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Construction and Optimization of Ecological Network Based on Landscape Ecological Risk Assessment: A Case Study in Jinan

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Abstract: Due to the rapid development of urbanization, land-use types have changed greatly, which has led to many ecological problems. Therefore, the current research objective is to solve the problems in existence in Jinan, so as to determine the existing landscape ecological risks and optimize the landscape structure. Using 2 m high-resolution remote sensing images and related natural economic data, this study evaluated the landscape ecological risk and constructed a full-factor ecological network in Jinan with a landscape ecological risk assessment method (ERI) and a minimum cumulative resistance model (MCR) based on landscape ecology theory. The results showed that: (1) The ERI in Jinan presented a spatial concentration of high value areas in the central and central–eastern regions, while other levels in ERI areas presented a spatial distribution around the ecological regions with high risk. (2) The important corridors were mainly distributed in the south of Jinan, which were stable and not easily destroyed. The corridors in other areas were secondary, mainly passing through cultivated land and urban greenways, which were unstable and susceptible to interference.

Keywords: landscape ecological risk assessment; ecological source; ecological network; minimum cumulative resistance; landscape pattern

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1. Introduction

With the rapid development of urbanization, ecosystem structures, functions and processes have been strongly disturbed, resulting in increased ecological risks, reduced ecological connectivity and the fragmentation of ecological networks [1–3]. How to preserve the stability and connectivity of ecosystems in the processes of social and economic development has become an urgent issue for regional sustainable development. The ecological risk assessment can indicate environment vulnerability from outside the ecosystem [4], and ecological network optimization can strengthen the guidance for the allocation of regional ecological resources. Ecological risk assessment and ecological network optimization not only play a key role in ensuring regional ecological security, but have also become hot issues in the construction of ecological civilization.

As an important branch of ecological risk assessment, landscape ecological risk assessment relies on landscape ecology to measure the possibility of regional-scale ecosystems being threatened by external factors [5,6]. Landscape ecological risk assessment can reflect the adverse ecological impacts of external disturbance on the ecosystem, and provide guidance for ecosystem functions and health maintenance [7]. Two methods have been commonly used for landscape ecological risk assessment: the source–sink method and landscape pattern index method. However, the overall assessment effect of the former was relatively poor, especially for risk assessment in areas with obvious stress factors (such as agricultural non-point source pollution) [8,9]. The landscape pattern index method could quantitatively express the structure and function of an ecosystem, which had advantages in reflecting the structural composition and spatial configuration characteristics of a landscape [10–12]. Based on the relation between landscape pattern and ecological risk in an ecosystem, the landscape model of ecological risk index was established using the landscape pattern index, which could comprehensively consider the ecological characteristics of the landscape. However, in the process of ecological risk assessment, the landscape vulnerability index generally adopted the scoring method, which had great subjectivity [13]. In view of the limitation of the current subjective and qualitative methods, it was necessary to explore the selection and weighting of factors in an objective and quantitative way. Geographic detectors could provide a more effective way to quantify the weight of the landscape vulnerability index [14].

At present, there is no unified standard for the concept of the ecological network. From the perspective of landscape ecology, the ecological network is based on the theory of landscape connectivity. In an environment that can communicate with the outside world, ecological networks connect ecological land (ecological source) through ecological corridors [15,16]. It can be used to maintain the integrity of regional ecosystem functions and landscape patterns. The ecological network is a multilevel and complete network structure composed of various landscape elements through spatial connections [17]. The construction and optimization of the ecological network based on the interactions among the ecological processes and landscape patterns can effectively provide the scientific basis for the rational allocation of resources and reduction in ecological risks. The basic paradigm of ecological network construction is mainly divided into three parts, namely, ecological source identification, resistance surface construction and corridor extraction. Some scholars directly used natural reserves or forest parks as ecological sources only from the perspective of the importance of the ecosystems [18], while others used Morphological Spatial Pattern Analysis (MSPA) to extract the source from the perspective of patch connectivity [19]. These two methods could not comprehensively consider patch ecological value and connectivity. Based on the goals and principles of comprehensively improving the function of ecosystem services and landscape connectivity, the combination of ecosystem services value and landscape connectivity was more conducive to ecological source recognition.

In most studies, the construction of a resistance surface was generally composed of land-use type, elevation, the Normalized Difference Vegetation Index (NDVI) and other factors, while the external disturbance intensity and internal resistance of the ecosystem were ignored [20]. Using landscape ecological risk to optimize the resistance surface could greatly improve its effectiveness. For the construction of the ecological network, the research methods have gradually shifted from qualitative analysis to quantitative construction. The MCR model [21], current theory model [22], gravity model [23] and graph theory method [24] were usually used to extract ecological corridors. According to the different research purposes, the construction of ecological networks could be based on a single element, such as green spaces and waters, or on various ecological elements [25–27]. Most of the existing ecological networks were established on single-factor ecological networks. These studies were more concentrated on urban planning, and lacked research on other areas outside the city [28]. In addition, ecological network optimization was mainly used to make the network structure more complex and complete by adding ecological sources and ecological corridors [29]. These optimizations could improve the anti-interference ability of the ecological network to a certain extent, in which stepping stones played an important role in the process of optimization [30]. Therefore, this paper aimed to clarify the overall ecological situation in the study area from the perspective of a network by constructing a full-factor ecological network and optimizing the network according to the stepping stones.

