Article

Identification and Optimization of Ecological Network in Arid Inland River Basin Using MSPA and Spatial Syntax: A Case Study of Shule River Basin, NW China

Jinghu Pan 1,*, Yimin Wang 1 and Zhao Zhang 2

1 College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China
2 College of Urban and Environmental Sciences, Northwest University, Xi’an 710127, China
* Correspondence: panjh_nwnu@nwnu.edu.cn

Abstract: Habitat fragmentation has become an important factor in the reduction of biodiversity. Identifying and optimizing ecological networks (ENs) can help alleviate the negative impact of habitat fragmentation and improve regional biodiversity. Taolai River Basin is an inland river basin in Northwest China. Due to the impact of climate change and human activities, there are many ecological problems such as grassland degradation and shortage of water resources. It is urgent that we identify and optimize the EN. This study comprehensively uses morphological spatial pattern analysis (MSPA), the minimum cumulative resistance model (MCR), and circuit theory to identify ENs, evaluates ENs based on Spatial Syntax, and determines the protection priority of ENs, then diagnoses ecological “pinch points” and ecological obstacles by combining remote sensing and GIS spatial analysis methods. The results show that: (1) the ecological source area of the basin is 3061.63 km², with uneven spatial distribution, mainly distributed in the Qilian Mountains in the south of the basin; (2) there are 106 ecological corridors in the basin, with a total length of 2267.30 km and an average length of 21.38 km, which is not conducive to species migration; (3) the optimum widths of ecological corridors in the south, middle, and north of the basin are 100 m, 60 m, and 300 m, respectively; (4) the key areas of watershed ecological restoration include the “pinch area” between the southern core area and the central core area and 108 ecological barrier points; and (5) combined with the spatial characteristics of various key areas of ecological protection and restoration, the spatial pattern of “one core—four rings—five belts” of watershed EN construction is obtained.

Keywords: ecological network; landscape connectivity; morphological spatial pattern analysis (MSPA); spatial syntax; Taolai River Basin

1. Introduction

Biodiversity refers to the diversity among various living things, including aquatic (marine and inland waters) and terrestrial organisms, and the ecological complexes to which they belong, including within-species diversity, between-species diversity, and ecosystem diversity [1]. Biodiversity is currently under threat from several processes, including global warming and human activity [2]. Human activities (urbanization, agriculture, road infrastructure construction, etc.) have changed more than 75% of the global land area, and the resulting habitat loss and degradation are considered to be the main driving factors of biodiversity decline [3,4]. As a consequence of landscape modification, in addition to the reduction of habitat area, large areas of natural habitat are also divided into small patches, called habitat fragmentation. Previous studies have shown that habitat fragmentation reduces wild population size [4]. Landscape connectivity has a major positive impact on many ecological processes, such as animal migration, dispersal of plant seeds, the richness of regional species [5], and so on. Improving landscape connectivity within a region is considered an important study in the field of biodiversity conservation [5,6]. At present, measurement models of landscape connectivity are mainly based on theories of ecology.
and mathematics. According to their principles, they can be divided into graph theory, permeation principle, distance model, and so on. The model based on graph theory is the most widely used. Related software based on graph theory includes Guidos, Conefor Sensinode, Circuitscape, Zonation, Marxan, etc. [7].

The construction and optimization of the ecological networks (ENs) can effectively improve landscape connectivity [8]. The EN is an open system, which makes use of ecological corridors to organically combine different ecosystems in the landscape, forming a network system that is closely connected in space and structure, which can alleviate the negative impact caused by habitat fragmentation. The ENs can combine different landscape types organically, effectively improving the connectivity of regional landscape, which is conducive to the protection of biodiversity and can also provide a reference for determining the boundary of regional development [9]. EN identification has formed a research paradigm of “source identity–resistance surface construction–corridor identification” [10]. The identification of ecological sources has evolved from a simple selection of nature reserves, natural scenic areas, and habitats of key species, to a quantitative assessment of the importance of various ecosystem services, ecological sensitivity, stability, connectivity, etc. [11,12]. MSPA (morphological spatial pattern analysis) has been widely used to identify ecological sources and corridors [13]. The method emphasizes structure connection, and only depends on the data of land use. It takes forest land, wetland, water, and other natural ecological elements as the foreground, and other natural ecological elements as the background. A series of image-processing methods could be divided into seven categories of non-overlapping outlook (that is, the core, the bridge, the loop, the edge, the perforation, the branch, and the islet), then identify landscape types that are important for maintaining connectivity [14–16]. This method increases the scientific nature of the ecological sources and ecological corridor selection. The resistance surface reflects the migration difficulty of species between different ecological sources [17]. However, the current research fails to fully consider the landscape heterogeneity between different regions when constructing the resistance surface.

Among the many models used to simulate ecological corridors, the MCR (minimum cumulative resistance model) is the most widely used one, which serves for regional landscape planning and habitat protection [12]. However, more and more studies have found that MCR neglects the characteristic of species random walk in corridor simulation. By comparison, circuit theory can complement the deficiency of MCR well, and gradually becomes the mainstream method of corridor simulation. The application of this theory improves the rationality of corridor simulation [18]. In addition, the graphic theory and algorithmic deduction of spatial syntax have unique advantages in studying landscape connectivity. The “axis diagram” of space syntax is suitable for evaluating the structure of ENs, and a topological network parameterized by Connectivity, Integration, Mean depth, Choice, and other indicators is obtained [18].

At present, the identification of ENs mainly focuses on urban green space system planning at the urban scale [16–18], and there is a lack of research at the watershed scale. The watershed is the cradle of human civilization and the main space for harmonious coexistence between human and nature. It is crucial to build an ecological civilization on the scale of the watershed [19]. As a first-grade tributary of the Heihe River, the second largest inland river in China, the Taolai River is an important ecological barrier in northwest China, which is of great significance in supporting the country’s “Belt and Road initiative”, “Western Development”, and “high-quality development of the Yellow River Basin”. The upstream of the river basin is the Qilian Mountain National Nature Reserve, which is rich in frozen soil, glacier, and wetland resources, and plays an important role in water conservation and biodiversity protection. In recent years, due to the disturbance of climate change and human activities, their water conservation function has weakened, vegetation and biodiversity have decreased, soil and water loss have increased, and other problems have intensified [20]. The rapid development of industry and agriculture in the middle and lower reaches of the basin occupies a large amount of ecological land, which brings
great challenges to the sustainable development of the economic–social–ecological complex system, and “production–living–ecological space” [21].

Landscape connectivity analysis, MSPA, space syntax, and other spatial analysis methods combined with remote sensing and GIS were used to (1) scientifically evaluate the ecological and environmental quality of the Taolai River Basin, (2) identify and evaluate the ecological sources suitable for the survival of species in the basin, (3) simulate and evaluate the possible migration paths of species in the watershed, and (4) propose a scientific and feasible EN optimization scheme according to the EN constructed by ecological sources and potential ecological corridors, in order to provide a scientific basis for regional ecological protection and restoration.

