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Methodology for Mapping the Ecological Security Pattern and Ecological Network in the Arid Region of Xinjiang, China

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Abstract: Xinjiang is an important arid region in the northwest of China and plays an important role in the field of ecological security protection in China. Because of its aridity, the identification of critical areas for ecological protection and the optimization of ecological space structure in Xinjiang are of great significance for promoting the harmonious development of the oasis economy, enhancing the ecological environment, and improving human well-being. This study applied an ecological security evaluation from the three dimensions of habitat quality, ecosystem service value, and soil-water conservation to identify the basic situation of the ecological security pattern. The core "source" area of ecological protection was extracted using the morphological spatial pattern analysis (MSPA) method, while the ecological corridor and important ecological nodes were identified using the minimum cumulative resistance model (MCR). The "point-line-plane" three-dimensional ecological network structure was then constructed, providing a case for the development of the ecological security and construction in the oasis. The results showed that in the arid regions of Xinjiang, the ecological land is extremely fragmented and is mainly distributed in the mountains and waters distant from human activities. Overall, there is a substantial geographical disparity with a low level of ecological security, particularly in the ecological marginal areas. The ecological network framework of Xinjiang is characterized by an uneven distribution of "sources", broken corridor structure, and a low degree of networking. Therefore, this study proposed an ecological space layout system consisting of "7 ecological subsystems, 51 source areas, 87 ecological corridors, and 33 ecological nodes" by combining the regional physical and geographical characteristics with the overall development plan.

Keywords: arid region; ecological security; ecological network; ecological management

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1. Introduction

Ecological security is emerging as a new research area that focuses on ensuring the sustainable development of Chinese society. The environment has been severely harmed over the past few decades as a result of intensifying human activity, as well as the expansion of the urban area, agricultural land, and transportation network. This has led to a number of ecological problems [1–4]. The construction of an ecological network is a key strategy to ensure regional ecological security. The level of ecological security and the quality of the ecological environment can be effectively improved by constructing ecological networks to accomplish the efficient management of regional ecological environments, and to adjust the resilience and risk resistance of ecological environments [5].

Based on the pattern–process coupling theory, the ecological security pattern is a key spatial approach to maintaining environmental safety and health. It aims to promote an optimal distribution of various ecosystem components through human active intervention, and, ultimately, to improve the regional ecological security situation [6]. The content of ecological security involves natural, social, and economic dimensions, which are the differences between different temporal and spatial scales. A relatively complete ecosystem is normally considered in the ecological security pattern design to effectively identify and protect potential ecological key elements. This is an important way to ensure regional ecological security and achieve sustainable development [7,8]. The ecological security pattern constructed in this study aims to serve as a reference for national land space planning. Specifically, this study has an emphasis on people and their environment when considering the objects of ecological security services, which are rarely reported in the literature. At present, research on ecological security mainly focuses on water and soil loss, soil erosion, biodiversity protection, pollution control, and other microelements [1,9–11]. The research contents are primarily concerned with evaluating ecological security, estimating ecological footprints, and identifying ecological security landscape patterns and ecological health [12–14]. The primary research methods include an index system, ecological network, and granularity reverse inference scenario analysis [15–17]. From the literature, the current ecological security research has formed a systematic research system, and it has technical standards from theory to system and has been widely applied in reality.

Landscape ecology uses an ecological network to link the landscape structure and ecological function. These networks are mostly composed of local, point, and spatial relationships that are essential for controlling or maintaining the ecological process. The "source-corridor-resistance surface" ecological network model is currently the standard model for regional ecological security pattern analysis [9,18]. Source areas are habitat patches that play a decisive role in regional ecological processes and functions, and which have a major impact on regional ecological security or provide important radiation functions. They are often demarcated based on nature reserves, forest parks, wetlands, etc., as well as via quantitative methods, such as ecosystem service value and morphological spatial analysis [19]. A corridor is an important channel for connecting ecological sources, undertaking species movement, and transferring material and energy flows. Corridor identification methods mainly include the minimum cumulative resistance model (MCR), circuit theory, graph theory, etc. Among these, the MCR model, which is favored by scholars, has been extensively applied to accurately simulate the trend of biological spatial movement and landscape changes [20–23]. Overall, the "source-corridor-resistance surface" ecological network framework can better explain the relationship between landscape pattern and ecological process, achieving good results in optimizing landscape pattern, land use planning, and species protection management.

Many scholars have carried out quantitative and qualitative research on the construction of ecological networks since it is an important means of ecological security management. The Flanders network in Belgium and the Catalonia nature reserve network in Spain focus on biodiversity, cultural, and recreational values [24]. Urban-scale ecological networks, such as the Tokyo Green Project, mainly focus on "ecological infrastructure" and "green infrastructure" to optimize urban ecology and spatial layout to provide a livable and green living environment [25]. China has established a national ecosystem research network, covering typical farmland, forests, grasslands, deserts, swamps, lakes, oceans, and urban ecosystems. This network reflects the structure and function, models and processes of ecosystems, and offers guidance for ecosystem restoration and ecosystem management [26].

Xinjiang Uygur Autonomous Region (hereinafter referred to as Xinjiang), a typical arid area in China, is facing serious ecological problems due to its poor ecological resources and conditions. As a typical arid climate zone in China, Xinjiang's fragile ecological environment and sparse vegetation cover severely restrict the regional ecosystems, which frequently causes ecological problems and poses a danger to the local population. Like in many other cities, human activities have intensified the occupation of ecological space, resources, and the environment. The spatial conflict of urban development in Xinjiang has recently grown greatly, but the value of the regional ecosystem service and health has decreased. Thus, the ecological risk has also increased [27–29]. To effectively limit, guide, and manage human interference activities to ensure the sustainable development of human society and the ecological environment, it is necessary to carry out land spatial ecological restoration in an organized and scientific manner [17,30–33].

In light of the given background, this study selects Xinjiang as the research object. On the basis of understanding the basic situation of its ecological security, an ecological security network was constructed to achieve the goal of optimizing regional ecological management. The aims of this study are (1) to determine and construct the regional ecological security pattern, and (2) to develop a regional ecological network using ecological analysis methods. This study will provide case support, and theoretical practice, for the land ecological governance of Xinjiang.