As the only megacity in the lower reaches of the Yellow River in Shandong Province, Jinan is the leader in high-quality development and the growth pole of the new kinetic economy, which puts forward higher requirements for its development. Jinan has better ecological conditions due to its unique geological conditions and suitable climate. However, with the expansion of urban areas, the cropland and grassland are gradually decreasing. The cropland and grassland are mainly converted into urbanized land and garden land, while the cropland and grassland in the southern mountainous areas are converted into forestland and garden land [31]. The frequent conversion of land-use types has also affected the ecology of Jinan, resulting in the fragmentation and reduction in ecological land. Therefore, based on the theory of landscape ecology and using high-resolution images to organically combine ecological risk assessment and ecological networks, this study focuses on Jinan as the research area. The following questions were studied: (1) How can the spatial characteristics of urban-scale landscape ecological risk be effectively quantified? (2) How can ecological networks be scientifically constructed and optimized to improve the stability and connectivity of the network? The results provide scientific references for ecosystem management and regional planning.

2. Materials and Methods

2.1. Overview of the Study Area

Jinan, the capital of Shandong Province, is located at E116°11′~117°44′, N36°01′~37°32′ (Figure 1), with an average elevation of 57.8 m. According to the Jinan Statistical Yearbook 2021, the GDP of Jinan reached CYN 1014.09 billion in 2020, and all industries have varying degrees of growth compared to last year.

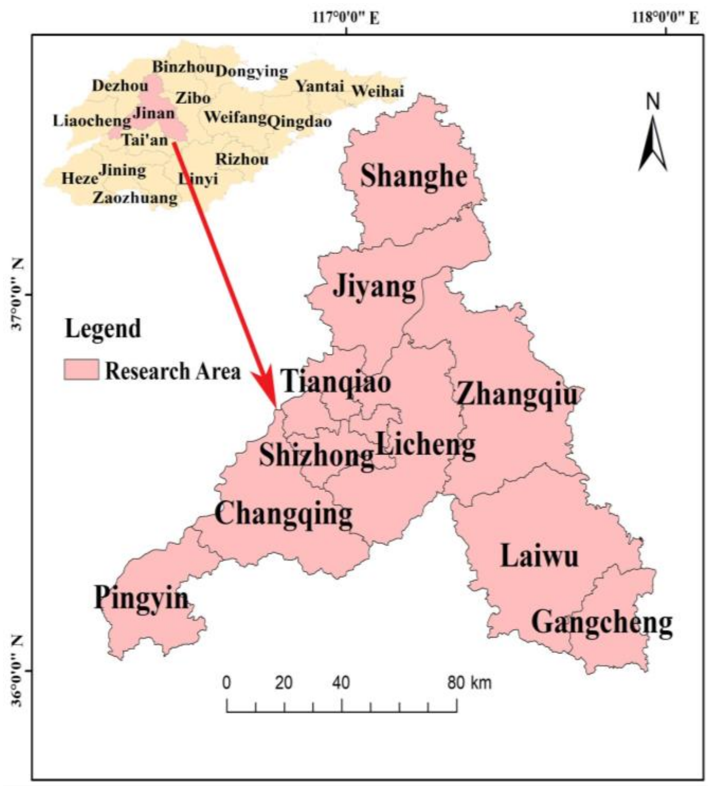

Figure 1. Study Area.

2.2. Materials

Based on high-resolution satellite images, seven types of land use were obtained by relevant pre-processing and interpretation (as shown in Figure 2). Other data sources are shown in Table 1. Distances from city center, attractions, highway, railroad and water bodies were obtained using Euclidean distance calculations based on city center, location of attractions, highway data, railroad data and river water bodies. Thematic maps were made using ArcGIS10.3.

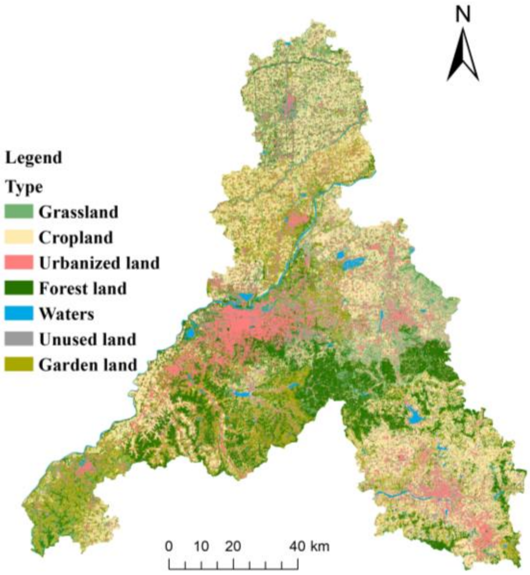

Figure 2. Land-use type.

Table 1. List of data used for the study.

No.	Type of Data	Source
1	Three levels of administrative divisions vector data	Sky Map—Shandong Province: Geographic Information Public Service Platform (http://www.sdmap.gov.cn/) accessed on 9 January 2022
2	City center location vector data	
3	Spot location vector data	
4	Highway vector data	
5	Railroad vector data	
6	Elevation data 10 m raster data	CAS Resource and Environmental Science and Data Center (https://www.resdc.cn/) accessed on 9 January 2022
7	NDVI1 km raster data	
8	Water body vector data	Open Street Map SiteWorldPop Site (https://www.worldpop.org/) accessed on 13 January 2022
9	Population density 1 km raster data	
10	Annual average precipitation 1 km raster data	European Centre for Medium-Range Weather Forecasting(https://www.ecmwf.int/) accessed on 16 January 2022
11	Soil data 1 km raster data	National Science and Technology Resources Sharing Service Platform-National Earth System Science Data Center-Soil Sub-center [32] (http://soil.geodata.cn) accessed on 13 January 2022
12	Net Primary Productivity (NPP) 500 m raster data	MOD17A3HGF data from MODIS(https://search.earthdata.nasa.gov/) accessed on 16 January 2022
13	Soil erosion volume data 25 km raster data	European Soil Data Center (ESDAC)(https://esdac.jrc.ec.europa.eu/) accessed on 16 January 2022
14	Jinan City Statistical Yearbook	Jinan City Bureau of Statistics (http://jntj.jinan.gov.cn/) accessed on 16 January 2022

2.3. Methods

In view of the theory of landscape ecology, a landscape ecological risk assessment model based on landscape index was constructed. Ecological risk assessment results (obtained using Kriging interpolation of landscape pattern index) and landscape types were chosen as the main factors that constituted the comprehensive resistance surface. Then, the MCR model was used to construct and optimize the ecological network. The specific process is shown in Figure 3.