2. Study Area and Data

2.1. Study Area

The Taolai River Basin is located in the central and western parts of the Hexi Corridor in Gansu Province, northwest China, with a geographical location ranging from 38°24′–39°36′ N, 97°16′–99°12′ E, and an altitude of 1153–5583 m. The annual average temperature is about −5 °C, the annual precipitation is between 300 and 450 mm, and the annual actual evapotranspiration is between 2000 and 2500 mm [22]. The Taolai River originates in the upstream for the Taolainanshan mountains, total length of 370 km. The annual average runoff is 637 million m³. The administrative division of the watershed includes Jiayuguan City, Suzhou District of Jiuquan City, most of Jinta County, Sunan County, and a small part of Gaotai County, Subei County, and Qilian County [23]. In 2020, the total population of the basin is about 890,000. In the upper reaches of the basin, due to serious overloading and overgrazing, grassland rat poisoning and rampant poisonous weeds have led to the degradation of some grasslands and serious land desertification. In the mountainous areas of the basin, the vegetation coverage is poor, the soil is poor, there are frequent debris flows in the rainstorm season, the species of organisms are scarce, and the microclimate indicators vary greatly, which are not conducive to plant growth. The industrial and agricultural production in the middle and lower reaches of the basin is developed, and it is the key area of water resource utilization in the basin. Due to the acceleration of urbanization and the increase of the agricultural irrigation area, the demand for water resources is increasing, which squeezes ecological water and leads to the deterioration of the ecological environment (Figure 1) [22].

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Source</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study area boundary</td>
<td>Vector</td>
<td>The Digital Heihe</td>
<td><a href="http://heihe.tpdc.ac.cn/zh-hans/">http://heihe.tpdc.ac.cn/zh-hans/</a></td>
</tr>
<tr>
<td>National primary water system</td>
<td>Vector</td>
<td>Urban and environmental geography data</td>
<td><a href="http://geodata.pku.edu.cn">http://geodata.pku.edu.cn</a></td>
</tr>
<tr>
<td>Basic geographic data</td>
<td>Vector</td>
<td>National Center for Basic Geographic Information</td>
<td><a href="http://www.ngcc.cn/">http://www.ngcc.cn/</a></td>
</tr>
<tr>
<td>Remote sensing image data</td>
<td>Raster</td>
<td>United States geological survey website</td>
<td><a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a></td>
</tr>
<tr>
<td>Land use/cover data</td>
<td>Raster</td>
<td>GlobeLand30 V2020 data set</td>
<td>globallandcover.com</td>
</tr>
<tr>
<td>DEM</td>
<td>Raster</td>
<td>Geospatial Data Cloud Platform</td>
<td><a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a></td>
</tr>
<tr>
<td>Nighttime light data</td>
<td>Raster</td>
<td>National Center for Environmental Information</td>
<td><a href="https://eogdata.mines.edu/products/vnl/">https://eogdata.mines.edu/products/vnl/</a></td>
</tr>
</tbody>
</table>

Figure 1. Overview of the study area.
2.2. Data

Table 1 presents the data used in this paper. ENVI 5.3 was used for radiometric calibration and Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) Atmospheric correction of the image data, and remote sensing images of the study area were obtained by mosaic and trimming. All data were converted to a uniform spatial reference (WGS1984, UTM Zone 47N). The grid size of raster data was uniformly 30 m × 30 m.

Table 1. Data sources.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Source</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study area boundary</td>
<td>Vector</td>
<td>The Digital Heihe</td>
<td><a href="http://heihe.tpdc.ac.cn/zh-hans/">http://heihe.tpdc.ac.cn/zh-hans/</a> (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>National primary water system data</td>
<td>Vector</td>
<td>Urban and environmental geography data platform of Peking University</td>
<td><a href="http://geodata.pku.edu.cn">http://geodata.pku.edu.cn</a> (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>Basic geographic data</td>
<td>Vector</td>
<td>National Center for Basic Geographic Information</td>
<td><a href="http://www.ngcc.cn/">http://www.ngcc.cn/</a> (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>Remote sensing image data</td>
<td>Raster</td>
<td>United States geological survey website</td>
<td><a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>Land use/cover data</td>
<td>Raster</td>
<td>GlobeLand30 V2020 data set</td>
<td>globeandcover.com (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>DEM</td>
<td>Raster</td>
<td>Geospatial Data Cloud Platform</td>
<td><a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a> (accessed on 8 October 2022)</td>
</tr>
<tr>
<td>Nighttime light data</td>
<td>Raster</td>
<td>National Center for Environmental Information</td>
<td><a href="https://eogdata.mines.edu/products/vnl/">https://eogdata.mines.edu/products/vnl/</a> (accessed on 8 October 2022)</td>
</tr>
</tbody>
</table>

3. Methods
3.1. Ecological Sources Extraction

Ecological sources are the core ecological patches of interregional species dispersal, ecological function transfer, and flow, which play an important role in promoting ecological processes, maintaining ecosystem integration, and providing ecosystem services [13]. MSPA method and landscape connectivity analysis were introduced to extract ecological sources.

3.1.1. Identification of Landscape Elements Using MSPA

MSPA is an image processing technology, which measures, identifies, and divides the spatial pattern of raster images based on mathematical morphological principles such as dilation, erosion, opening operation, and closing operation, and obtains the fine landscape types at pixel level [13–15]. Woodland, grassland, water area, and wetland have high ecological value and less human disturbance, which is a good space for species to survive. Construction land and cultivated land are greatly affected by human activities. Bare land has poor ecological quality and lacks an environment for species to forage and rest. Grassland, shrub land, water area, and wetland were used as foreground pixels, and other land use types were used as background pixels. ArcGIS 10.4 was used to reclassify the land use/cover data (Figure 2) in the study area into binary TIFF raster data, with the foreground pixel assigned as 2 and the background pixel as 1.

The mathematical morphology calculation was completed with the help of Guidos-Toolbox, and the connection mode between the central pixel and its neighbors was set as eight-neighborhood connection. The Edgewidth parameter defines the width or thickness of edge non-core class of core landscape type in unit of pixel size. The actual distance is equal to the number of edge pixels multiplied by the resolution of TIFF raster data. The Edgewidth is set as 2, and the resolution of binary TIFF raster data is 30 m. In other words, the real distance of edge width is 60 m. MSPA obtained seven non-overlapping categories (core area, bridge area, roundabout area, edge area, pore area, spur line, and island patch). The detailed meanings of each landscape element are shown in Table 2. Among them, the core area is usually a large ecological patch of woodland or grassland in the foreground.
image, and also contains some small patches that have important contributions to ecological connectivity. It is a good space for species habitat and migration, and can be used as an ecological source [23,24].

Figure 2. Status of land use in the study area.

Table 2. Definition of landscape type based on MSPA.

<table>
<thead>
<tr>
<th>Landscape Type</th>
<th>Ecological Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>The larger habitat patches in the foreground pixels can provide larger habitats for species, which is of great significance for biodiversity conservation and is an ecological source in the EN. The narrow area connecting the core area, which represents the corridor connecting patches in the EN, is of great significance for biological migration and landscape connectivity. The edge is the transition area between the core area and the predominantly non-green landscape area. Corridors connecting the same core area are shortcuts for species to migrate within the same core area. The transition area between the core area and the non-green landscape patch, the inner patch edge. An area where only one end is connected to an edge zone, a bridge zone, a roundabout, or a pore. Isolated, fragmented patches that are not connected to each other, with low connectivity between patches and less potential for internal material and energy exchange and transfer.</td>
</tr>
</tbody>
</table>
3.1.2. Selecting Ecological Sources Based on Landscape Connectivity

Landscape connectivity refers to the role of landscape structure in promoting or hindering the diffusion and movement of ecological flows within the landscape, reflecting the response of ecological processes to landscape patterns, and playing an important role in maintaining ecological environment stability and biodiversity [8,9]. Integral Index of Connectivity (IIC) and Probability of Connectivity (PC) can not only reflect the connectivity of the landscape, but also calculate the importance of patches in maintaining landscape connectivity [25,26]. The delta values for probability index of connectivity (dPC) was calculated by selecting PC index, and the calculation formula is shown in Equations (1) and (2) [25–27]:

$$PC = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{p_{ij}a_i a_j}{A_L}$$

$$dPC = \frac{PC - PC_{remove}}{PC}$$

where $n$ represents the total number of patches in the landscape; $p_{ij}$ is the maximum possibility of direct dispersal of species between patches $i$ and $j$; $a_i$ and $a_j$ denote the area of patch $i$ and patch $j$, respectively; $A_L$ is the total area of the landscape; and $PC_{remove}$ is the value of the possible connectivity index of the landscape after removing patch $i$ from the landscape.

