, data normalization and principal component analysis on the patch type pattern index calculated by the Fragstats software, and the analysis extracted a total of three principal components. The analysis weights of the three principal components were determined according to the contribution rate of each principal component, which were 77.19%, 13.82% and 8.99%, respectively (Table 3). The index analysis term with the load coefficient of each principal component greater than 0.4 was extracted for risk analysis. Then, the ecological risk assessment model (ERI) of the Taishan region at the patch type scale was constructed. The formula is as follows [18]:

$$ ERI = E_1 \sum_{n=1}^{13} (F_n \times L_n) + E_2 \sum_{n=1}^{3} (F_n \times L_n) + E_3 \sum_{n=1}^{1} (F_n \times L_n) $$

(1)

In Equation (1), ERI is the ecological risk value of each risk cell unit; $E_1$, $E_2$, $E_3$ are the weight values of principal components 1, 2 and 3, respectively; $F_n$ is the absolute value of the load of each index analysis item; and $L_n$ is the normalized value of the nth index analysis item.

Figure 3. Ecological network construction approach of the life community of mountains–rivers–forests–farmlands–lakes–grasslands under the guidance of multi-objective optimization.
Table 3. Relationship table between principal components and landscape pattern indices.

| Title  | Load Coefficient | Common Degree |
|--------|------------------|---------------|
|        | Principal Component 1 | Principal Component 2 | Principal Component 3 | (Common Factor Variance) |
| PLAND  | -0.973           | -0.184         | -0.04               | 0.981               |
| LPI    | -0.937           | -0.336         | 0.05                | 0.993               |
| AI     | -0.957           | -0.025         | -0.26               | 0.983               |
| NP     | 0.889            | 0.293          | -0.197              | 0.91                |
| PD     | 0.886            | 0.278          | -0.217              | 0.91                |
| TE     | 0.89             | -0.196         | 0.383               | 0.977               |
| ED     | 0.901            | -0.219         | 0.356               | 0.987               |
| LSI    | 0.938            | -0.087         | 0.325               | 0.993               |
| AREA_MN| -0.771           | 0.511          | 0.295               | 0.943               |
| SHAPE_MN| -0.606          | 0.384          | 0.597               | 0.871               |
| PARA_MN| 0.692            | -0.623         | -0.187              | 0.902               |
| DIVISION | 0.98          | 0.157          | 0.02                | 0.985               |
| SPLIT  | 0.489            | 0.681          | -0.289              | 0.786               |

2.3.2. Ecological Source Identification Based on Multi-Objective Optimization

1. Ecological source identification based on MSPA analysis.

MSPA is an image processing method based on the principle of mathematical morphology to measure, recognize and segment raster images. Based on the Guidos Toolbox platform, three land use types of forest land, grassland and water in the Taishan area are used as the foreground elements of MSPA analysis (value 2), and cultivated land and construction land are used as the background elements (value 1). The eight-neighbor analysis method is used for MSPA analysis; then, the MSPA landscape types in the Taishan area are obtained (Figure 4) [19]. In this study, the core area with strong continuity but fracture due to fine data is corrected, and two core areas within the range of the Taishan Mountains with spacing less than 1 km and a gentle slope without human factors (such as roads, residential areas, etc.) are combined into the core area. According to the principle of island biogeography, 25 core areas with a large area are selected as the basic data for further landscape connectivity analysis.

Figure 4. MSPA landscape types in Taishan area.
Then, Conefor was used to obtain the landscape probability index of connectivity (PC) and the patch importance value of probability of connectivity (dPC) of 25 core area landscape patches in the Taishan area. PC is an important indicator to characterize the connectivity of patches. The removal of a patch will change the landscape structure, and then, the overall connectivity of the landscape changes. The size of the change shows that the patch is important to the overall connectivity of the landscape. The specific calculation formula of the patch dPC index is [20]

\[ dPC_i = \frac{PC - PC_{\text{remove}}}{PC} \times 100\% \] (2)

In Equation (2), PC is the probability index of connectivity of the region when all patches exist, and PC_{\text{remove}} is the probability index of connectivity of the region after the removal of patch \( i \). The higher the value of \( dPC_i \), the more important patch \( i \) is to landscape connectivity, and it also shows that patch \( i \) has a significant central role in the landscape.