2. Data Sources and Research Methods

2.1. Study Area

Xinjiang is located in the northwestern part of China, the hinterland of the Eurasian continent. It lies between 73°40′E and 96°18′E longitudes and 34°25′N and 48°10′N latitudes (Figure 1). It is the largest province with longest land boundary in China, with an area of approximately 1.66×10^6 km^2, accounting for about one-sixth of the entire country's area. It has a unique topography of "three mountains and two basins", and also has the country's largest mobile desert and semi-fixed desert under a typical temperate continental climate [34]. Precipitation distribution is extremely uneven, with limited vegetation coverage and development land, as well as low utilization efficiency. Xinjiang has limited water resources as well, and most of the urban development is dependent on the oasis, forming a unique oasis urban ecology. However, urban development is severely restricted due to the fragile oasis ecological environment. A large population and human activities are mainly concentrated in the oasis, leading to a conflict between man and the environment that is more obvious compared to that seen in other regions of China. Unsurprisingly, protecting the region's ecological security is becoming a very urgent task in this area.

2.2. Data Sources

The data used in this study mainly include land use/cover data, meteorological data, soil data, etc. The sources, descriptions, and uses of related data are shown in Table 1.

Considering the difference and computability of the basic data, in order to unify the spatial resolution of the above multi-source data, this study uses the aggregation tool in the ArcGIS software to convert all the data into 1×1 km raster data. Then, the resampled data are projected to the Asia Lambert Conformal Conic projection.

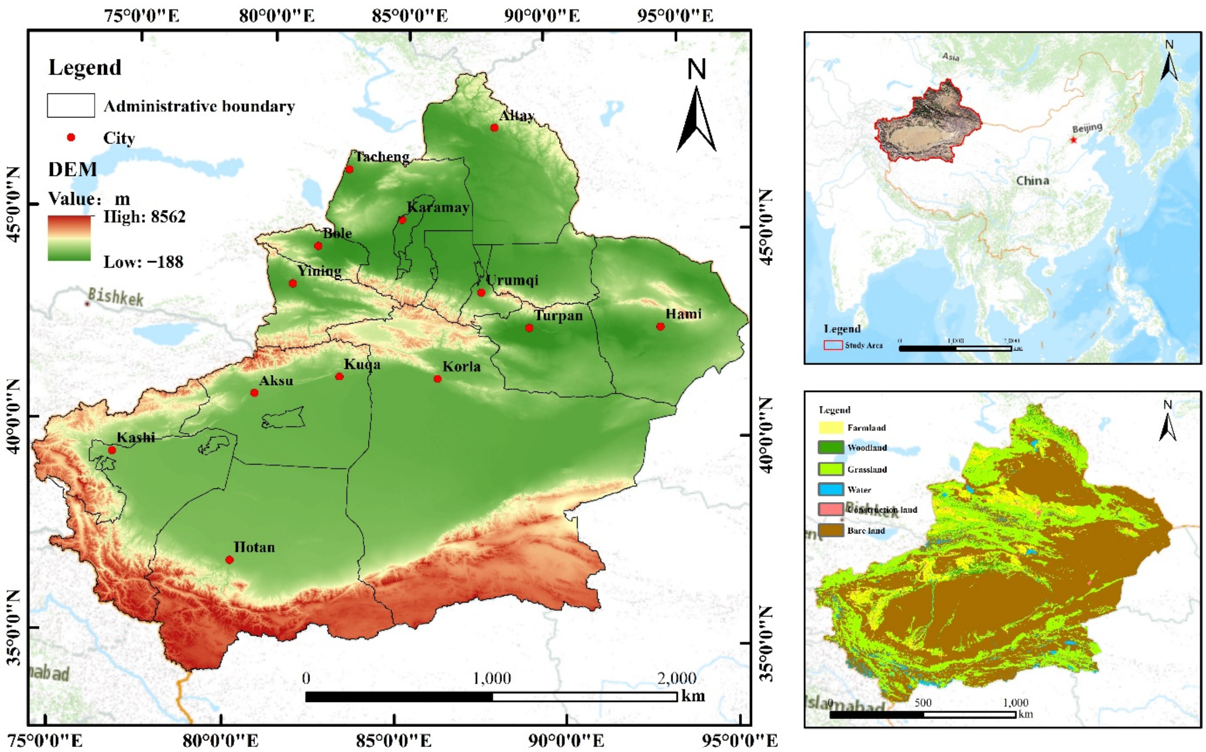

Figure 1. Location map of the study area.

Table 1. General status of data.

Data	Resolution	Time (Year)	Source	Application
Land use/cover type	30 m	2018	REDCP (http://www.resdc.cn, 15 March 2022)	InVEST mode data/ESV model data
Normalized difference vegetation index	250 m	2018	NASA (https://www.nasa.gov, 15 March 2022)	ESV correction
Night-time light data	1 km	2018	NASA (http://reverb.echo.nasa.gov, 15 March 2022)	InVEST mode data
Road vector	1 km	2018	OSM (http://www.openstreetmap.org, 1 May 2022)	RUSLE model data
Population density	1 km	2018	ORNL (https://www.satpalda.com, 1 May 2022)	InVEST mode data
Soil properties	1 km	-	HWSD (http://webarchive.iiasa.ac.at, 1 May 2022)	RUSLE model data
National administrative boundary	1:1,000,000	2017	NGCC (https://www.tianditu.gov.cn, 15 March 2022)	Basic data
Meteorological data	-	2018	CIMISS (http://data.cma.cn/, 1 May 2022)	RUSLE model data

2.3. Methods

First, a three-factor ecological security system was constructed. Next, the weighted superposition method was used to integrate the three-factor ecological security assessment and the composite ecological security pattern. Then, the MSPA method and MCR model were used to extract source areas and corridors based on the complex ecological security pattern. In order to build a regional ecological network, the gravity model was used to screen key ecological sources, corridors, and nodes based on the regional physical and geographical backgrounds (Figure 2).