Because the patch area of the largest core area was 1228.91 km$^2$, the minimum core patch area is 0.0099 km$^2$, the standard deviation was as high as 24.299, and the degree of habitat fragmentation was high. To avoid large core patches from participating in the connectivity analysis and suppressing the value of other core patches, this paper referred to the existing literature [28] and multiple calculation results, and eliminated six giant core patches with an area greater than 100 km$^2$ in the connectivity analysis. The connectivity analysis was performed with the help of Conefor 2.6 software, and the connectivity probability parameter was set to a medium connectivity probability of 0.5 [29]. Based on the Matrix Green tool in GIS software, the distance analysis method is used to analyze the number of landscape networks and the percentage of the largest landscape network area in the total area of the core patch under different connection distances, and further analyze the impact of distance effect on the overall landscape connectivity of the research area network. The results show that 2.5 km is a critical diffusion distance threshold for network connectivity in the study area. This paper surveys the species of wild animals and plants in the Shule River basin and their search scope, sums up the average diffusion range of birds, some large, medium, and small mammals and amphibians and reptiles, and sets the distance threshold. Considering the large range of large mammals such as *Ursus arctos*, *Panthera uncia*, and *Equus kiang* in the study area, as well as the open grassland and bare land in the study area, without the shelter of forest and other ground features, the connectivity distance parameter was set as the larger connectivity distance of 2500 m [29].

3.2. Build the Comprehensive Resistance Surface

The resistance surface represents the impact of landscape heterogeneity on ecological processes. The resistance value is not only related to distance, but also related to land cover, topography, human disturbance, and other factors [30]. Multi-source datasets were selected to construct resistance surfaces, including digital elevation model (DEM), slope, land cover, river network density, road network density, and remote sensing ecological index (RSEI) (Figure 3). Slope and DEM directly affect the distribution of vegetation and animal migration. Land cover affects material and energy exchange within and between ecological spaces. Rivers provide many ecological services and functions and play an important role in maintaining ecological balance. Artificial surfaces (roads and buildings) divide ecological land and directly block the communication between species. RSEI can comprehensively and objectively reflect the quality of the regional ecological environment [31–33].
land in the study area, without the shelter of forest and other ground features, the connectivity distance parameter was set as the larger connectivity distance of 2500 m [29].

3.2. Build the Comprehensive Resistance Surface

The resistance surface represents the impact of landscape heterogeneity on ecological processes. The resistance value is not only related to distance, but also related to land cover, topography, human disturbance, and other factors [30]. Multi-source datasets were selected to construct resistance surfaces, including digital elevation model (DEM), slope, land cover, river network density, road network density, and remote sensing ecological index (RSEI) (Figure 3). Slope and DEM directly affect the distribution of vegetation and animal migration. Land cover affects material and energy exchange within and between ecological spaces. Rivers provide many ecological services and functions and play an important role in maintaining ecological balance. Artificial surfaces (roads and buildings) divide ecological land and directly block the communication between species. RSEI can comprehensively and objectively reflect the quality of the regional ecological environment [31–33].

Figure 3. Build and correct resistance surface in Taolai River Basin: (a) slope; (b) RSEI; (c) road network density; (d) drainage density; (e) night-time light; and (f) resistance value.

River network density and road network density in the study area were obtained by kernel density analysis using water system and road data. Combined with existing studies [33,34] and the actual situation of the Taolai River Basin, the resistance value of each resistance factor in the study area was divided into 1–5 levels from low to high, and the weight of each resistance factor was determined by spatial principal component analysis (SPCA). It is found that night light (Figure 3) has a significant linear relationship with the distribution of regional gross domestic product (GDP) and population, which can well correct the resistance surface. The correction formula is shown in Equation (3) [33]:

$$ R' = \frac{TLI_i}{TLI_a} \times R $$

where $R'$ is the grid drag coefficient modified based on night light index, $TLI_i$ is the light index of grid $i$, $TLI_a$ is the average light index of different resistance levels corresponding to grid $i$, and $R$ is the basic resistance coefficient of grid landscape type. The construction result of the resistance surface is shown in Figure 3.

3.3. Simulate Potential Ecological Corridors

The MCR model is widely used in the simulation of the potential paths of species migration [17]. In recent years, more and more studies have shown that MCR ignores the random walk characteristic of animals, and circuit theory can better compensate for the
3.3.1. Simulation of Potential Optimal Paths Based on MCR

MCR was first proposed by Knaapen in 1992 [35]; the model determines the minimum cost path in the current environment based on the cost of ecological flow moving between sources [36]. MCR can be used to identify ENs under different resistance conditions and provide targeted and scientific suggestions for the optimization of regional landscape connectivity. The ecological source and resistance surface data were used as input data, and the simulation of the potential optimal path was completed based on the MCR model with the help of Linkage Mapper v2.0 (for ArcGIS 10.x). The expression of the MCR model is shown in Equation (4):

$$MCR = f \min \sum_{i=1}^{n} D_{ij} \times R_i$$

where $MCR$ is the minimum cumulative resistance value of the source diffusion to any point in space, that is, the minimum cumulative resistance of the species to migrate from the ecological source to a certain point in the region. $f$ is the positive correlation function between the minimum cumulative resistance at any point in space and the distance to all other points and the landscape basal surface characteristics. $D_{ij}$ is the spatial distance of species from ecological source $j$ to landscape unit $i$ in the region. $R_i$ is the resistance value of landscape unit $i$ to species movement.

3.3.2. Simulating Potential Sub-Optimal Paths Using Circuit Theory

Circuit theory is widely used to model ecological flows to identify areas that have an important impact on maintaining landscape connectivity. Circuit theory complements other commonly used connectivity models by taking into account the haphazard nature of animals. This paper uses Circuitscape 4.0 to simulate potential sub-optimal paths, which is based on circuit theory to establish connections between heterogeneous landscape types. In the numerical simulation of the potential of ecological flow sub-optimal path, gene flow is seen as an electric charge, ecological source was seen as a node, all kinds of landscape of natural surface are considered to be conductive surface, low resistance is assigned to be suitable for mobile animals and to promote the landscape of gene flow, and high resistance value is assigned to prevent animal migration and landscape of gene flow [37]. The current density map calculated by Circuitscape 4.0 is related to ecological processes, with warmer colors indicating higher current density and a higher probability of species migrating along this path. Cool-colored areas indicated almost zero current, while areas with weak connectivity were called “pinch points”, with less current distribution.