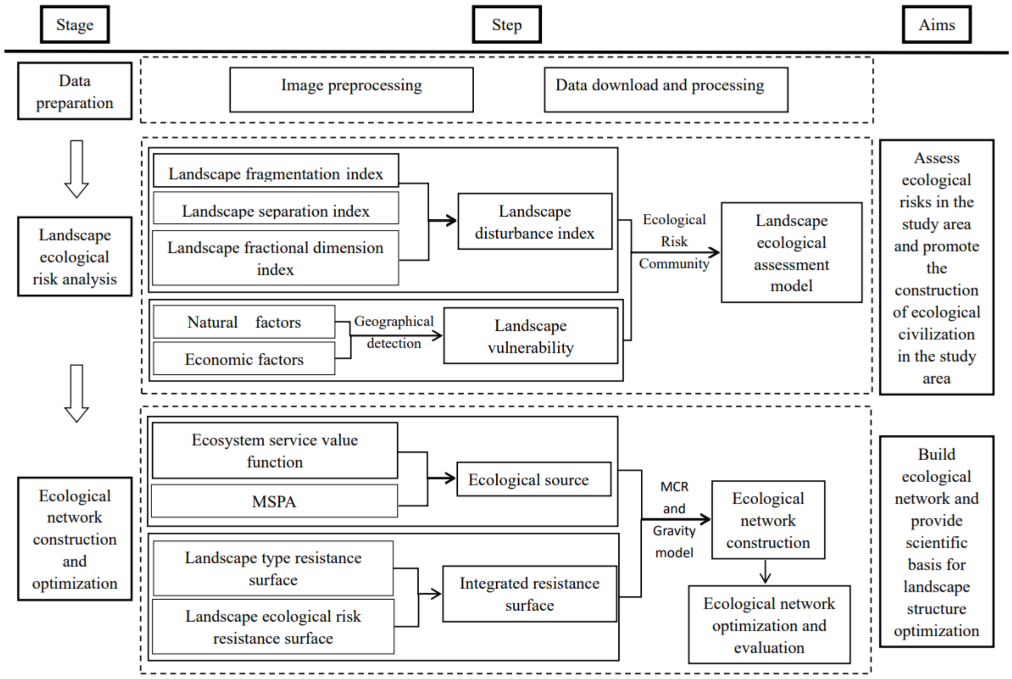

Figure 3. Flow diagram of ecological network construction and optimization.

2.3.1. Landscape Ecological Risk Assessment Model

In this study, based on the landscape fragmentation index (C_i), the landscape separation index (D_i) and the landscape fractional dimension index (F_i), the degree of landscape disturbance (S_i) was constructed. In addition, ecosystem impact factors were introduced to quantify landscape vulnerability (E_i). Finally, the landscape ecological risk assessment model was built based on S_i and E_i. The formula is as follows:

$$ERI_k = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} \times S_{ki} \times E_k \quad (1)$$

In this formula, ERI_k is the ecological risk value of the k-th ecological risk community; n is the number of different landscapes; i is the i-th landscape type in the study area; A_{ki} is the area of landscape type i in the k-th ecological risk community (ha^2); A_k is the total area of the k-th ecological risk community (ha^2); S_{ki} is the degree of landscape disturbance in landscape type i in the k-th ecological risk community; E_k is the landscape vulnerability of the k-th ecological risk community.

The patch was a spatial entity that was different in nature or appearance from the surrounding environment [33]. When dividing the ecological risk plots, not only should the accuracy and intensity of calculation be considered, but the conditions for ensuring that the area can fully reflect the distribution law of the landscape pattern should also be considered [34]. To the end, this study used the specifications of 2500 m × 2500 m to divide 1600 ecological risk plots.

2.3.2. Landscape Disturbance Index

The landscape disturbance index (S_i) can reflect the ability of the class i landscape to resist external disturbances (mainly human activities) [35]. Referring to existing studies, this paper selected the landscape fragmentation index (C_i), the landscape separation index (D_i) and the landscape fractional dimension index (F_i) to construct the landscape disturbance index [36]. The formula is as follows:

$$S_i = aC_i + bD_i + cF_i \tag{2}$$

In this formula, C_i is the landscape fragmentation index of landscape type i; D_i is the landscape separation index of landscape type i; F_i is the landscape fractional dimension index of landscape type i. Referring to previous studies, the weights a, b and c of the above three indices were 0.5, 0.3 and 0.2, respectively [36]. To avoid the impact of different dimensions, the results of the above three landscape indices were normalized. Each landscape index was calculated using FRAGSTATS software.

The landscape fragmentation index (C_i) refers to the degree of landscape fragmentation caused by external damage. It can also describe the degree of fragmentation of a landscape or ecosystem after human activities and natural disturbances [37]. The formula is as follows:

$$C_i = \frac{n_i}{A_i} \tag{3}$$

In this formula, n_i is the number of patches in landscape type i; A_i is the area of landscape type i. When the area of landscape type i is certain, the more patches in the range of the landscape type, the greater the landscape fragmentation index, and the more fragmented the landscape type.