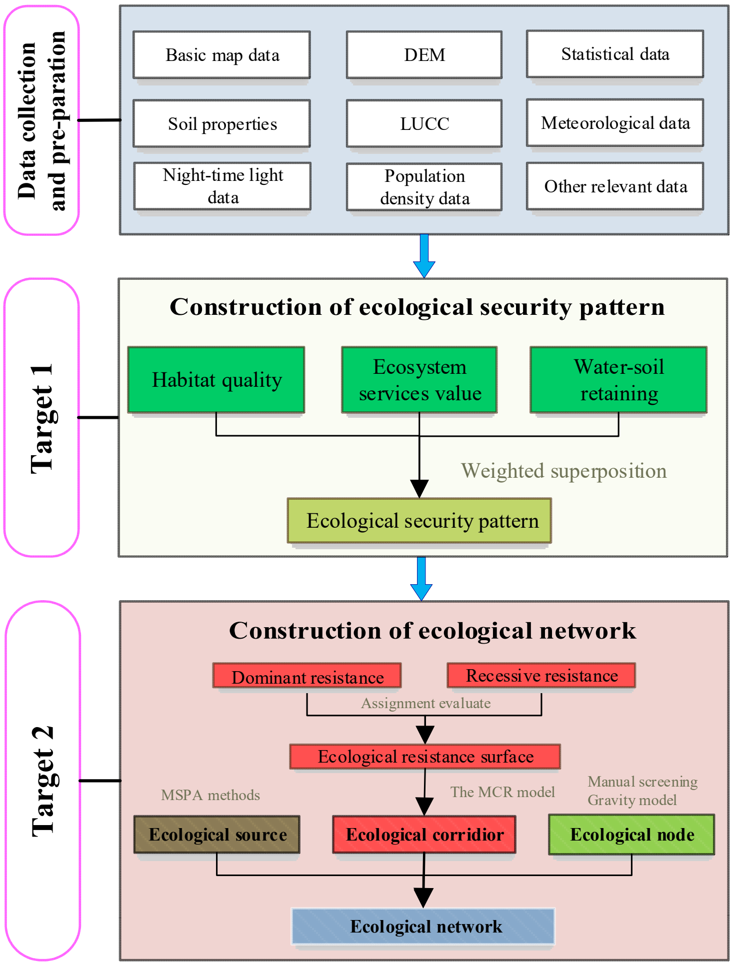

Figure 2. The workflow diagram of this study.

2.3.1. Construction of Ecological Security Pattern

Habitat quality, which is positively correlated with biodiversity, reveals the potential of ecosystems to support life and promote the development of new species. Biodiversity is the foundation of ecosystem function, supporting a range of ecosystem functions such as ecosystem stability, and regulating climate, food, and nutrients. Habitat quality can therefore describe the richness of biodiversity. It has recently become an important method for analyzing biodiversity [35–38]. The conservation of soil and water is an important indicator of regional soil safety. Analyzing the differentiation of regional soil conservation functions and clarifying the important areas of soil conservation functions can provide a scientific basis for (1) determining key ecological protection areas, (2) conducting soil conservation function zoning, and (3) delineating soil conservation function protection red lines [39–41]. The ecosystem service function refers to the natural environmental conditions and utilities on which humans depend for survival. The value of the ecosystem service is the most scientific and reasonable value basis for quantifying the ecosystem service's functions [42]. One of the most common techniques in the ecological security research is the construction of composite ecological security patterns by overlaying factors such as habitat quality, and soil and water conservation [8,11,15].

(1) Habitat quality

The habitat quality indicators include the availability of survival resources, biological reproduction and growth capabilities, and individual and population development levels. The values range between 0 and 1, whereby the higher the value, the better the habitat quality [43–45]. This study used the Habitat Quality Module in the InVEST model (3.8.1 version) to quantitatively evaluate the regional habitat's quality. Since the ecological security targets involved in this study are mainly humans, the characteristic elements of human activities are selected as the main threat factors affecting the quality of the habitat. The calculation formula is shown as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_x^Z}{D_{xj}^Z + K^Z} \right) \right] \tag{1}$$

where Q_{xj} is the habitat quality of land use type j grid x, H_j is the habitat suitability of land use type j, D_{xj}^Z is the habitat stress level of land use type j grid x, Z is the model parameter (Z = 2.5), and K is the half-saturation constant (take the default value, k = 0.5). We considered the characteristics of the study area and the data availability in accordance with the InVEST work manual and other studies [46,47] to set the threat factor parameters and the applicability of the sensitivity value of each habitat, as shown in Tables 2 and 3.

Table 2. Threat factors and their stress intensities.

Threat	Maximun Impact Distance/km	Weight	Recession Type
Farmland	4	0.6	Linear
Urban	8	0.8	Linear
Village	6	0.6	Exponential
Other construction land	7	0.7	Exponential
Bare land	4	0.4	Exponential
Night-time light	7	0.8	Linear
Population	6	0.8	Linear

Table 3. Habitat suitability and sensitivity of land use types.

Land Use Type	Habitat Suitability	Farmland	Urban	Village	Other Construction Land	Unused Land	Population	Night-Time Light
Farmland	0.5	0	0.8	0.6	0.7	0.4	0	0
Forest land	1	0.7	0.9	0.8	0.8	0.5	0.7	0.8
Shrub land	1	0.6	0.8	0.7	0.7	0.4	0.7	0.8
Sparse forest land	0.9	0.7	0.9	0.8	0.8	0.5	0.7	0.8
Other forest land	1	0.7	0.9	0.8	0.8	0.5	0.7	0.8
High coverage land	0.9	0.6	0.7	0.7	0.7	0.7	0.7	0.8
Medium coverage land	0.8	0.7	0.8	0.8	0.8	0.7	0.7	0.8
Low coverage land	0.7	0.7	0.8	0.8	0.8	0.7	0.7	0.8
Water	0.9	0.4	0.7	0.6	0.7	0.4	0.6	0.6
Urban land	0	0	0	0	0	0	0	0
Rural resident land	0	0	0	0	0	0	0	0
Other construction land	0	0	0	0	0	0	0	0
Bare land	0.3	0.4	0.6	0.5	0.6	0	0.2	0.2

(2) Ecosystem service value

Ecosystem service value is the process through which humans assign value attributes to quantify and evaluate ecosystem service functions. It is an important method for clarifying the distribution of different types of ecosystems, as well as their functions and values in sustainable urban development [48]. This study used the value equivalent method for calculation, which refers to the ecosystem service value equivalent formulated by some experts in the Xinjiang region to determine the basic ecosystem service value equivalent of the region [49–51], as listed in Table 4. The calculation method is shown as follows:

$$ESV_T = \sum (A_i \times VC_i) \tag{2}$$

where ESV_T is the ecosystem service value at time T, A_i is the area of land use/cover type i (hm^2), and VC_i is the ecosystem service value coefficient (CNY/($hm^2 \cdot a$)).