3.4. Evaluation of ENs Based on Spatial Syntax

Spatial syntax is widely used in the planning and research of urban transportation networks. In recent years, many scholars have applied it to the research of ENs and made great progress [38,39]. Spatial syntax considers that the street space within the visual range of the subject plays a guiding role in its social movement [38]; the longest street within the perceptual range of the subject is considered as the basic unit of spatial syntactic analysis, axis. The longest and least axis covering the whole space constitute the axis system [40]. The axis system can reflect the species’ spontaneous decision on the landscape elements in the perceived space, and also reveal the “non-equal weight path selection” of species when they move freely. The relationship diagram is called an axis map.

Spatial syntax has a series of morphological variables, such as Connectivity, Integration, Mean depth, and so on. The value of each morphological variable corresponds to a single axis in the axis map, which is used to quantitatively describe the network configuration [40]. The EN of the Taolai River Basin was evaluated based on spatial syntax. Firstly, the potential
optimal path was transformed into an axis map, and then the global integration index was used to quantify the axis map. The global integration degree represents the degree of connection between the local space and all the spaces in the system. The higher the integration degree, the stronger the accessibility of the space and the more integrated the space. The smaller the integration degree, the lower the accessibility of the space, and the more discrete or separated the space [40]. The calculation formula of integration degree is shown in Equations (5) and (6), and the specific calculation is completed with DepthmapX 8.0 software.

\[
MD_i = \frac{\sum_{j=1}^{n} d_{ij}}{(n-1)} (j \neq i) \tag{5}
\]

\[
RA_i = \frac{2(MD_i - 1)}{(n-2)} \tag{6}
\]

where the \( RA_i \) is integration degree, \( n \) is the total number of “free spaces” defined by space syntax [38]. \( MD_i \) is the average depth value of space. Space syntax stipulates that the distance between two adjacent nodes is one step; then, the shortest distance from node \( i \) to node \( j \) is the depth value from node \( i \) to node \( j \), denoted as \( d_{ij} \). \( d_{ij} \) is calculated by Dijkstra algorithm using the spatial adjacency matrix of the axis map.

The study route for this paper is shown in Figure 4.

**Figure 4.** Study routes and block diagram.
4. Results

4.1. EN Identification Results

4.1.1. Landscape Element Identification Results

The identification results of landscape elements in the Taolai River Basin are shown in Table 3 and Figure 5. The area of landscape elements in the basin was 4432.39 km$^2$, which only accounted for 26.28% of the total area of the basin, indicating that the ecological foundation of the Taolai River Basin was poor. Among the landscape elements, the total area of the core area is the largest, which is 3250.35 km$^2$, accounting for 78.10% of the total landscape elements and 20.53% of the total area of the study area.

Table 3. Area and proportion of different landscape elements.

<table>
<thead>
<tr>
<th>Landscape Type</th>
<th>Area (km$^2$)</th>
<th>Percentage of Nature Landscape Area (%)</th>
<th>Percentage of Research Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>3250.35</td>
<td>78.10</td>
<td>20.53</td>
</tr>
<tr>
<td>Bridge</td>
<td>77.52</td>
<td>1.99</td>
<td>0.52</td>
</tr>
<tr>
<td>Edge</td>
<td>364.33</td>
<td>11.33</td>
<td>2.98</td>
</tr>
<tr>
<td>Branch</td>
<td>119.28</td>
<td>2.87</td>
<td>0.75</td>
</tr>
<tr>
<td>Loop</td>
<td>34.58</td>
<td>0.83</td>
<td>0.22</td>
</tr>
<tr>
<td>Islet</td>
<td>121.57</td>
<td>2.93</td>
<td>0.77</td>
</tr>
<tr>
<td>Perforation</td>
<td>63.94</td>
<td>1.95</td>
<td>0.51</td>
</tr>
<tr>
<td>Total</td>
<td>4432.39</td>
<td>100.00</td>
<td>26.28</td>
</tr>
</tbody>
</table>

A bridging area is a structural corridor connecting the core area, which plays an important role in species migration and maintaining landscape connectivity [26], with a total area of 77.52 km$^2$, only accounting for 1.99% of the total landscape elements and 0.52% of the total area of the study area, respectively. The proportion of the total area of the bridge area to the total area of the study area was too low, indicating that the patches in the core area were isolated from each other.

The branch lines are fractured corridors and have a certain connectivity [26]; the total area is 2.87 km$^2$, accounting for 2.87% of the total landscape elements and 0.75% of the total area of the study area, respectively. The construction of a green network should consider restoring the connectivity of branch lines.
The island patch could be used as a stepping stone for species migration, with a total area of 121.57 km$^2$, accounting for 2.93% of the total landscape elements and 0.77% of the total study area, respectively. In terms of spatial distribution, the large core patches were mainly distributed in Qilian Mountain area, and the land use type was mainly grassland. However, the patches in the core area were divided by the Gobi Desert, and the landscape was fragmented. In addition, the Beihai Wetland in Jinta County, Jiefangcun Reservoir, and Yuanyangchi Reservoir in Suzhou District of Jiuquan City were the core patches with large areas in the northern end of the study area. There were more small patches in the core area in Huahai Wetland in Xinchengtong in the east and lower reaches of Jiayuguan City and the agricultural areas in Suzhou District of Jiuquan City. The bridge areas were mainly scattered in the farmland of Jinta County and Suzhou District of Jiuquan City.

4.1.2. Location Selection Results Based on Landscape Connectivity Index

Referencing the existing literature [26], 32 core patches with dPC $>$ 1 were selected as ecological sources (Table 4 and Figure 6), and a total of 38 ecological sources were identified in the study area. The No. 29 ecological source had the highest priority, with a dPC value of 31.015. It was located in the center of multiple ecological sources, connected with multiple ecological corridors, and had the highest importance. The No. 1 ecological source located at the edge of the agricultural area in Jinta County ranked third in priority, with a dPC value of 13.929. Its north end was connected with the No. 33 ecological source of Beihai Wetland, and its south end was connected with multiple ecological sources in Jiayuguan City and Suzhou District of Jiuquan City. The No. 33 Beihai wetland ecological source area was the northernmost ecological source area in the study area, with a large area of 127.64 km$^2$. In the regional ecological environment protection, attention should be paid to the stabilization of the Gobi Desert in the lower reaches of Jinta County and the protection of Beihai wetland.