The landscape separation index (D_i) is used to describe the degree of spatial dispersion of patches in a landscape type. The larger the Di, the greater the dispersion of patches in a landscape type, and the faster the succession between this landscape type and other landscapes [38]. The formula is as follows:

$$D_i = \frac{1}{2} \times \sqrt{\frac{n_i}{A}} \times \frac{A}{A_i} \tag{4}$$

In this formula, A is the sum of the areas of each landscape type; n_i is the number of patches in landscape type i; A_i is the area of landscape type i.

The landscape fractional dimension index (F_i) can reflect the degree of shape change of a landscape after external interference and the impact of human activities on the landscape [39]. The formula is as follows:

$$F_i = \frac{2In(\frac{P_i}{4})}{InA_i} \tag{5}$$

In this formula, P_i is the perimeter of the landscape i in the study area; A_i is the area of landscape type i.

2.3.3. Landscape Vulnerability Index

Landscape vulnerability (E_i) indicates sensitivity to external disturbances, such as human activities and natural disasters [40]. A total of 11 quantitative natural and economic factors were selected in this study. Various factors were correlated with vulnerability through land-use types, and the landscape vulnerability index was calculated quantitatively. The geographic detector can reflect both linear and nonlinear correlation between the dependent variable Y and the independent variable X, taking into account the spatial consistency of the two variables [41]. This study analyzed the correlation between 11 natural and economic factors and vulnerability using the factor detection of geographic detectors (geographic detectors include factor detection, interaction detection, risk detection and ecological detection), which provided a scientific basis for factor weight assignment.

This result showed that the correlation between urbanized land and ecological vulnerability was the most significant [42]. Grassland, forest land, garden land, waters and cropland were classified as low-vulnerability sensitive areas, while urbanized land and unused land were classified as high-vulnerability sensitive areas. In addition, the spatial distribution of sensitive and non-sensitive areas was used as the dependent variable Y, and 11 selected factors were used as the independent variables X. Based on several experiments at different scales, the optimal scale was determined as 7000 m. Each independent variable X was divided by the natural breakpoint method to ascertain the optimal number of classes based on values of q and p. The q value was used to measure the spatial scale effect, and the p value was used to measure the data classification effect. The results are shown in Table 2.

Table 2. Weight assignment based on Geodetector.

Type	q	p	Classification	Weights
Water bodies	0.045	0.101	5	0.05
NDVI	0.361	0.000	7	0.40
DEM	0.065	0.051	7	0.07
Slope	0.047	0.049	5	0.05
Population density	0.156	0.017	6	0.17
Railroad	0.036	0.112	5	0.04
Highway	0.057	0.065	5	0.06
Cities and towns	0.143	0.000	6	0.16

2.3.4. Identification of Ecological Sources

The ecological sources were continuous in the landscape, which were stable patches with high ecosystem service function [43]. This study selected the ecological sources by calculating the ecosystem service value and the accessibility of the patches, which not only considered the spatial form of patches, but also supplemented the patches with important ecological functions through the ecosystem service value.

On the one hand, this study adopted the ecosystem service value equivalent factor method proposed by Xie Gaodi to measure the ecosystem service function in the study area [44]. The ecosystem value of each land-use type in the study area was calculated using this method, so as to extract the patches with higher ecosystem service functions as the ecological sources (as shown in Figures 4 and 5).

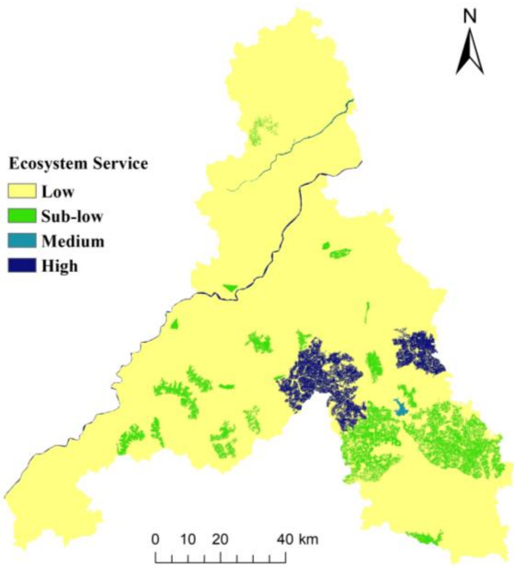

Figure 4. Ecosystem service value.

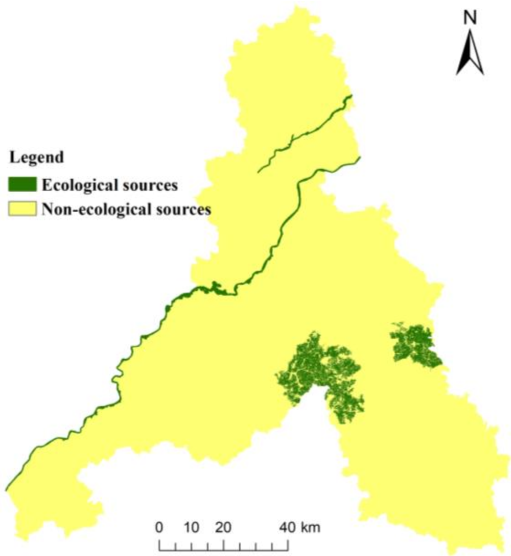

Figure 5. Ecological sources based on the value of ecosystem services.

On the other hand, this study used MSPA to extract ecological sources by considering the connectivity and location structure of patches. MSPA recognized and classified images based on their geometric features through mathematical operations, which could spatially reflect the location structure and connectivity of images [45]. Grassland, forest land and waters were used as the foreground in MSPA analysis. Cropland, garden land, urbanized land and unused land were used as the background. The core area was extracted according to the size of the patches in the foreground elements. Then, the Probability of Connectivity (PC) of the top 50 core area patches was calculated (see Table 3). Finally, the ecological source land was extracted according to the connectivity index and area of patches (see Figure 6).