Table 4. Values per unit area of ecosystem services in China (CNY/ha/year).

Land Use Types	Farmland	Woodland	Grassland	Water	Construction Land	Bare Land
Unit value	4.37×10^3	19.95×10^3	2.15×10^3	24.06×10^3	0.30×10^3	0.22×10^3

(3) Water-soil retention

Soil erosion has a serious impact on the environment and is one of the important factors restricting economic development [52]. The Revised Universal Soil Loss Equation (RUSLE) was used to estimate the potential soil erosion amount (A_p) and the actual soil erosion amount (A_r). The difference between A_p and A_r is known as the soil conservation amount (A_c), which can be effectively used as an indicator of the regional soil erosion situation, and the need for soil conservation and security [53]. The calculation formula is shown as follows:

$$A_c = A_p - A_r = R \times K \times LS - R \times K \times LS \times C \times P = R \times K \times LS \times (1 - C \times P) \quad (3)$$

where A_c is soil retention by the model, in 100 ton hm^{-2} a^{-1}; R is the precipitation erosion factor, in MJ mm hm^{-2} h^{-1} a^{-1}, which is the dynamic index of erosion caused by precipitation and is mainly affected by rainfall intensity [54]; K is soil erodibility, and the unit is ton hm^2 hhm^{-2} MJ^{-1} mm^{-1}, which reflects the sensitivity of soil to erosion and is mainly calculated using the EPIC model [55,56]; LS is a terrain factor which is dimensionless, and its calculation method mainly refers to related research [57]; C is a vegetation coverage and management factor which is dimensionless, and it represents the effect of different vegetation coverage and management measures on soil erosion; p factor is a water-soil retaining factor which is dimensionless, and it is the soil loss caused by the tillage effect under specific water-soil retention measures; the C and p factors mainly reflect the impact of human activities on soil erosion, which is generally determined by the assignment method [58] (see the Table 5).

Table 5. The values of C and p of different land use types.

	Farmland	Woodland	Grassland	Water	Construction Land	Bare Land
C	0.2	0.05	0.3	0	0	1.0
p	0.15	1.0	1.0	0	0	0

(4) Construction of a comprehensive ecological security pattern

Combined with the natural background characteristics of the arid area in the study area and the uniqueness of the functions of various ecological elements, the equal weight superposition method was adopted in the superposition process of a single ecosystem's service function. Three single ecosystem service functions of habitat quality, soil and water conservation, and ecosystem service value were superimposed with equal weight. Then they were combined with the existing research results. Lastly, they were classified to form a five-level ecological security pattern (mainly using natural breakpoint method [59–61]. The results was divided into five levels: (1) ecological marginal area: poor resources and no protection value located at the edge of the ecosystem; (2) ecological transition zone: an area in the ecosystem that has complex ecological and environmental protection; (3) ecological connection zone: an intermediate zone in the ecosystem that connects areas of higher and lower ecological value; (4) ecological buffer zone: an area in the ecosystem that bears certain ecological functions and has a protection value; and (5) ecological core area: an area in the ecosystem that bears important ecological functions and has a high protection demand. The result is also the ecological substrate used to construct the ecological network.

$$CESP = Sum(SP_i), i = 1,2,3 \tag{4}$$

In the above formula, SP_i represents a single ecological security pattern of three ecological processes.

2.3.2. Construction of Ecological Network

(1) Source identification

This study mainly chose the MSPA method to determine the basic ecological patches, and selected the source sites through the landscape function and connectivity [62]. The specific operation involves selecting the ecological core area and ecological buffer zone in the comprehensive ecological security pattern as the prospect data for MSPA, with the other levels serving as the background. Based on the ConeforSensinode software [63], the possible connectivity index (*PC*) and the important value of a single patch (*dPC*) were calculated. Considering the scope of the study region, the area $\geq$10 km^2 with *dPC* in the top 20% was selected as the ecological source.

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \times a_j \times P_{ij}^*}{A^2} \tag{5}$$

$$dPC = \frac{PC - PC_{remove}}{PC} \times 100 \tag{6}$$

where n represents the number of patches; a_i and a_j are the areas of patches i and j; A represents the total area of the landscape; represents the maximum possibility of spreading between patch i and patch j; PC_{remove} represents the overall index of removing the remaining patches after a certain patch; *dPC* represents the change in the possible connectivity index, which can evaluate the importance of the elements to the overall landscape connectivity, and the size represents the importance.

(2) Corridor extraction and screening

Different ecological flows also have different resistances during the spreading process, so the patency of ecological passages is also different. Therefore, the identification and diagnosis of different resistance areas are often achieved by constructing ecological resistance surfaces [16,64]. This study combined the landscape profile and topographic characteristics of the study area to construct a resistance factor system (Table 6).

Table 6. Weights and coefficients of comprehensive ecological resistance surface.