**Table 4. Priority evaluation of “source”.

<table>
<thead>
<tr>
<th>No</th>
<th>Priority Rank</th>
<th>Area (km$^2$)</th>
<th>dPC</th>
<th>No</th>
<th>Priority Rank</th>
<th>Area (km$^2$)</th>
<th>dPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>49.05</td>
<td>13.93</td>
<td>17</td>
<td>16</td>
<td>2.54</td>
<td>2.15</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>1.47</td>
<td>2.61</td>
<td>18</td>
<td>20</td>
<td>4.60</td>
<td>1.90</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>1.69</td>
<td>3.02</td>
<td>19</td>
<td>23</td>
<td>1.97</td>
<td>1.59</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>1.22</td>
<td>1.98</td>
<td>20</td>
<td>30</td>
<td>8.49</td>
<td>1.07</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>6.02</td>
<td>2.01</td>
<td>21</td>
<td>22</td>
<td>9.93</td>
<td>1.66</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>3.37</td>
<td>1.48</td>
<td>22</td>
<td>28</td>
<td>1.09</td>
<td>1.13</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>6.11</td>
<td>1.83</td>
<td>23</td>
<td>26</td>
<td>1.37</td>
<td>1.43</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>7.84</td>
<td>5.64</td>
<td>24</td>
<td>2</td>
<td>28.37</td>
<td>14.44</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>28.85</td>
<td>9.12</td>
<td>25</td>
<td>7</td>
<td>21.87</td>
<td>10.35</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>5.83</td>
<td>1.46</td>
<td>26</td>
<td>13</td>
<td>4.57</td>
<td>2.77</td>
</tr>
<tr>
<td>11</td>
<td>29</td>
<td>1.06</td>
<td>1.09</td>
<td>27</td>
<td>4</td>
<td>20.72</td>
<td>13.52</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>20.25</td>
<td>10.99</td>
<td>28</td>
<td>17</td>
<td>6.06</td>
<td>2.03</td>
</tr>
<tr>
<td>13</td>
<td>27</td>
<td>0.97</td>
<td>1.16</td>
<td>29</td>
<td>1</td>
<td>59.38</td>
<td>31.02</td>
</tr>
<tr>
<td>14</td>
<td>15</td>
<td>3.32</td>
<td>2.59</td>
<td>30</td>
<td>10</td>
<td>10.42</td>
<td>4.36</td>
</tr>
<tr>
<td>15</td>
<td>32</td>
<td>0.71</td>
<td>1.01</td>
<td>31</td>
<td>5</td>
<td>45.52</td>
<td>12.51</td>
</tr>
<tr>
<td>16</td>
<td>31</td>
<td>1.04</td>
<td>1.04</td>
<td>32</td>
<td>11</td>
<td>31.91</td>
<td>3.32</td>
</tr>
</tbody>
</table>

The last three ecological sources were No. 15, No. 16, and No. 20, which had a small area of 0.709 km$^2$, 1.036 km$^2$, and 8.486 km$^2$, respectively. The spatial distribution of ecological sources was quite different, and most of them were distributed in the Qilian Mountain area of Sunan County, and the area was large. Some smaller ecological sources were scattered in new towns in the lower east of Jiayuguan City and agricultural areas in Suzhou District of Jiuquan City. In Jinta County, there are only two large ecological sources, No. 33 Beihai Zi and No. 1, and several smaller ecological sources. There were no ecological sources in other vast areas of the study area, and the ecological conditions were poor.
4.1.3. Optimal Path Simulation Results Based on MCR

The potential optimal path obtained based on MCR simulation is shown in Figure 6. A total of 106 ecological corridors were simulated in the study area, with a total length of 2,267.30 km, and the average length of the corridors was 21.38 km. Among them, the longest ecological corridor 18–9 was 76.67 km, and the shortest ecological corridor 18–19 was 1.91 km. In the upper reaches of the Qilian Mountain area and in the middle reaches of Jiayuguan City and Suzhou District, the interconnecting ecological corridors were shorter, the migration distance of species was closer, and the resistance was smaller. However, in the upper Qilian Mountain area, the middle Jiayuguan City, and the lower Jinta County ecological source areas, there are long ecological corridors connecting the ecological source area, especially in the ecological corridor between the upper and middle ecological source areas; the land use type is mainly Gobi, the species migration distance is long, the resistance is high, and the lack of suitable habitat environment. Too-long ecological corridors are not conducive to species migration. It is necessary to construct foot stones for species migration on the too-long ecological corridors to improve the success rate of migration.

4.1.4. Simulation Results of Sub-optimal Path Based on Circuit Theory

The current density map of the Taolai River Basin based on circuit theory simulation is shown in Figure 7. The minimum value of current density is 0, and the maximum value is 42.73. The area with high current density occupies less than 40% of the total area of the study area. As can be seen from Figure 7, all ecological sources are high-value current density areas. In Jinta County, except for ecological sources and a small part of the high-value current density areas in the upstream, there is almost no current distribution in other areas, and the current density decreases as you go to the northern end of the study area. The eastern lower reaches of Jiayuguan City and the agricultural areas of Suzhou District of Jiuquan City have more current distribution, which is the area with high current density. The surrounding areas have less current distribution, and the ecological connection is weak, which is the ecological “pinch” area. The northwestern corner of Sunan County also had current distribution, while the surrounding areas had weak ecological connections. There was almost no current distribution in the alpine bare rocks in the upstream Qilian Mountains, which separated the ecological source areas, indicating that the bare alpine rocks in the upstream Qilian Mountains seriously hindered the communication and connection between the ecological source areas.
value current density areas in the upstream, there is almost no current distribution in other areas, and the current density decreases as you go to the northern end of the study area. The eastern lower reaches of Jiayuguan City and the agricultural areas of Suzhou District of Jiuquan City have more current distribution, which is the area with high current density. The surrounding areas have less current distribution, and the ecological connection is weak, which is the ecological “pinch” area. The northwestern corner of Sunan County also had current distribution, while the surrounding areas had weak ecological connections. There was almost no current distribution in the alpine bare rocks in the upstream Qilian Mountains, which separated the ecological source areas, indicating that the bare alpine rocks in the upstream Qilian Mountains seriously hindered the communication and connection between the ecological source areas.

The area with a current density greater than 0.43 A/cell was considered as the sub-optimal path for species migration (Figure 8), and the area with a weak ecological connection between 0.22 A/cell and 0.43 A/cell was considered as the ecological “pinch point” (Figure 8) [37].

The global integration degree of the EN of the Taolai River Basin based on spatial syntax evaluation is shown in Figures 9 and 10. In Figure 9, the warmer the axis color, the higher the global integration degree and the higher the accessibility of the system. The colder the axis color, the lower the integration degree and the worse the accessibility of the system. The minimum value of the global integration degree is 0.139, the maximum value is only 0.334, the average value is 0.23, and the spatial distribution of the integration degree is not uniform. As can be seen from Figure 10, the global integration degree of most axes is
below 0.2, the global integration degree of a few axes is between 0.2 and 0.3, and the global integration degree of a few axes is above 0.3, indicating that the connection degree between various ecological spaces is too low [27]. By stacking the global integration layer and the ecological source layer, it was found that the axes with higher integration degrees were the ecological corridors connected with the ecological source with a higher dPC value.

![Figure 9. Global integration of EN in the study area.](image_url)

![Figure 10. Integration value of each axial based on the space syntax.](image_url)

4.3. Optimization Results of EN

Although the average dPC of the ecological source area of the Taolai River Basin was 4.37, the average dPC of the core area patches was only 0.17. The landscape in the study area was fragmented, with an uneven spatial distribution and poor connectivity. The
maximum value of global integration of the ecological corridors was only 0.334, and the average value was 0.23, indicating that the degree of ecological spatial connection in the study area was too low. This paper optimized the EN from two aspects: ecological source and ecological corridor.

4.3.1. Determine the Protection Priority of Ecological Sources

Patches of core areas meeting the following conditions were selected as planned ecological sources: (1) dPC greater than 0.2 [26], (2) area greater than 0.8 km$^2$ [41], (3) in the potential sub-optimal path, and (4) it does not belong to the existing ecological source. After a comprehensive screening, a total of 28 planned ecological sources were obtained in the study area (Figure 11). Since species migration always tends toward green space with better ecological conditions, we suggest that ecological source should be protected first, followed by planned ecological source, and finally other core patches. The core area with high landscape connectivity and a certain area was selected as the planning source area, which could balance the spatial distribution of ecological source areas in the study area and increase the area of ecological source areas.