The sources extracted based on MSPA were mainly concentrated in the south of Jinan; while four ecological sources were extracted based on the ecosystem service value equivalents method, located in both the north and south of the study area. The ecological sources extracted based on the two methods were integrated together. In addition, considering the flow direction of the Yellow River from west to east, the whole study area was divided into two parts: north and south. In order to facilitate communication between these two parts, the Yellow River and the Tuhai River were finally selected as ecological sources. The ecological sources in the study area are shown in Figure 7.

Table 3. Calculation results of landscape connectivity in the core area.

No.	Patch No.	PC [1]
1	186577	86.07
2	164998	35.13
3	163885	32.64
4	190157	12.76
5	150146	8.10
6	191225	7.88
7	185126	4.94
8	202848	4.41
9	177507	1.28
10	182721	1.15
11	260725	1.00
12	263305	0.97
13	174919	0.78
14	220720	0.70
15	262934	0.18

[1] Calculate the likelihood of connectivity between patches.

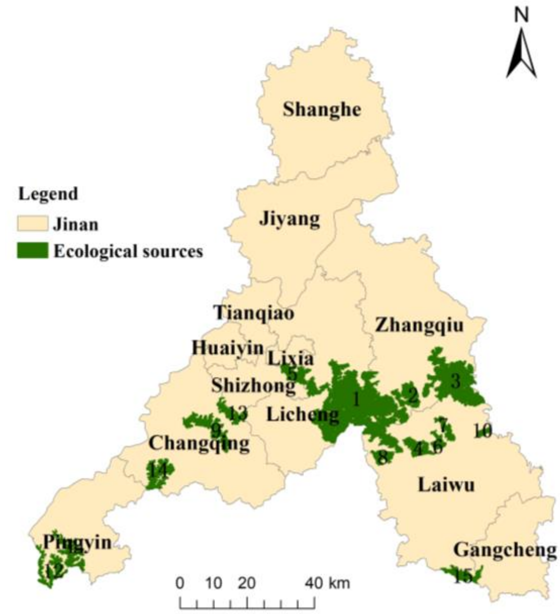

Figure 6. Ecological sources based on MSPA.

Figure 7. Ecological sources in the study area.

2.3.5. Comprehensive Resistance Surface Construction

The resistance surface refers to the resistance that needs to be overcome in the process of material flow in the ecosystem [46]. Different landscapes resulted in different resistances, as shown in Table 4. In addition, ecological risk reflected the degree of loss in the ecosystem after external interference. The assignment ranges of ecological risk index are shown in Table 4. Based on the two kinds of factors, this paper constructed a comprehensive resistance surface. The weight of land-use type was 0.6 and ecological risk index was 0.4. The results are shown in Figure 8.

Table 4. Landscape type and ecological risk index assignment table.

Landscape Type	Resistance	Ecological Risk Level	Resistance
Forest	1	Low	1
Grass	20	Lower	10
Gardens	30	Medium	30
Crops	40	Higher	80
Water	60	High	100
Unused land	80		
Construction	100		

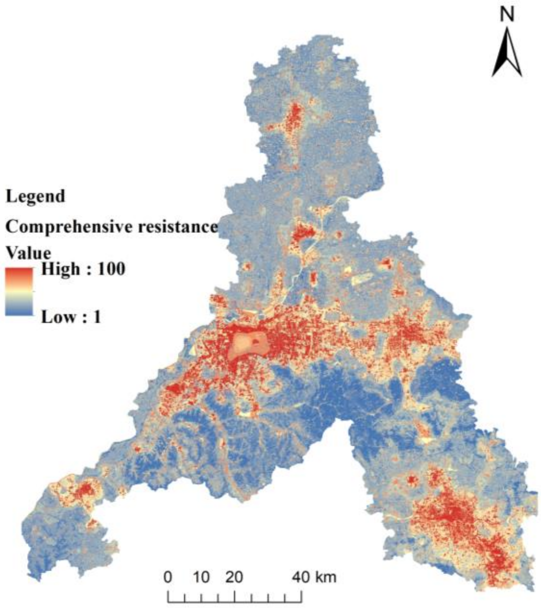

Figure 8. Spatial distribution of comprehensive resistance.

2.3.6. The Minimum Cumulative Resistance

The *MCR* model can identify the path with the least resistance cost between different sources based on the patch–corridor–matrix pattern. It is a comparatively good method for extracting potential ecological corridors because it can simultaneously consider the impact of various natural and human activities. It is widely used in the field of simulating ecological corridors [47]. The calculation formula is as follows:

$$MCR = \int_{\min} \sum_{j=n}^{i=m} G_{ij} \times E_i \quad (6)$$

In this formula, G_{ij} is the distance between patches i and j; E_i is the size of the diffusion resistance of the landscape.

2.3.7. The Gravity Model

The gravity model can calculate the mutual attraction between different ecological sources. Animals can migrate more smoothly in ecological corridors with greater mutual attraction. The gravity model is often used for ecological corridor classification [48]. The calculation formula is as follows:

$$G_{ab} = \frac{H_a H_b}{L_{ab}^2} = \frac{F_{\max}^2 \ln(S_a) \ln(S_b)}{F_{ab}^2 R_a R_b} \quad (7)$$

In this formula, G_{ab} is the interaction force between patches a and b; H_a and H_b are the quantitative weights of patches a and b; L_{ab} is the resistance value of the corridor extracted between patches; F_{max} is the largest value of resistance; S_a and S_b are patch areas; F_{ab} is the resistance value between patches; R_a and R_b are the resistance values.