Resistance Factor		Weight	Indicator	Resistance Coefficient
Landscape types		0.40	Woodland	10
			Water	15
			Farmland	25
			Grassland	30
			Bare land	80
			Construction	100
Geomorphological factors	Slope	0.30	<8°	1
			8~15°	10
			15~25°	50
			25~35°	75
			>35°	100
	RDLS	0.30	<25°	1
			25~50°	10
			50~70°	50
			70~100°	75
			>100°	100

The minimum cost distance model was used to construct the resistance surface. The minimum cost path represents the cost distance and size of different sources. It is a conceptual distance, representing a weighted distance but not an actual distance. By constructing the resistance cost matrix between patches, the lowest cost corridor connecting all the sources, namely the potential corridor, was identified [18].

$$MCR = fmin \sum_{j=n}^{i=m} D_{ij} \times R_i \tag{7}$$

where *MCR* is the minimum cumulative resistance value between the source areas; f represents the positive correlation between the minimum cumulative resistance and the ecological process; D_{ij} is the spatial distance from the source grid j to the landscape unit i; R_i is the effect of the landscape unit i on a certain organism and the resistance coefficient of the movement.

The gravity model can screen out the key corridors that play an important role in global ecological connectivity from the huge number of potential corridors in the study area [65]. The calculation formula is shown as follows:

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} = \frac{\left[\frac{1}{P_a} \times \ln(S_a)\right]\left[\frac{1}{P_b} \times \ln(S_b)\right]}{\left(\frac{L_{ab}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln(S_a) \ln(S_b)}{L_{ab}^2 P_a P_b} \tag{8}$$

where G_{ab} is the force between source a and source b; N_a and N_b are the weight values of the two sources, respectively; D_{ab}^2 is the standardized value of the corridor resistance between a and b; P_a is the force of the source of a resistance value; S_a is the area of source a; L_{ab} is the cumulative resistance value of the corridor between source a and source b; and L_{max} is the maximum cumulative resistance of all corridors.

(3) Identification of ecological nodes

The ecological stepping-stone plays a key role in the ecological corridor and in ensuring the smooth flow of operation within the ecological network [66]. The identification strategies used in this research include the following steps: First, we draw reference to the hydrological analysis methods and then extract the "ridge line" of the resistance surface. Next, we take the intersection of the ridge line and the corridor as the ecological stepping-stone. After that, we classify all ecological stepping-stone points based on the position of the functional corridor.

The traffic road network has a major impact on ecological process and substantially harms the connection between various sources. The ecological break point, where the road systems meet the corridor, is where ecological corridor is the most susceptible to disruption [67,68]. In this study, the intersections of main roads, railways, and corridors are chosen as ecological breakpoints, and they are classified according to the different functions of the corridors.

3. Result and Analysis

3.1. Construction of Ecological Security Pattern

The comprehensive ecological security pattern is shown in Figure 3, where Figure 3a–c are the single element ecological security pattern, while Figure 3d is the comprehensive ecological security pattern. In order to facilitate quantification, the habitat quality, the amount of soil and water conservation, and the value of ecosystem services are normalized. From the sub-map, the three show similar rules, that is, the high-value areas are mainly composed of large water bodies and continuous woodlands. They are mainly gathered around the mountains and the edge of the river system.