![Figure 11. Optimal expansion distance of planned “source”](Contains 28 planned ecological sources.

4.3.2. Determine the Optimal Expansion Distance of the Ecological Source

Due to the insufficient area of the ecological source in the Taolai River Basin, the population and economic scale continue to increase, and the city is also expanding [23]. The area of the existing ecological source is difficult to meet the current ecological needs, and even more likely to be insufficient to meet the future ecological needs, which indicates that the radiation scope of the ecological source needs to be expanded. Shrubby land and grassland could provide suitable conditions for ecological processes, while bare land and construction land could hinder the ecological processes. Therefore, shrubby land and grassland were selected as favorable factors for the outward expansion of ecological source
areas, and bare land and construction land were selected as unfavorable factors for the outward expansion of ecological sources.

The planned ecological source with the smaller area was selected to explore the optimal distance for the outward expansion of the ecological source. Multi-loop buffer analysis (100 m, 200 m, 300 m, 400 m, 500 m, 600 m, 700 m, 800 m, 900 m, and 1000 m) was carried out with the planned ecological source as the center. The closer the ecological source is, the better the ecological conditions are. Therefore, this paper stipulates that the area ratio of shrub land to bare land within a certain buffer distance is less than 1.2 [16], indicating that the ecological conditions under this buffer distance are not suitable for ecological source expansion (Figure 11). For example, the optimal expansion distance of the No. 3 planned ecological source is less than 200 m, and the ecological conditions outside 200 m are not suitable for ecological source. The ecological conditions within the 1 km buffer range of the No. 11 planned ecological source were still relatively good, and the planned ecological source could be expanded in a large range.

4.3.3. Determining the Priority of Ecological Corridor Protection

According to the analysis results of spatial syntax and circuit theory, the ecological corridors with global integration greater than the average value of 0.23 and are located in potentially sub-optimal paths were considered as important ecological corridors, and the other corridors were considered as general ecological corridors (Figure 12). There were 56 important ecological corridors and 50 general ecological corridors. It is suggested that we give priority to the construction and protection of important ecological corridors in the planning and construction of ecological corridors. The vector data and remote sensing image data of ecological corridors were overlaid, and it was found that some ecological corridors traversed a large area of glacier and snow surface, which were manually removed through visual interpretation. Some ecological corridors directly pass through the built-up area. It is suggested that the urban green space system should be reasonably planned in the built-up area, and the urban landscape pattern should be optimized, to strengthen the connection between ecological sources, and to build a functional urban green space network, effectively improve the environmental benefits of urban green space, and overall improve the quality of human and animal living environment.

Figure 12. Planning of EN in Taolai River Basin. Note: A. B and C are enlarged images overlaid with special ecological corridor vector and remote sensing image: A. ecological corridors passing through the urban built-up areas, B, ecological corridors on both sides of the river, and C. ecological corridors that passes through a large area of glaciers and snow areas.
In addition, the superposition of landscape elements and water system vector data showed that there were abundant patches of bridging areas on both sides of the river. At the level of landscape elements, the bridging area is a narrow area connecting the core area, which is of great significance for landscape connectivity and biological migration. At the land use level, rivers are natural ecological corridors, which can promote ecological processes and provide ecosystem services. It is suggested that we protect and connect the ecological land on both sides of the river, expand the area of green space and bank protection forest, construct a riverfront landscape, and increase the width and connectivity of the river corridor.

4.3.4. Construct Ecological Nodes to Optimize the EN

The intersection of more than two ecological corridors is an ecological node (but not an ecological source). Ecological nodes located in low current density areas were not considered, and the intersection points of important ecological corridors were considered as important ecological nodes, while the intersection points of general ecological corridors were considered as general ecological nodes. After comprehensive selection, a total of 10 ecological nodes were selected in the study area, including eight important ecological nodes and two general ecological nodes (Figure 12).

The ecological nodes are mainly distributed in the transition zone between the up-stream core area and the midstream core area of the study area. The ecological corridor in this region is too long, and there is almost no core area patch, and the distribution of ecological nodes is an island-like patch. At the level of landscape elements, island patches can be used as “stepping stones” in the process of species migration to improve the success rate of species migration. Rationally utilizing the island patches around the ecological nodes and developing the ecological conditions around the ecological nodes can effectively consolidate the connection between the upstream core patches and the midstream core patches of the study area. On the contrary, since ecological nodes are generally the intersection of more than two corridors, they are of great significance for maintaining landscape connectivity. If ecological nodes are damaged, multiple ecological corridors may be directly lost, thus reducing alternative paths for species migration. The ecological nodes of the watershed should be rationally utilized to improve the landscape connectivity and promote the movement of species among patches.

5. Discussion

5.1. Comparison with Similar Studies

The resistance surface represents the influence of landscape heterogeneity on the migration process of species on the one hand, and the influence on landscape connectivity on the other. Constructing a resistance surface that reflects the real situation in a watershed is an important part of EN identification and ecological security pattern planning. Some researchers [14] used the land use type, elevation, slope, Fraction Vegetation Coverage (FVC), and distance from major rivers as natural influences and the index-based built-up index (IBI) as anthropogenic influences to correct the resistance surface. On the other hand, road network density and remote sensing ecological index are also used as natural influencing factors, and the nighttime light index is used to correct the resistance surface. Whether using the nighttime lighting index or IBI, it is also difficult to judge the advantages and disadvantages of these two correction indices with the current research. Finding correction factors that better represent the influence of human activities is the direction that research needs to focus on in the future.

The width of ecological corridors has an important influence on the migration of different species, ecological functions, and biodiversity within the landscape in the construction of ecological safety patterns. Compared with some researchers’ study [14], this paper considers the width of the ecological corridor, statistical land use types around the corridor through buffer analysis, and then zoning to determine the optimal width of the ecological
corridor. It also proposes that the corridor width should be determined by considering the influence of land ownership and social interest issues in addition to natural factors.

5.2. Construction of Ecological Security Pattern

5.2.1. Repairing Ecological “Pinch Points” and Clearing Ecological Obstacle Points

The ecological “pinch” obtained based on circuit theory analysis is the area with weak landscape connectivity (Figure 8). The main ecological problem in the ecological “pinch” area located in Sunan County is the serious degradation of grassland. Human activities, especially grazing, should be strictly controlled. The main ecological problems in the ecological “pinch” areas located in Jiayuguan City, Suzhou District of Jiuquan City, the upper reaches of Jinta County, and the western part of Gaotai County include poor drainage of reclaimed farmland, serious soil salinization, serious vegetation destruction, and increasing grassland degradation, and desertification. It is suggested that we strengthen the protection of grassland, use grass to regulate livestock, rationalize rotational grazing, promote semi-house feeding, eliminate extensive management mode, develop fine agriculture, strengthen the construction of shelterbelt, control the process of land desertification, and avoid the current density value of ecological “pinch” areas from low to zero value.

Ecological barrier points are high resistance points that hinder the normal flow of ecological flow. The barrier effect of the road network on species migration cannot be ignored [42]. The road itself divides large green areas, increases habitat fragmentation, and seriously reduces the success rate of species migration due to deaths and injuries caused by motor vehicle collisions. We obtained 108 ecological barrier points by overlay analysis of the vector data of major traffic road networks (highways, railways, national highways, and provincial highways) and ecological corridor vector data. Among them, 50 barrier points truncated important ecological corridors and 58 barrier points truncated general ecological corridors.