2. Ecological source identification based on evaluation of ecosystem services.

The measurement of the ecosystem service capacity is mainly realized through the evaluation of the ecosystem service value. The study adopts the ecosystem service value equivalent factor method proposed by Xie Gaodi to calculate the four ecosystem service units of various land types in the Taishan area, such as hydrological adjustment, water supply, biodiversity and soil conservation (Table 4) [21]. The value of four kinds of ecosystem service unit weight superposition assignments is calculated; then, the Taishan area comprehensive unit ecosystem service value classification is obtained (Figure 5).

![Figure 4. MSPA landscape types in Taishan area.](image)

![Figure 5. Classification of ecosystem service value in Taishan area.](image)
Table 4. Table of ecosystem service value equivalent per unit area.

| Classification of Ecosystems | Supply Services | Regulating Service | Support Services | Supply Services |
|------------------------------|-----------------|--------------------|-----------------|----------------|
| First-Class Classification   | Secondary Classification | Food Production | Raw Materials Production | Water Supply | Gas Conditioning | Climate Control | Environmental Purification | Hydrological Regulation | Soil Conservation | Nutrients Cycle Maintenance | Biodiversity | Landscape Aesthetics |
| farmland                     | dry land        | 0.85               | 0.40             | 0.02           | 0.67           | 0.36            | 0.10             | 0.27            | 1.03            | 0.12              | 0.13            | 0.06            |
|                              | paddy field     | 1.36               | 0.09             | −2.63          | 1.11           | 0.57            | 0.17             | 2.72            | 0.01            | 0.19              | 0.21            | 0.09            |
| forest                       | conifer         | 0.22               | 0.52             | 0.27           | 1.70           | 5.07            | 1.49             | 3.34            | 2.06            | 0.16              | 1.88            | 0.82            |
|                              | mixed           | 0.31               | 0.71             | 0.37           | 2.35           | 7.03            | 1.99             | 3.51            | 2.86            | 0.22              | 2.60            | 1.14            |
|                              | coniferous and  | 0.29               | 0.66             | 0.34           | 2.17           | 6.50            | 1.93             | 4.74            | 2.65            | 0.20              | 2.41            | 1.06            |
|                              | broad-leaved    | 0.19               | 0.43             | 0.22           | 1.41           | 4.23            | 1.28             | 3.35            | 1.72            | 0.13              | 1.57            | 0.69            |
|                              | forest          | 0.22               | 0.33             | 0.18           | 1.14           | 3.02            | 100              | 2.21            | 1.39            | 0.11              | 1.27            | 0.56            |
|                              | meadow          | 0.22               | 0.33             | 0.18           | 1.14           | 3.02            | 100              | 2.21            | 1.39            | 0.11              | 1.27            | 0.56            |
|                              | shrub           | 0.22               | 0.33             | 0.18           | 1.14           | 3.02            | 100              | 2.21            | 1.39            | 0.11              | 1.27            | 0.56            |
|                              | grass           | 0.10               | 0.14             | 0.08           | 0.51           | 1.34            | 0.44             | 0.98            | 0.62            | 0.05              | 0.56            | 0.25            |
|                              | shrub-plant     | 0.38               | 0.56             | 0.31           | 1.97           | 5.21            | 1.72             | 3.82            | 2.40            | 0.18              | 2.18            | 0.96            |
|                              | shrub-plant     | 0.22               | 0.33             | 0.18           | 1.14           | 3.02            | 100              | 2.21            | 1.39            | 0.11              | 1.27            | 0.56            |
|                              | meadow          | 0.22               | 0.33             | 0.18           | 1.14           | 3.02            | 100              | 2.21            | 1.39            | 0.11              | 1.27            | 0.56            |
|                              | water           | 0.80               | 0.23             | 8.29           | 0.77           | 2.29            | 5.55             | 102.24          | 0.93            | 0.07              | 2.55            | 1.89            |
|                              | water system    | 0.00               | 0.00             | 2.16           | 0.18           | 0.54            | 0.16             | 7.13            | 0.00            | 0.00              | 0.01            | 0.09            |
|                              | glacier         | 0.00               | 0.00             | 2.16           | 0.18           | 0.54            | 0.16             | 7.13            | 0.00            | 0.00              | 0.01            | 0.09            |
2.3.3. Ecological Corridor Extraction Based on Multi-Objective Optimization