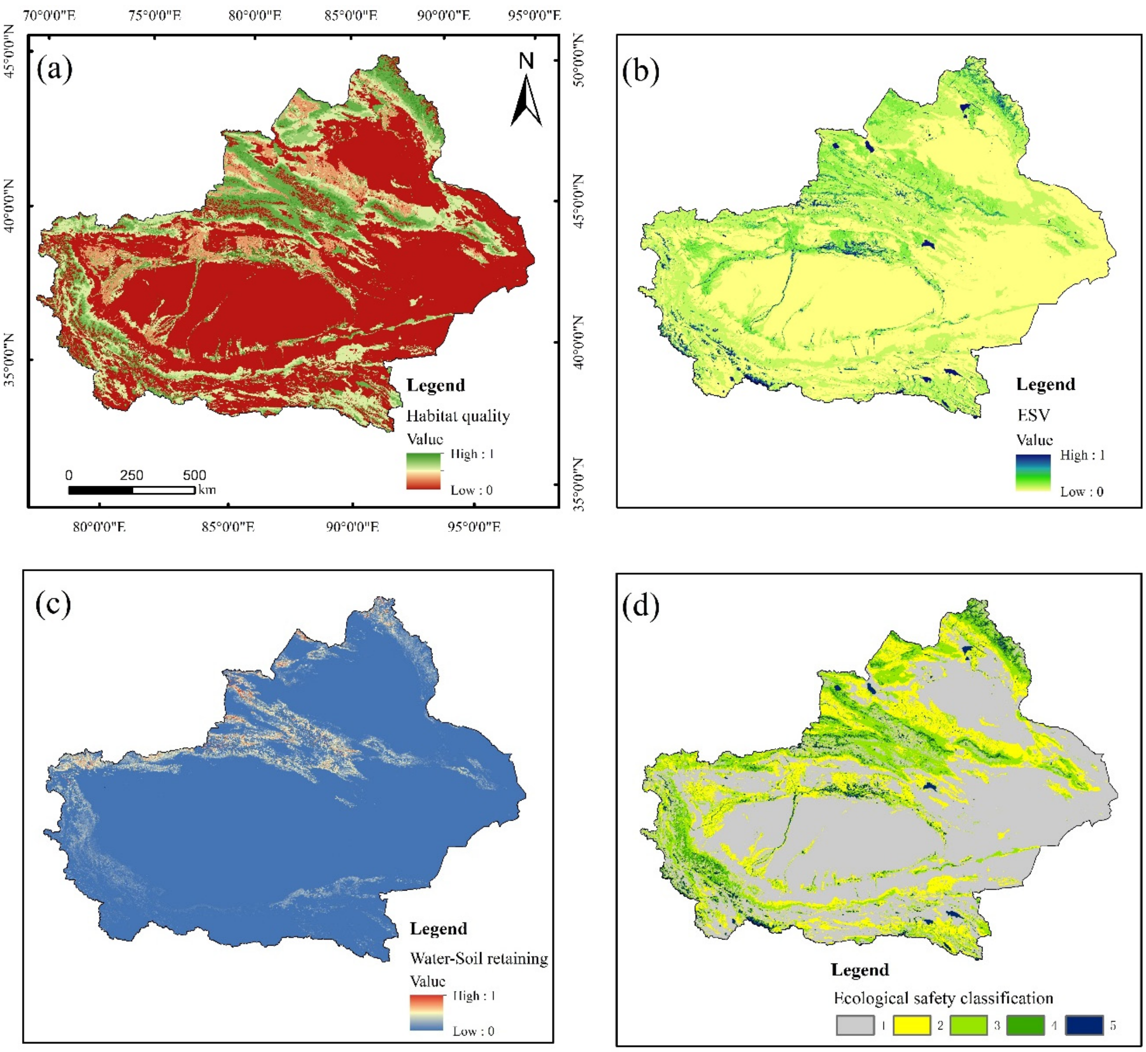

Figure 3. The ecological security pattern in Xinjiang ((**a**) habitat quality; (**b**) ecosystem services value; (**c**) water-soil retaining; (**d**) ecological safety classification). Note: 1 indicates ecological marginal area; 2 indicates ecological transition zone; 3 indicates ecological connection zone; 4 indicates ecological buffer zone; 5 indicates ecological core area.

The results show that the ecological core, ecological buffer, ecological connection, ecological transition, and ecological fringe areas are 3.22×10^4 km^2 (1.98%), 6.80×10^4 km^2 (4.17%), 2.50×10^5 km^2 (15.34%), 3.05×10^5 km^2 (18.70%), and 9.75×10^5 km^2 (59.80%), respectively (Figure 4a). The spatial differentiation of the ecological security pattern of a single element is basically consistent with the comprehensive ecological security pattern.

At present, the ecological security grade is mainly distributed based on the ecological marginal area. As seen in Figure 4b, bare land is the major land use and cover in this area, which is generally a large area of continuous patches, accounting for 94.49%, and most of them are inaccessible. The ecological transition zone is mainly composed of grasslands, accounting for 62.22%. It is accompanied by some agricultural land and bare land. The patch area is small, and the distribution is relatively fragmented. It is the main area of human daily activities. The ecological connection area is mainly composed of grassland, accounting for 82.78%. The grassland distribution is relatively neat and continuous, but the fragmentation of other land use types is high. This area consists of more frequent human activities. The land use of the ecological buffer zone is highly diversified. Although the main land use is grassland, the distribution of other land use types is more balanced. The patches of the same land use type are more concentrated and less affected by human activities. The ecological core area is mainly composed of water, grassland, and woodland. Although the overall distribution is relatively scattered, the patch area is smaller than other areas. However, the local aggregation is high, and the continuity between patches is strong. Moreover, this area is mainly located in inaccessible mountainous areas or large water bodies, so the human activities in this area are only slightly affected.

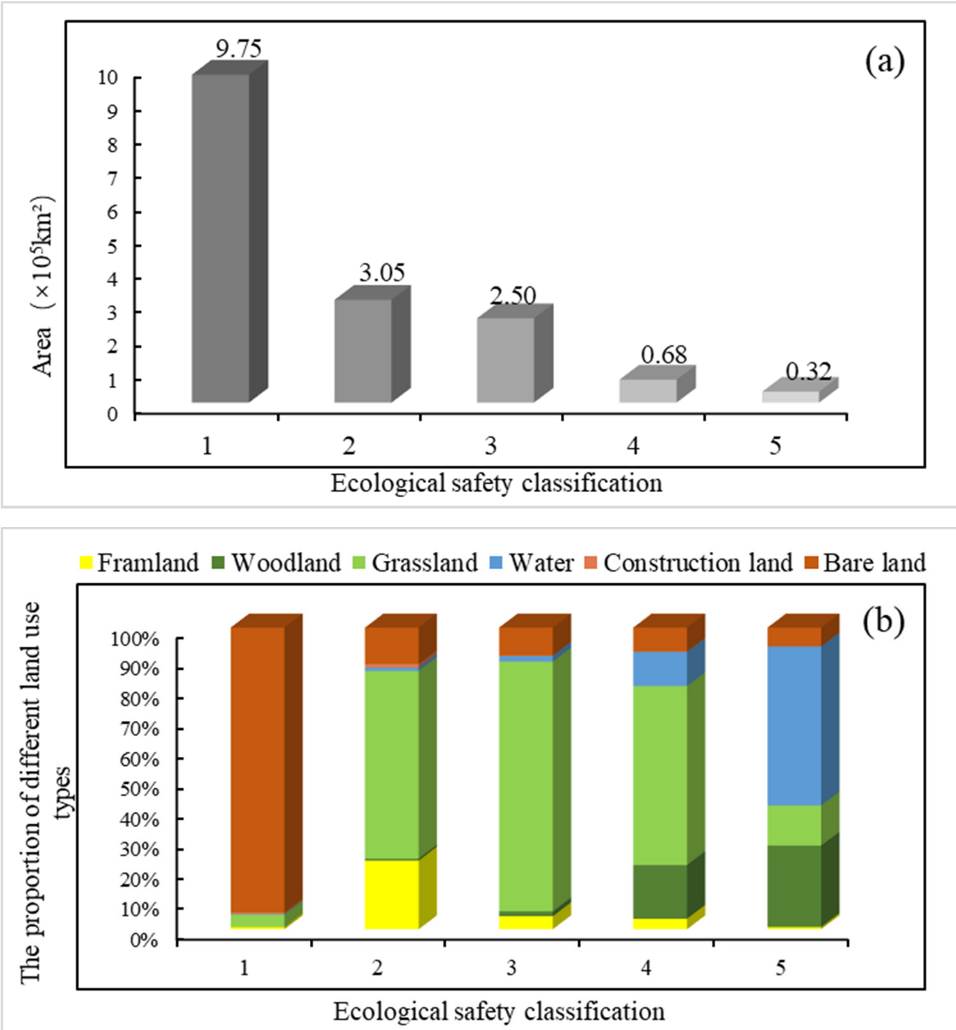

Figure 4. The statistics of ecological safety classification. ((**a**) Area occupied by different levels of ecological security; (**b**) The proportion of land use types in different ecological security levels).