There were 30 obstacle points on expressways, 37 obstacle points on railways, 16 obstacle points on national highways, and 25 obstacle points on provincial roads. The upper reaches of the study area are mainly railway obstacle points and provincial obstacle points, and there are 10 railway obstacle points in total, all of which are located in Jiajing Railway. Jiayuguan City and Suzhou District of Jiuquan City have developed transportation lines, and various kinds of obstacle points are more distributed. There are 14 railway obstacle points in total, 12 of which are located in Lanzhou-Xinjiang Railway and high-speed railway. The 16 national road obstacle points are all distributed on the G312 national road, and the 32 highway obstacle points are all distributed on the G30 expressway.

Due to the lack of ecological corridors and road facilities, there are no ecological barrier points in the downstream of the study area. We suggest that in future planning, sufficient ecological space should be reserved at the ecological barrier points, the green area should be increased, and the planning ideas such as “ecological corridor bridge” and “ecological culvert” should be considered, and an overpass for species should be built above the road or a tunnel for species to pass under the road should be opened.

5.2.2. Determine the Optimal Width of the Ecological Corridor

Only corridors with a certain width can ensure the normal life and migration needs of species. Corridor width has a significant impact on species migration, material and energy flow, and biodiversity [43]. To find out the optimal width of corridor construction in the study area, this paper conducted a multi-loop buffer analysis (30 m, 60 m, 100 m, 200 m, 300 m, 400 m, and 500 m) on the optimal ecological corridor, and counted the area of each land use type in the buffer zone to determine the optimal width of corridor construction. Due to the large landscape heterogeneity in the Taolai River Basin, the land use types in the upper reaches of the basin are mainly grassland and bare land, while the land use types in the middle reaches of the basin are rich, including arable land, water area, grassland, bare land, and construction land. The land use types in the lower reaches of the basin are single and mostly bare land. Based on the reference remote sensing image and other studies [23],
we divided the research area into the upstream ecological conservation area, the midstream ecological control area, and the downstream ecological stability area, and determined the optimal width of the corridor by region (Figure 13).

![Figure 13. Optimum width of the corridor in each area.](image)

It can be seen from the line diagram that the optimal buffer width of the corridor in the ecological conservation area of the upstream of the watershed is 100 m. Due to the good ecological conditions of the upstream, it is recommended that we appropriately increase the corridor width. The ecological control areas in the middle reaches of the watershed are mainly Jiayuguan City and Suzhou District of Jiuquan City, and the optimal buffer width of the ecological corridor is 60 m. In terms of biodiversity conservation, 30.5 m was the minimum recommended width to protect most species [44]. Considering the limited space of urban areas in the middle reaches, the width can be reduced appropriately, but it is not recommended to be less than 30.5 m. The optimal buffer width of the corridor in the ecologically stable area in the lower reaches of the watershed is 300 m. Although this width is relatively large, it is not recommended to blindly build downstream ecological corridors due to the fragile ecological conditions of the downstream. Instead, land desertification should be controlled to prevent desertification from encroaching on oasis farmland and grassland.

The optimal buffer width of the ecological corridor here is only the recommended value. In practice, the specific width should be determined with full consideration of land ownership and balance of interests. Under the pressure of urbanization, the EN should be more strictly protected.

5.2.3. Propose the Main Spatial Pattern of Green Network Construction

This paper proposes the spatial pattern of “one core, four rings, and five belts” for EN construction in the Taolai River Basin (Figure 14). “One core” is the ecological core area of Qilian Mountains. This area is an important ecological source of the Taolai River Basin, with the largest patch area of 1228.91 km², low ecological resistance, high ecological quality. This area is also an important water conservation area of the basin, which is of great significance to ensuring the social and economic development of the western region of the Hexi Corridor. It is suggested that any development activities damaging the ecological environment and biodiversity should be prohibited in this area.
Although this width is relatively large, it is not recommended to blindly build downstream ecological corridors due to the fragile ecological conditions of the downstream. Instead, land desertification should be controlled to prevent desertification from encroaching on oasis farmland and grassland. The optimal buffer width of the ecological corridor here is only the recommended value. In practice, the specific width should be determined with full consideration of land ownership and balance of interests. Under the pressure of urbanization, the EN should be more strictly protected.

5.2.3. Propose the Main Spatial Pattern of Green Network Construction

This paper proposes the spatial pattern of “one core, four rings, and five belts” for EN construction in the Taolai River Basin (Figure 14). “One core” is the ecological core area of Qilian Mountains. This area is an important ecological source of the Taolai River Basin, with the largest patch area of 1228.91 km², low ecological resistance, high ecological quality. This area is also an important water conservation area of the basin, which is of great significance to ensuring the social and economic development of the western region of the Hexi Corridor. It is suggested that any development activities damaging the ecological environment and biodiversity should be prohibited in this area.

Figure 14. EN structure of Taolai River Basin.

The “four rings” are the:

(1) Jinta oasis ecological control zone. Several ecological source areas in Jinta County, the northernmost part of the basin, were the core. The land use types of the source areas were water, wetland, and grassland, while the other areas were bare soil, bare rock, Gobi, and other unused land, with high ecological resistance and poor habitat quality. Different degrees of soil salinization have appeared in the oasis area. The farmland in oasis should solve the problems of irrigation and drainage, prevent salinization, adjust the structure of crops, reduce the area of crops with high water consumption, protect and restore the Haloxylon ammodendron forest and Populus euphratica forest along the Heihe River, control grazing intensity, prevent degradation of vegetation, and strictly control the land reclamation. In the desert area, human activities should be strictly controlled, especially the influence of grazing activities on the area, and the existing desert vegetation should be protected to reduce the harm of wind erosion and desertification.

(2) Qiwen ecological conservation area. The ecological source 34 is the core of this area, which is connected with several important ecological corridors and has high landscape connectivity. It is an important hub for species migration in the basin.

(3) Piedmont ecological restoration area. With the No. 36 ecological source as the core, the area is 410.82 km², and the land use type is mainly shrub land, which is an important ecological conservation area in the watershed. However, the surrounding areas are mainly alpine bare rock, bare land, farmland, and other areas with high ecological resistance, which hinder the migration channels of species. The restoration and connection of ecological corridors in this area should be strengthened.

(4) Hongshui Dam ecological protection area. The area takes the No. 37 ecological source area as the core, with a total area of 657.12 km², second only to the No. 38 ecological source, and is rich in water resources, mainly from the Qilian mountain snow melt water; the ecological conditions of the Flood Dam Ecological Reserve are directly related to the survival and development of Jiuquan City, Jinta County oasis and...
Jiayuguan City. All kinds of unsustainable human activities should be prohibited in this area; water conservation and biodiversity protection should be protected.

The “five belts” are the:

(1) Ecological corridor construction zone of Jiajiu Oasis. The grassland and farmland of Jiayuguan City and Suzhou District of Jiuquan City are scattered with some ecological sources with small areas, which are connected by several important ecological corridors with relatively close distance and high connectivity, and together constituting the oasis ecological corridors. In recent years, Jiuquan City of Jiayuguan City has developed rapidly, the scale of regional population, industry and agriculture has expanded, and all kinds of resources are tight. Under the pressure of urbanization, we should take the regional ecological carrying capacity as the premise, and give priority to the construction of ecological corridors, so as to provide better ecosystem services for urban population.