2.3.8. Ecological Network Structure Evaluation Indicator

In this paper, the network loop degree closure index (α index), line point rate (β index) and network connectivity index (γ index) were used as indicators to evaluate the ecological network before and after optimization. Larger values of α indicate more loops (the ring structures in the network are loops) in the network; $\beta > 1$ indicates a more complex level of connectivity; $\gamma = 1$ indicates that every node in the network is connected with each other with the highest level of network connectivity [49].

$$\alpha = \frac{L - v + 1}{2v - 5} \tag{8}$$

$$\beta = \frac{L}{v} \tag{9}$$

$$\gamma = \frac{L}{3(v - 2)} \tag{10}$$

In this formula, L is the number of corridors; v is the number of nodes.

3. Results

3.1. Landscape Ecological Risk Assessment

In this study, the spatial distribution of ecological risk was acquired using ordinary Kriging interpolation. The ecological risk index was divided into five levels based on the natural breakpoint method. The results are shown in Figure 9.

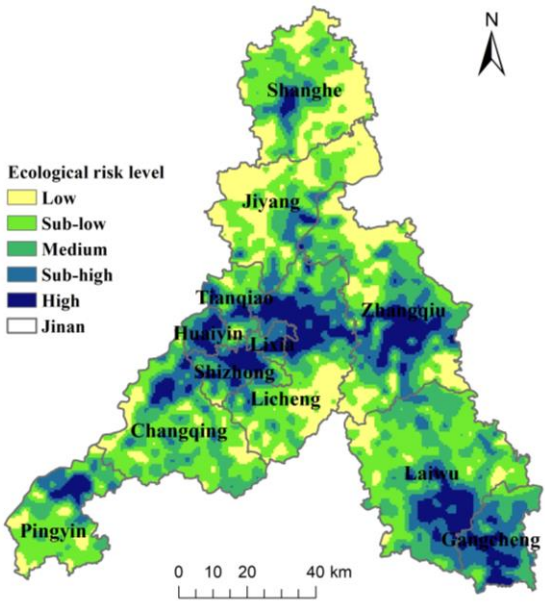

Figure 9. Spatial distribution of ecological risks.

The high ecological risk areas and sub-high ecological risk areas were mainly distributed in the central, central–eastern and southeastern parts of the study area, central Shanghe and some parts of Pingyin. These areas suffered fragile landscapes and high levels of ecological risk because they were mostly urban landscapes. The medium ecological risk areas were mainly concentrated around the high ecological risk areas and sub-high ecological risk areas. Under the influence of urban development, there was no large area of land for urbanization in these areas. However, as the transition zones between cities and other areas, these areas were still ecologically fragile due to the concentrated arable land and roads. After the preliminary ecological risk assessment of the study area, an ecological network was constructed based on the ecological risk assessment results, and the landscape pattern of the study area was studied in detail.

3.2. Ecological Network Construction Analysis

3.2.1. Ecological Corridor Extraction

Ecological corridors refer to the landscape units with a channel function in the landscape, which could connect the sources, facilitate the flow of material and energy and promote biological migration and diffusion [50]. Based on the sources and comprehensive resistance surfaces, potential ecological corridors were simulated using the MCR model. A total of 136 potential ecological corridors were calculated through a pairwise calculation among the 17 ecological sources, of which 101 were duplicated and 35 were calculated in the study area.

The gravity model was used to calculate the interaction force between two sources to extract the important corridors. In this study, corridors with gravity model calculation results greater than 100 were selected as the first-level corridors, and the rest as the second-level corridors. Ecological nodes, which were generally fragile but critical to the flow of material energy in the landscape, were identified based on the situation of the corridors [31,51]. A total of 27 ecological nodes were extracted, including 17 first-level nodes and 10 second-level nodes, to jointly construct the ecological network of the study area, as shown in Figure 10.

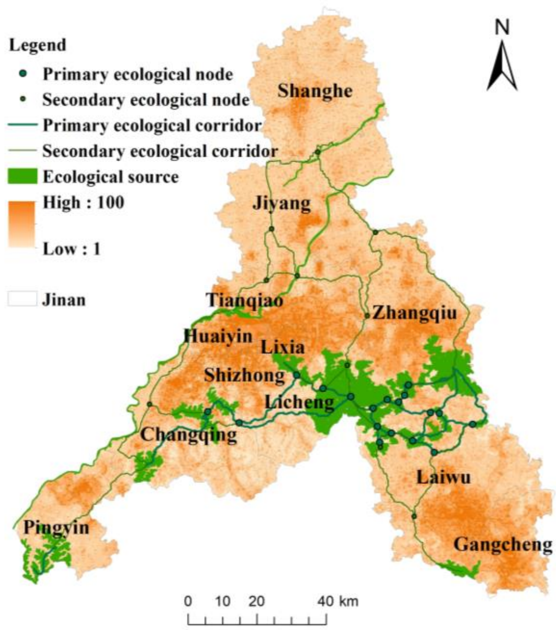

Figure 10. Spatial distribution of ecological network.

The primary ecological corridors and ecological nodes were mainly distributed in Changqing, Licheng and the southern part of Laiwu. With concentrated ecological sources and the landscape dominated by forest, these areas should be well protected for the ecological environment of the study area. Other secondary ecological corridors were mainly distributed at the edge of Jinan, far from the main urban areas of Jinan and the areas with relatively large building coverage.

Both the quality and quantity of the sources and corridors in the south were much better than that in the north. There were no sources and corridors in Shanghe and the main urban area. Significant differences between the sources and corridors were not conducive to the development of ecosystems. Therefore, for the ecological health and sustainable development of the study area, it was necessary to optimize the ecological network to maintain the regional ecological health.

3.2.2. Ecological Network Optimization

There is no unified standard for ecological network optimization, but the stability of the network can be improved by increasing the number of corridors and building a multi-level network, to achieve the optimization effect. The optimization method includes identifying ecological addition points, obstacle points and adding stepping stones. Adding stepping stones can strengthen the connection between the local and the whole, and improve the integrity [29]. Therefore, this study optimized the ecological network by adding stepping stones.