1. Potential ecological corridor identification based on MCR.

On the basis of determining the resistance value of land use types, the ecosystem service value of each land use type is taken as the weight to correct the resistance value of land use type, and the index system of ecological resistance factor is constructed by combining five resistance factors, including elevation, slope, distance from highway and distance from water (Table 5) [22]. Then, the comprehensive ecological resistance value of the Taishan area is obtained by the ArcGIS overlay analysis.

Table 5. Ecological resistance factor grading assignment and weight.

| Resistance Factor   | Classification Index | Loss Coefficient | Weight |
|---------------------|----------------------|------------------|--------|
| types of land use   | construction land    | 1000             | 0.49   |
|                     | water                | 400              |        |
|                     | cultivated land      | 90               |        |
|                     | grassland            | 11               |        |
|                     | woodland             | 5                |        |
| elevation           | >1000 m              | 100              |        |
|                     | 800~1000 m           | 80               |        |
|                     | 400~800 m            | 50               | 0.17   |
|                     | 200~400 m            | 30               |        |
|                     | <200 m               | 10               |        |
| gradient            | >25°                 | 100              |        |
|                     | 15°~25°              | 70               |        |
|                     | 10°~15°              | 40               | 0.21   |
|                     | 5°~10°               | 10               |        |
|                     | <5°                  | 5                |        |
| distance from water | >2000                | 100              |        |
|                     | 1000~2000 m          | 70               |        |
|                     | 500~1000 m           | 50               | 0.06   |
|                     | 200~500 m            | 30               |        |
|                     | <200 m               | 10               |        |
| distance from road  | <100                 | 100              |        |
|                     | 100~250              | 80               |        |
|                     | 250~500              | 60               |        |
|                     | 500~1000             | 40               | 0.07   |
|                     | >1000                | 10               |        |

The minimum cumulative resistance (MCR) model is used to generate the resistance surface of the study area, and the minimum cumulative cost distance between the source and the target source is calculated. Then, the potential ecological corridor between the ecological source areas in the Taishan area is obtained (Figure 6). The model considers three factors—source attributes, source-to-source distance and landscape interface characteristics—by calculating the probability of the movement of matter, energy and species in each landscape element type. The ecological resistance surface is constructed, and the minimum cumulative resistance path of the source and target points is obtained. The formula for calculating the minimum cumulative resistance model is [23]

$$MCR = f \min_{i=m}^{i=n} \sum_{j=n}^{i=m} (D_{ij} \times R_i)$$  \hspace{1cm} (3)

In Equation (3), MCR is the value of the minimum cumulative resistance; \(f\) denotes the positive correlation between the minimum cumulative resistance and the ecological process; \(D_{ij}\) is the distance traveled by a species from its point of origin \(i\) to a point \(j\) in space; \(R_i\) is the resistance coefficient of the landscape \(i\) to the movement of species [24]. Although the function \(f\) is usually unknown, the cumulative value of \((D_{ij} \times R_i)\) can be
In Equation (3), MCR is the value of the minimum cumulative resistance; \( f \) denotes the potential cumulative resistance of all corridors in the study area.

3. Assessment of connectivity of ecological networks.

Potential corridor resistance between plaque patches—the greater the possibility of biological migration between them. The gravity model formula is as follows [25]:

\[
G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left( \frac{1}{P_i} \times \ln(S_i) \right) \left( \frac{1}{P_j} \times \ln(S_j) \right)}{\left( \frac{L_{ij}}{L_{max}} \right)^2} = \frac{L_{max}^2 \ln(S_i) \ln(S_j)}{L_{ij}^2 P_i P_j} \tag{4}
\]

In Equation (4), \( G_{ij} \) is the mutual attraction between plaque \( i \) and plaque \( j \). \( N_i \) and \( N_j \) are the weights of plaque \( i \) and plaque \( j \), respectively. \( D_{ij} \) is the standardized value of the potential corridor resistance between plaque \( i \) and plaque \( j \). \( P_i \) and \( P_j \) are the resistance values of plaque \( i \) and plaque \( j \), respectively. \( S_i \) and \( S_j \) are the area of plaque \( i \) and plaque \( j \), respectively. \( L_{ij} \) is the cumulative resistance value of the potential corridor between plaque \( i \) and plaque \( j \). \( L_{max} \) is the maximum cumulative resistance of all corridors in the study area.