The spatial differentiation of ecological security also has obvious regularities. Areas with higher ecological security levels are mainly distributed in mountainous areas and water bodies far away from human activities, and therefore suffer less damage. On the other hand, due to the natural characteristics of arid areas, the distribution of forest land and water bodies is relatively concentrated, which makes it easier to store precipitation in the complex mountains. Hence, the overall ecological security level of mountainous areas is better. In other areas, bare land is mainly composed of desert, i.e., in the Gobi Desert. Even though the desert area is also inaccessible, the natural background is relatively poor as it is naturally an area with a harsh ecological environment.

3.2. Construction of Ecological Network

3.2.1. Source Identification

In this study, the ecological core area and the ecological buffer zone are used as foreground data, and the remaining areas are used as background areas for the MSPA

(Figure 5). Table 7 shows the statistical results of the area and the proportion of each landscape.

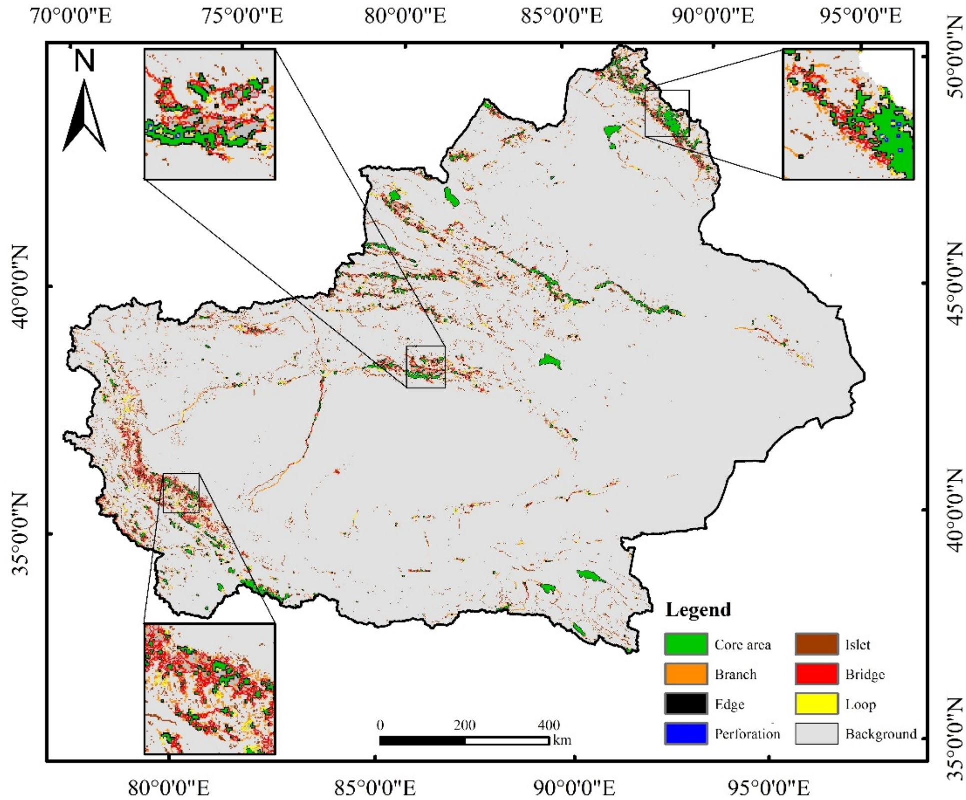

Figure 5. The landscape type of ecological safety based on MSPA.

Table 7. Statistic of landscape types based on MSPA.

Landscape Type	Area/km^2	Proportion of Prospects/%	Proportion of Total Area/%
Core	1.86×10^4	18.51	1.14
Islet	2.52×10^4	25.12	1.54
Perforation	0.02×10^4	0.18	0.01
Edge	1.94×10^4	19.29	1.19
Loop	0.38×10^4	3.81	0.23
Bridge	1.53×10^4	15.18	0.93
Branch	1.80×10^4	17.91	1.10
Total	10.1×10^4	100.00	6.15

Figure 5 and Table 7 show that the ecological core area and ecological buffer zone are relatively small, only accounting for 6.15% of the total. In the foreground landscape, the isolated island area accounts for the largest proportion, followed by the edge area and the core area. The core area and the ring road area account for a smaller proportion, indicating that the connectivity between patches in this area is weak, where the distribution is relatively scattered, with complex edges and a broken shape. There are few branch lines around the core patches, indicating that the core patches lack contact with each other. The material exchanges formed in the outer landscape are easily disturbed by the environment, and the migration and diffusion of species are restricted to a certain extent, which is not conducive to the protection of biodiversity in the long run. From a spatial point of view, the core patches are far apart, mainly distributed along the oasis.

Interestingly, the core patches have a relatively high degree of aggregation and are mostly large-area continuous patches, with a strong ecological potential. The bridging areas that play the role of structural corridors in the landscape account for 15.18% and are mainly distributed around the core area. Overall, subject to the natural characteristics and spatial scope of the study area, the landscape in this area presents certain distribution characteristics, with strong local landscape effects, but the overall difference is obvious.

On the basis of MSPA, by taking the connectivity of the landscape and its effective value into account, an area greater than 10 km^2 and with a *dPC* value in the top 20% was selected as the ecological source. A total of 51 sources were screened out with a total area of 1.08 $\times$ 10^4 km^2. The area is composed of forest land and water bodies (Figure 6).