(2) Ecological corridor construction belt of grassland and water area in Qilian Mountain. The ecological corridor construction zone is mainly composed of grassland and water land, close to the side of the Hongshui River, and has excellent ecological background conditions. It is an important ecological corridor to realize the connection of various ecological sources in the upper reaches of the basin.

(3) Ecological corridor construction zone on the eastern side of the basin. The ecological corridor construction belt connects the ecological core area No. 37, 36, 12, 1, and 33, and other large ecological sources from south to north. The connectivity of ecological corridors is high, and the upstream, middle, and downstream ecological sources are connected in the east of the basin. The protection and construction of this ecological corridor is of great significance.

(4) Main belt of ecological corridor construction in the western part of the basin. The ecological corridor construction belt connects the ecological core area No. 34, No. 9, and No. 33, and other large ecological sources from south to north, and connects the upstream, middle, and downstream ecological sources in the west side of the watershed, which is of great significance for the construction of the green network system of the watershed. However, some corridors of this construction zone are too long, and the land use is mainly bare land and other unused land, which spans the urban area. In practice, the protection and construction of ecological nodes and urban green landscape should be considered first.

(5) Sub-zone of ecological corridor construction on the west side of the watershed. The ecological corridor construction belt connects the ecological core area No. 24 and No. 25, and other ecological sources with high priority, and intersects with the main ecological corridor construction belt on the west side of the watershed to the No. 9 ecological source in Jiayuguan City, forming the ecological corridor construction belt on the west side of the watershed. The five ecological corridor construction zones showed a spatial pattern of “three vertical and two horizontal”. Among them, the eastern side of the watershed and the ecological corridor construction zones of the grassland and water area of Qilian Mountain were all composed of important ecological corridors, with better ecological background conditions and higher priority. The "five belts" connected the “one core” and the “four rings” to form a green network system with both spatial connectivity and landscape ecological functions in the basin [45].

5.3. Limitation

The global integration degree of the EN of the Taolai River Basin based on spatial syntax evaluation is low, which is due to the high degree of habitat fragmentation in the study area. In addition, the higher the global integration degree is, the higher the accessibility of the system is. Therefore, whether the potential ecological corridors simulated can play a real role needs to be further analyzed. When selecting ecological sources based on landscape connectivity, it is necessary to set the connection distance parameters and
the connection probability. This paper mainly set the connection distance parameters and
the connection probability based on the research of other research areas and the diffusion
distance of large animals in this research area. However, there are species differences in
the diffusion distance of species, and the ecological conditions of different research areas
are different. There is no universal standard of value. Therefore, the setting of parameters
related to landscape connectivity requires in-depth investigation and analysis in the study
area to be better determined.

In the study of EN and ecological security pattern, most of the literature simply
selected nature reserves, natural scenic spots, and habitats of key species as ecological
sources. MSPA was used to identify ecological source areas, considering the connectivity
of the ecosystem, which was more scientific. However, the results of MSPA analysis
varied with the change of grain size and edge width, and in order to make the results
more scientific, the influence of particle size and edge width on the results of MSPA
analysis can be further studied. Although natural factors and social–economic factors were
comprehensively considered to construct the resistance surface during the study, there are
still two points that can be optimized. One is that this paper uses night light data to correct
the resistance surface, and the impact of human activities on ecological processes is not so
simple. Therefore, it is necessary to consider whether there are other data to better express
the impact of human factors on the ecology, or whether there is a combination of multiple
data synthesis to represent human factors. The other is that there is no unified standard for
the construction of resistance surfaces in China. In the construction of resistance surfaces
for species migration, principal component analysis (PCA) and analytic hierarchy process
(AHP) are used in many literatures. This paper argues that the construction of resistance
surface should be considered a factor that plays the main role of obstruction. The weighted
summation method will average the resistance value of each region. We hope to propose a
more scientific method to construct the resistance surface in the subsequent research, so as
to identify ecological corridors more accurately.

The comprehensive application of MSPA, MCR, circuit theory, and space syntax is
realized, and all the methods are well connected and complementary to each other. At
present, spatial syntax is mostly used in the research of urban traffic road network. The
in-depth study of this method in the quantification of the spatial morphology of the EN
and green infrastructure network is worthy of further discussion. In addition, according
to the simulated results of ecological corridors in the Taolai River Basin, although some
corridors realize the connection between ecological sources, the length of the corridors is
too long, and most of the corridors are in the Gobi and deserts. It is uncertain whether
species will choose such routes with poor ecological conditions as migration corridors. We
do not consider the path characteristics of specific biological species migrating between
ecological sources through ecological corridors. In future studies of the ecological corridor
simulation, this issue should be fully considered from the perspective of species, to avoid
the artificial subjectivity of the ecological corridor simulation.

6. Conclusions

(1) The ecological space of Taolai River Basin is insufficient and the spatial distribution is
uneven. MSPA and landscape connectivity index were used to identify 38 ecological
sources with a total area of 3061.63 km², accounting for 19.34% of the watershed area,
mainly distributed in Qilian mountains.

(2) The ecological corridors in the Taolai River Basin were generally long, which was not
conducive to species migration. The MCR model was used to simulate 106 optimal
ecological corridors, with a total length of 2267.30 km and an average length of
21.38 km. The circuit theory was used to simulate the sub-optimal ecological corridors
with a certain width distributed in the surrounding areas of the optimal ecological
corridors. The minimum and maximum integration degree of the EN were 0.139 and
0.334, respectively. The connection degree of each ecological space in the watershed
was too low.
(3) According to the Taolai River Basin ecological environment present situation, optimization measures such as priority protection of key ecological space, optimal expansion distance of ecological source, optimal width of ecological corridor construction, ecological node construction, ecological “pinch-point” restoration, ecological obstacle point removal, and the main spatial pattern of “one core, four rings, and five belts” for watershed EN construction were proposed. This study can provide a scientific reference for the EN construction and biodiversity protection in the Taolai River Basin.

Author Contributions: Conceptualization, J.P.; methodology, Z.Z. and J.P.; software, Z.Z. and Y.W.; validation, Y.W. and Z.Z.; formal analysis, Z.Z.; resources, Z.Z. and J.P.; data curation: Z.Z.; writing—original draft preparation, Z.Z. and Y.W.; writing—review and editing, J.P.; supervision, J.P.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the National Natural Science Foundation of China (no. 42071216) and Natural Science Foundation of Gansu Province (no. 21JR7RA145).

Data Availability Statement: The data and statistical analysis methods are available upon request from the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References
6. Shi, F.N.; Liu, S.L.; An, Y.; Sun, Y.X.; Zhao, S.; Liu, Y.X.; Li, M.Q. Spatio-temporal dynamics of landscape connectivity and ecological network construction in Long Yangxia Basin at the Upper Yellow River. Land 2020, 9, 265. [CrossRef]


38. Xia, C.; Zhang, A.Q.; Wang, H.J.; Yeh, A.G. Predicting the expansion of urban boundary using space syntax and multivariate regression model. *Habitat Int.* 2019, 86, 126–134. [CrossRef]


42. Wei, J.Q.; Zhang, Y.; Liu, Y.; Li, C.; Tian, Y.S.; Qian, J.; Gao, Y.; Hong, Y.S.; Liu, Y.F. The impact of different road grades on ecological networks in a mega-city Wuhan City, China. *Ecol. Indic.* 2022, 137, 108784. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.