Given the uneven distribution of ecological sources and ecological corridors, stepping stones were introduced in this study to enhance the north–south ecological communication [52]. With reference to Jinan and Laiwu in the ecological red line of Shandong Province in 2021, the remaining core areas and patches with high ecological service value, such as the Changbai Mountain Range in eastern Zhangqiu, Qishan National Forest Park in Laiwu District, Daming Lake, the Baiyun Lake scenic area and the northern reservoir in Shanghe County, were used as stepping stones to optimize the ecological network and landscape pattern (see Figure 11).

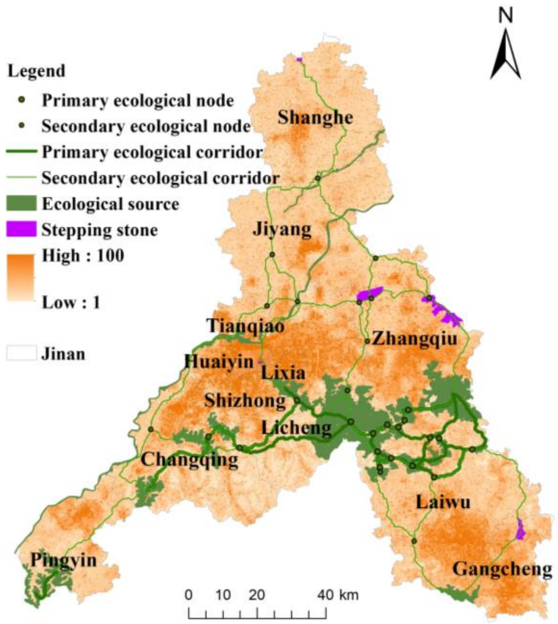

Figure 11. Optimized ecological network.

The area of the stepping stones was smaller than that of the other ecological sources. The fragmentation degree of woodland stepping stones was high and needs to be improved in the future. The land around the water stepping stones was mainly arable land and urbanized land, which seriously destroyed the ecological functions of the three water stepping stones. Therefore, it is necessary to strengthen the environment construction around the three stepping stones in future regional planning. The new ecological corridors can be incorporated into the ecological network as secondary corridors.

A total of 48 ecological corridors were constructed through the optimized ecological network, including 17 primary corridors and 29 secondary corridors. In addition, 30 ecological nodes were identified, including 17 primary nodes and 13 secondary nodes. The optimized ecological network was conducive to the north–south exchange of material and energy, together with the stabilization of the landscape pattern in the entire study area.

3.2.3. Ecological Network Structure Evaluation

As shown in Table 5, after the optimization of the sources, the total length of the ecological network rose by 212.88 km, which would not only increase the number of channels for material and energy flow and exchange in the study area, but also make the ecological sources more closely linked. After optimization, three increased indices showed that the number of loops increased, the network became more complex and the connectivity of the network was improved.

Table 5. Calculation results of ecological network structure indicators before and after optimization.

Index	Before Optimization	After Optimization
Total length of the corridor/km	1398.21	1611.09
α	0.24	0.36
β	0.30	0.60
γ	0.47	0.57

4. Discussion

4.1. Spatial Heterogeneity of Ecological Risk

The spatial distribution of ecological risk revealed that the ecological risk levels were higher in areas with dense urbanized land and also a disorderly distribution in various types of land, while the ecological levels were lower in areas with relatively high vegetation cover, and also a stable and orderly landscape structure. Natural factors affect the distribution of natural landscape types, which have different sensitivities to external disturbances. Urban areas belong to the landscape types with high ecological sensitivity and vulnerability, which are easily disturbed by human activities, and the ecological loss is relatively significant [53]. The southern mountainous areas belonged to the landscape types with luxuriant vegetation and good landscape integrity. High vegetation coverage and low human disturbance provides a good habitat for biological survival, foraging and reproduction, and maintains a high level of biodiversity [54]. The luxuriant vegetation is also an important carbon sink, and the root system of the vegetation also has the function of soil consolidation and water conservation at the same time, maintaining the stability of the ecosystem [55]. Therefore, in order to reduce the ecological risk level, the urban development of the study area should be planned in advance, and should continue to enhance the protection of the southern mountainous areas and other areas with lower ecological risk.

4.2. The Optimization of Ecological Network

The effectiveness of the implemented methodologies and the practical guiding significance for ecological protection are discussed in this section. Ecological sources are key components of ecological networks, and most research studies of ecological source identification were performed either by evaluating a single ecological index or simply by selecting nature reserves, scenic spots and habitats for a certain species. Only a certain scale of ecological sources can provide stable and sustainable ecosystem services [56]. In this study, the ecosystem services value and landscape connectivity were given priority to effectively identify ecological sources. The stepping stones provided a novel approach for enhancing the north–south ecological communication from the perspective of structural connectivity. The ecological resistance surface was the most fundamental component of corridor extraction and reflected the degree of difficulty in species movement. The scientific reference value of the ecological network construction was improved by integrating landscape ecological risk into the ecological resistance surface establishment process.

The construction of an ecological network provides important references for ecological protection and restoration [57,58]. First, strengthening the protection of ecological sources is key to improving the stability of ecological security. The southern mountainous areas are important ecological barriers for Jinan city. The overexploitation of natural resources should be prohibited in mountainous areas, and reforestation and afforestation should be given increased attention. The key ecological patches within the ecological red line are important stepping stone for species migration and movement. Therefore, it is necessary to avoid the disordered expansion of cities and the occupation of ecological land for construction. The Yellow River provides important compositions of ecological sources and connects the western and eastern regions, so the maintenance of its ecological connectivity should be strengthened. The construction of ecological corridors can connect ecological sources to improve ecological connectivity. It is necessary to maintain and increase the ecological land within the corridors to enhance their internal connectivity and cohesion.