2. The importance identification of ecological corridor based on gravity model.

Based on the gravity model, the interaction matrix between 19 ecological sources in the Taishan area is constructed to quantitatively evaluate the connection intensity between the sources, and the ecological corridor with a high action intensity is selected as an important ecological corridor. The gravity model is used to analyze and predict the mathematical equation of the spatial interaction level. Through the gravity model, to quantify the mutual attraction level between the ecological sources, the stronger the interaction forces—indicating that the more important the potential ecological corridor between the patches—the greater the possibility of biological migration between them. The gravity model formula is as follows [25]:

\[
G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left( \frac{1}{P_i} \times \ln(S_i) \right) \left( \frac{1}{P_j} \times \ln(S_j) \right)}{\left( \frac{L_{ij}}{L_{max}} \right)^2} = \frac{L_{max}^2 \ln(S_i) \ln(S_j)}{L_{ij}^2 P_i P_j} \tag{4}
\]

3. Assessment of connectivity of ecological networks.

Finally, the network closure index (\( \alpha \) index), network connectivity index (\( \beta \) index) and network connectivity index (\( \gamma \) index) commonly used in corridor network structure analysis are selected to evaluate the degree of ecological network connectivity [26]. Network analysis is based on the graph theory. Through the quantitative analysis of network structure, analyze the importance of the network, the formula is

\[
\alpha = \frac{l - v + 1}{2p - 5} \tag{5a}
\]
In Equation (5), \( l \) is the number of corridors, \( v \) is the number of nodes, and \( l_{\text{max}} \) is the maximum number of possible connections. The \( \alpha \) index is the network closure index, which is used to describe the degree to which loops appear in a network. The higher the \( \alpha \) index, the more diffusion paths a species has to choose when crossing an ecological network. The \( \beta \) index represents the average number of connections per node in the network, indicating the degree of network connectivity. When \( \beta < 1 \), it indicates that the ecological network is a tree-like knot; when \( \beta = 1 \), it indicates the formation of a single loop; when \( \beta > 1 \), it denotes a more complex level of network connectivity. The \( \gamma \) index is used to describe the extent to which all nodes in the network are connected, and the cost ratio index is used to quantify the average consumption cost of the network, primarily reflecting the effectiveness of the network [27].

3. Results

3.1. Ecological Risk Assessment Based on Landscape Pattern Index

The ecological risk index value is assigned to the central point of each risk unit in the Taishan area, and 1570 points with risk assessment results are visualized through the Kriging interpolation analysis method. Then, the results are divided into six risk levels by the natural segment method: extremely high ecological risk, high ecological risk, slightly higher ecological risk, medium ecological risk, slightly lower ecological risk and low ecological risk (Figure 7). Combined with the natural background and ecological risk assessment of the Taishan area, the following findings are revealed. (1) The east–west trend of the Taishan Mountains and the Dawen River–Dongping Lake area forms an isolation zone of low ecological risk. It can be seen that the Taishan Mountains, the Dawen River and the Dongping Lake are areas with high landscape connectivity and low fragmentation in the Taishan area. (2) The high-value area of ecological risk is mainly located along the edge of the cities along the Yellow River, the southwest side of the Taishan Mountains and the south side of the Dawen River Basin, which is consistent with the pilot distribution of the ecological protection and restoration project of mountains–rivers–forests–farmlands–lakes–grasslands in the Taishan area.

![Figure 7. Ecological risk assessment of the life community of mountains–rivers–forests–farmlands–lakes–grasslands.](image-url)
3.2. Ecological Source Identification and Optimization Based on Multi-Objective Optimization

Based on the morphological spatial pattern analysis (MSPA) and landscape pattern index evaluation, 15 core areas with dPC (importance value of probability of connectivity) greater than 0.4 were selected as ecological source areas (Figure 8a), and the remaining 10 core areas were selected as important core areas. Through statistical calculation, the total area of the ecological source area in Taishan is about 1714.79 km², accounting for 12.63% of the total area of the study area, which is mainly distributed in the Taishan Mountains, the Dongping Lake, the Culai Mountain and the Lianhua Mountain.

![Ecological Source Map](image)

**Figure 8.** Ecological sources in Taishan area: (a) Identification of ecological sources in Taishan area based on MSPA analysis; (b) Comprehensive ecological source of Taishan area; (c) Service scope of ecological source area of Taishan area; (d) Optimization of ecological source area of life community of mountains–rivers–forests–farmlands–lakes–grasslands in Taishan area.

Based on the evaluation of ecosystem services, the results are obtained that the values of water, grassland, forest land and cultivated land are CNY 114.01/hm², CNY 8.71/hm², CNY 8.47/hm² and CNY 1.45/hm², respectively. The ecosystem service unit value of water is the highest. According to the importance of ecological sources, Dawen River, Chaiwen River, Dongping Lake, Xueye Lake and Dongzhou Reservoir are increased as ecological sources.
Based on the low level of ecological risk as the basis for the selection of ecological sources, the objectives of ecological structure systematicness and ecological service efficiency can be realized by identifying the ecological risk of the landscape pattern and ecological protection and restoration pilot sites, respectively. By comparing and analyzing the spatial distribution of the two, we selected the ecological restoration pilot site located in the low ecological risk area of the study area as the ecological source site and obtained one ecological source site.

By overlaying the ecological sources identified based on the MSPA analysis, screening for land with a high ecosystem service value and excluding the ecological space with corridor characteristics (Dawen River and Chaiwen River as ecological corridors), 15 ecological sources were obtained, with an area of about 1688.29 km$^2$ (Figure 8b), which is mainly distributed in forest land, such as the Taishan Mountain, the Culai Mountain and the Lianhua Mountain, and water bodies, such as the Dongping Lake and the Dongzhou Reservoir. Taking the geometric center points of 15 ecological sources as the center, according to the size of the ecological source area, two radii of 20 km and 15 km were set as the radiation distance of the source buffer; then, 8847 km$^2$ of the service range of ecological sources were obtained, accounting for 65.15% of the total area of the Taishan area. In order to improve the ecological source service proportionality and the ecosystem functional stability in the Taishan area, the range of the ecological source service was increased to 75%. Combined with the existing provincial nature reserves, national forest parks and ecological protection red line areas, four ecological source sites were optimized and added, mainly for water bodies and woodlands (Figure 8c). Finally, a total of 19 ecological source sites were obtained, with a total area of about 1725.70 km$^2$, accounting for 12.70% of the total area of the study area (Figure 8d).

3.3. Ecological Corridor Extraction and Ecological Network Construction

The high-value areas of ecological resistance are mainly distributed along the Yellow River in Jinan City and the south side of the Taishan area. The low-value areas of ecological resistance are mainly distributed around the Taishan area, the Culai Mountain, the Lianhua Mountain, the Dawen River and the Dongping Lake. Taking the identified and optimized 19 eco-source geometric centers as the source–sink point, the minimum-cost path between every two eco-sources is calculated based on the eco-resistance surface of the source, and 61 effective potential ecological corridors are obtained by the redundant potential ecological corridors caused by repetition and passing through the same patch. According to the matrix evaluation results, the potential ecological corridors with an interaction greater than 9 are extracted as important ecological corridors, and the others are general ecological corridors. Finally, a total of 16 important ecological corridors and 45 general ecological corridors are obtained (Figure 9a).

The current river ecological corridor is an important channel for regional material and energy connection and species migration. Based on the potential ecological corridor identified by the MCR model, the river ecological corridor should be supplemented and optimized. According to the width, length and flow of the rivers used to determine the important river ecological corridor, we determined the five river corridors of the Dawen River and its important tributaries, the Chaiben River, the Yingwen River, the Xiaoqing River and the Yufu River, as important ecological corridors. A total of 65 ecological corridors were obtained by integrating the potential ecological corridors and the current ecological corridors and deleting the redundant corridors, including 20 important ecological corridors and 45 general ecological corridors.