Ecological network optimization can improve the overall connectivity of the network and promote regional material and energy exchange by restoring broken patches [59]. Therefore, the ecological network can be optimized by improving corridors and nodes [60]. This study optimized the ecological network based on the optimization of corridors. Qi et al. found that the ecological network can be improved by adding stepping stones [61]. In order to strengthen the connection between north and south, and strengthen the connection between the part and the whole, the method of adding stepping stones was adopted in this study to optimize the ecological network. By adding stepping stones to increase the corridors, the ecological network becomes more complex and stable. Most of the optimization methods are completed by adding ecological sources, and the network can also be adjusted according to relevant planning to achieve the optimization effect [62,63]. From the perspective of ecological protection, the method of adding stepping stones can avoid the areas with a high density of urbanized land and avoid the interference of economic construction on ecological sources, which is more in line with the needs of this study.

4.3. High-Resolution Scale Effect

The research based on a high-resolution scale was more accurate in sources selection, compared with similar studies in the same region [31]. The garden land was transformed by human beings, which was quite different from the forest land, and the ecosystem is damaged [64]. The garden land was not suitable as a source. Using a high-resolution scale, the impact of the garden land could be excluded as much as possible, so the resulting network was more accurate. A high-resolution scale could optimize the network construction, making the network more detailed and accurate.

The scale effect has always been a key issue in landscape ecology [65]. Different scales result in different outcomes for source recognition and corridor extraction. How to overcome this scale effect has become a difficult and hot topic for many scholars. Therefore, future research can build ecological networks at different scales, and further explore the impact of the scale effect on the construction of ecological networks by comparing the similarities and differences in ecological networks at different scales. This study was an application of a high-resolution scale in Jinan. Through the feedback of the research results, it was found that the ecological network constructed at the 2 m scale was more accurate. However, whether a high-resolution scale is valuable for large-scale research needs further study.

4.4. Limitations and Future Research Directions

In order to reduce the subjectivity and improve the landscape ecological risk assessment model, this paper introduced the geographical detector to determine the weight when calculating the landscape vulnerability index, and carried out a quantitative calculation according to the index. However, in terms of the weight calculation, only the geographical detector method was attempted. In order to make the calculation results more accurate, other methods should be tested. The selected indicators only considered eight natural and economic factors, without considering other factors, such as policy factors. There were deficiencies in the selection of the indicators. In future research, the selected indicators should be more comprehensive.

In this study, the assessment of landscape ecological risk was achieved by quantifying landscape patterns through landscape indicators. However, the landscape indicators were largely unable to quantify the landscape patterns well [66]. Boltzmann entropy has been widely applied in the field of landscape ecology, with the main research focusing on spatial heterogeneity, unpredictability of pattern dynamics and pattern scale dependence [67,68]. Recently, Boltzmann entropy has made progress in computing landscape. Based on landscape gradients, this method can sensitively characterize the structure of the landscape [69]. Therefore, Boltzmann entropy should be introduced into landscape ecological risk assessments in future research, and the risk assessment model should be further optimized by discussing the effects of the existing methods with Boltzmann entropy methods.

With the limitation of the available high-resolution data, this paper only assessed the landscape ecological risks in Jinan in 2019. The impact of spatial changes in land use/cover on ecological risk assessment should be considered. Long-term change in landscape ecological risk could be helpful to further understand where the regional ecological quality is improving and where it is declining.

The study of network optimization remains at the experimental stage. The extracted sources and the construction network should be surveyed on the spot, and the value of the sources and corridors should be measured according to the actual situation. The ecological network could be further optimized and become more practical. This would make the research results more in line with the needs of the planning department.

5. Conclusions

This study analyzed landscape ecology risk and constructed and optimized an ecological network based on 2 m high-resolution remote sensing images, together with different kinds of data in the Jinan study area. The main conclusions of the paper are as follows:

(1) The ecological risk in the study area was spatially clustered in the central, northern, southwestern and southeastern urban areas. One of the low-value areas was inside the high-value areas in the middle of the study area, indicating that the ecological risk would be reduced after the long term and stable development of the urbanized land. Therefore, the landscape ecological risk index was more susceptible to the areas where the landscape type changed frequently in the short term.

(2) By constructing an ecological network in Jinan, it was found that the large ecological sources and important ecological corridors were mainly concentrated in the south of Jinan, showing a state of uneven distribution from north to south. To optimize the result, stepping stones were introduced. However, the landscape types of the newly added ecological corridors were mainly cultivated land and urban greenways. This situation made the ecological corridors very fragile and vulnerable, requiring a long-term protection plan for the harmonious coexistence of humans and nature.

(3) Building an ecological network at a high-resolution scale could accurately reflect the surface conditions on the one hand. On the other hand, the high spatial resolution resulted in a high heterogeneity of the image pixels, which resulted in high fragmentation of the patches to a certain extent, affecting the ecological risk assessment and ecological network construction. Therefore, the selection of an appropriate scale has a great impact on the "patch–corridor–matrix" model, and relevant research should be carried out in the future.

(4) In this study, the Tuhai River was chosen as an ecological source. In fact, the construction of ecological corridors in Jinan also regarded it as a key governance goal. The actual construction was consistent with the results of this study, which proved that this study had practical significance and could better connect with key projects. In order to further accelerate the construction of the ecological network and solve the problems of the broken ecological sources and unstable corridor landscape composition, the ecological source areas in the southern mountains and northern lakes should be protected to increase the area of the ecological sources. Relevant departments should pay attention to returning farmland to forests and strengthen the construction of ecological corridors. Jinan should focus on improving biodiversity, actively connecting with the ecological green corridor along the river, and create a "green ecosystem".

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