By combining the high ecological risk area, the important core area of the MSPA analysis and the intersection of ecological corridors, the ecological nodes of the ecological network are identified, and the ecological nodes located near the ecological source are deleted. Finally, 19 ecological nodes are obtained, which, together with the optimized ecological source and the ecological corridor, constitute the ecological network of the Taishan area.
1.39, 3.37 and 1.25 respectively, which shows that the ecological network has a high level of works. A single method of construction often tends to ignore the coupling of ecological processes with other ecological spaces and the importance of ecological functions in the region, so it is necessary to combine ecological structures and ecological functions to build ecological networks with multiple objectives and achieve ecosystem integrity. The core of the “mountains–rivers–forests–farmlands–lakes–grasslands life community” is to change from single-factor protection and restoration in the past to multi-factor ecosystem service function enhancement-oriented protection and restoration.

Figure 9. Ecological corridors in Taishan area: (a) Identification of important ecological corridors in Taishan area; (b) Ecological network construction of life community of mountains–rivers–forests–farmlands–lakes–grasslands in Taishan area.

4. Discussion

Integrating all the ecological sources, ecological corridors and ecological nodes, the Taishan regional ecological network is composed of 19 ecological sources, 20 important ecological corridors, 45 general ecological corridors and 19 ecological nodes, and based on the ecological network, the structure of the Taishan regional ecological network is established. Among them, the total area of the ecological source area in Taishan is about 1725.70 km², accounting for 12.70% of the total area of the study area. It is mainly distributed in the Taishan Mountains, the Culai Mountains, the Lianhua Mountains and other mountains with high vegetation coverage in the Taishan ecological area, and the Dongping Lake and Dawen River basin in the Dawen River–Dongping Lake ecological area. There are a total of 65 ecological corridors, with a total area of about 96.89 km², accounting for 0.71% of the total area of the study area. Among them, 20 important ecological corridors are mainly distributed in the Dawen River Basin and the Taishan area.

The utility of the optimized ecological network is compared with that of the unoptimized ecological network. The network closure index (α index), network connectivity index (β index) and network connectivity index (γ index) commonly used in corridor network structure analysis are selected to evaluate the degree of ecological network connectivity. The α index, β index and γ index of the Taishan regional ecological network are 1.39, 3.37 and 1.25 respectively, which shows that the ecological network has a high level of connection, and the spatial structure is optimized, which is conducive to the development of ecological benefits.

The construction of a regional ecological network structure is an attempt of regional integrity based on solving ecological problems. Regional ecological networks run through the ecological space, production space and living space, and different spatial zones carry different main functions, requiring different structures and functions of ecological networks. A single method of construction often tends to ignore the coupling of ecological processes with other ecological spaces and the importance of ecological functions in the region, so it is necessary to combine ecological structures and ecological functions to build ecological networks with multiple objectives and achieve ecosystem integrity. The core of the “mountains–rivers–forests–farmlands–lakes–grasslands life community” is to change from single-factor protection and restoration in the past to multi-factor ecosystem service function enhancement-oriented protection and restoration.
It is no accident that the idea of a “mountains–rivers–forests–farmlands–lakes–grasslands life community” is put forward. With the development of the human society, the people’s cognition of nature changes constantly. The interaction between human beings and nature has changed from the initial confrontation with nature to a harmonious coexistence with nature. In the face of the economic, social and environmental conditions in different periods, our country’s environmental policy is not perfect. The idea of a “mountains–rivers–forests–farmlands–lakes–grasslands life community” has gradually become the systematic embodiment of the construction of a regional ecological network in response to the fragmentation of regional landscape in our country. At the same time, because of the different aspects of the structure and function of the ecological network, it is easy to neglect the coupling relationship with other ecological processes and the importance of the ecological function in the region. It is necessary to combine ecological structure and ecological function to construct an ecological network and to realize the systematization and integrality of the ecological system. Therefore, this paper takes the mountains–rivers–forests–farmlands–lakes–grasslands life community in the Taishan area with Chinese characteristics as the research object. By combing the research progress of the concept of a “mountains–rivers–forests–farmlands–lakes–grasslands life community” and ecological network, it clarifies the internal system relationship between human beings and nature and natural elements, specifying the importance of the ecological network to territorial and spatial planning. From the perspective of “pattern–process–function” in landscape ecology, this paper explores the ways to optimize the construction of a regional ecological network. This study changes the previous research, which only emphasizes a single construction objective, and integrates the three objective orientations of ecological structure systematicness, ecological process integrity and ecological service efficiency. On the basis of ecological risk assessment, the construction of the Taishan area ecological network is realized by the identification of the ecological source, ecological corridor and ecological node.

Studies have shown that this method can improve the connectivity of landscape patches to protect ecological processes and biodiversity. Compared with ecological security patterns, ecological infrastructure and other ecological protection approaches with a single objective, the multi-objective-oriented ecological network can not only identify the ecological spatial units with ecological functions but also identify the important ecological corridors connecting the broken habitats at the regional scale. It can protect the ecological process by establishing the effective connection of the ecological space, the transmission of material flow, energy flow and information flow in the process of protecting ecology, ensuring the systematicness and integrity of the ecosystem. It can not only effectively promote the evaluation of regional ecological resources, the rational construction and optimization of a multi-objective ecological network structure but also provide the scientific basis and technical support for urban development control boundary determination, ecological red line delineation, identification and protection and restoration of important ecological space in territorial spatial planning and promote the sustainable development of regional ecology.

Based on the construction of the ecological network under multi-objective optimization, this study compares and analyzes the shortcomings of the existing ecological protection red line delineation in the Taishan area. It can guide and optimize the ecological protection red line delineation in the Taishan area and guide the ecological elements of ecological protection and restoration strategy for the ecological protection and restoration project of mountains–rivers–forests–farmlands–lakes–grasslands to provide scientific guidance. In this study, ecological function is the main goal of constructing the multi-objective ecological network, and the ecological network is not only the ecological spatial structure to maintain the stability of the ecosystem but also serves an ecological function. In order to realize the integrity of ecosystem services, we should add some factors, such as culture, leisure, education and transportation, in further research. In the next step, on the basis of constructing a perfect ecological network structure of the Taishan area, we can identify ecologically damaged spaces with high ecological sensitivity and focus on the mutual
influence of different ecological units on the mountain and below the mountain, so as to achieve the goal of systematic restoration and collaborative restoration. On the basis of ecological restoration, we can explore the supply of high-quality ecological products by means of composite construction, realize the transformation from natural resources to natural assets and create a mountains–rivers–forests–farmlands–lakes–grasslands life community with “green mountains, green water, rich forests, fertile fields and beautiful lakes” in the Taishan area.

At present, the study of the ecological network is mature in theory, but it does not play a relevant role in our country’s spatial planning. The main reason is that there is no clear control element, control index and control measure to link up with the planning, and more accurate research and analysis should be carried out on the ecological network to realize the scientific quantification and effective implementation of the planning results and to deliver effective results with the ecological space management and control approach to prepare effectively.

5. Conclusions

In this paper, a framework of multi-objective optimization-oriented eco-network assessment and construction is proposed, and the steps for identifying and optimizing the source, corridor, node and constructing a regional eco-network under different objectives are clarified. Based on this framework, we take the Taishan region as an example to construct a regional ecological network. In future studies, we plan to improve the accuracy of the study through a more accurate assessment of the ecosystem services and to achieve the integrity of ecosystem services by increasing factors such as cultural services to explore the effective link between the theoretical level of ecological network construction and the planning practice. This study provides further scientific guidance for regional ecological protection red line delineation, ecological protection and restoration project implementation, and ecological product value embodiment.

“Mountains, rivers, forests, fields, lakes and grasses are the community of life”. This idea was put forward against the background of ecological civilization construction, and a coordinated development of multi-functional space was realized through the overall planning of all-round natural elements, and the systematic thinking of ecological environment protection was emphasized. The finding provides the experience and inspiration for the construction of a regional ecological network, which can be applied to the construction and sustainable development of an ecological network in other regions.

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