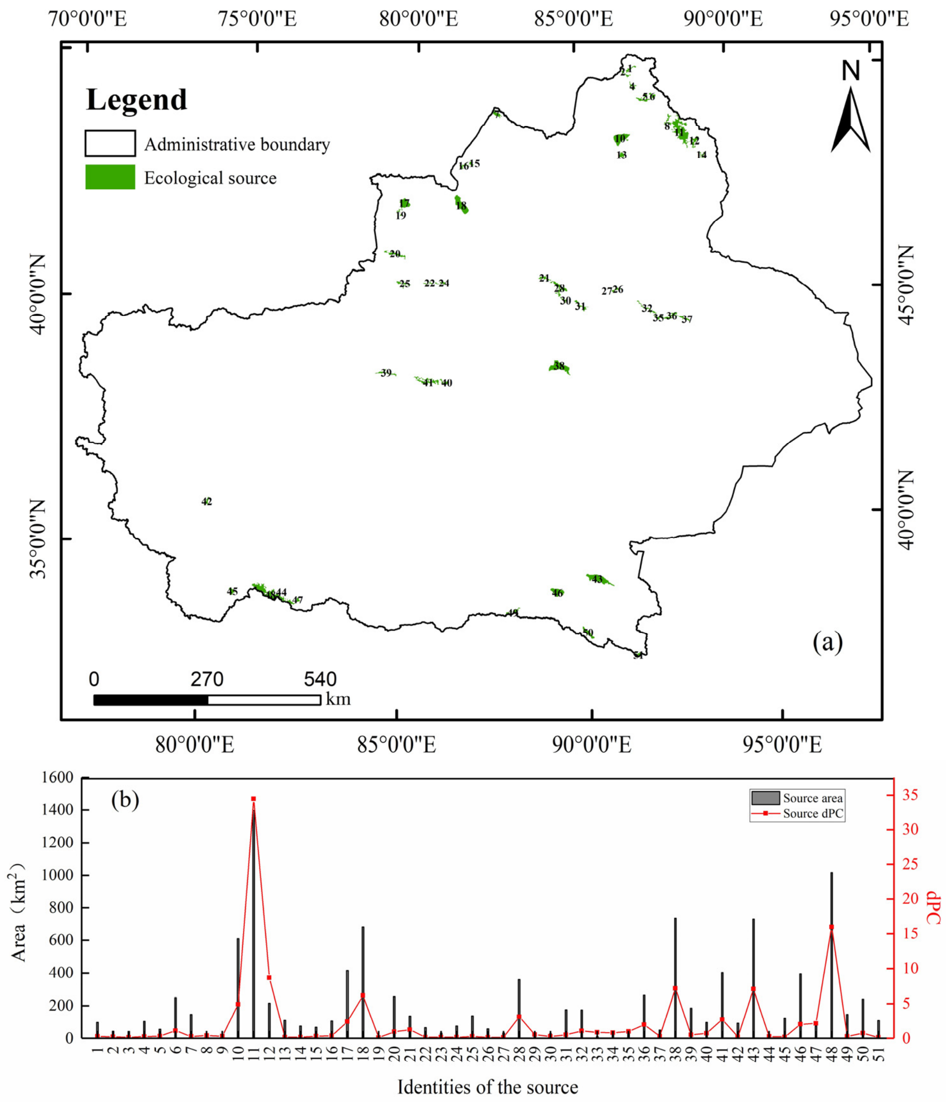

Figure 6. Information on ecological source attributes ((**a**) the features and identification of the source; (**b**) the spatial distribution of ecological sources).

3.2.2. Corridor Recognition and Screening

The cost past module in ArcGIS 10.2 uses the core source as the input source and uses the integrated resistance surface (Figure 7a) as the input resistance. The cumulative value of the resistance from each source to other sources was calculated, and the minimum threshold was obtained. The cumulative resistance surface (Figure 7b), on the basis of the minimum cumulative resistance surface, generated the path of least resistance and connected the ecological sources two by two, resulting in a total of 1276 potential corridors with a total length of 4.76 $\times$ 10^5 km (Figure 7c). The potential ecological corridors show a north–south direction in space and run through the entire study area. They are the main channels of the ecological flow and the species diffusion in the region. The ecological corridors are mainly distributed on both sides of the Tianshan Mountains in central Xinjiang. These corridors connect large-scale sources. Thus, improving the connectivity of ecological land is conducive to protecting biodiversity, maintaining the stability of the ecosystem, and providing a structural foundation for enhancing the value of ecosystem services.

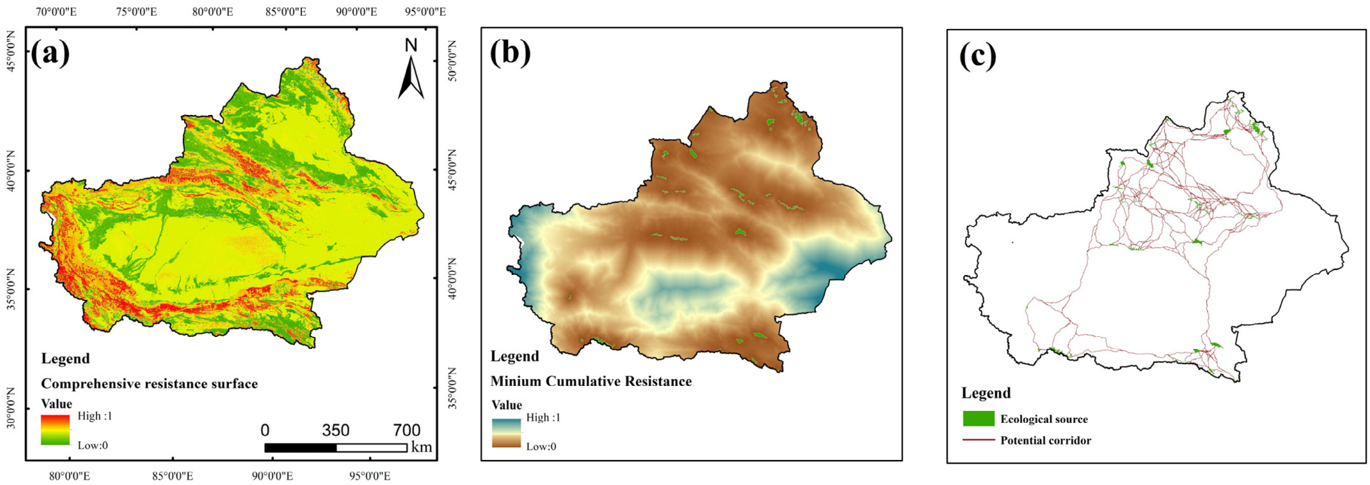

Figure 7. The result of corridor recognition ((**a**) comprehensive resistance surface; (**b**) minimum cumulative resistance surface; (**c**) potential corridor).

A total of 79 optimal corridors were selected by the gravity model. We determined the model's function classification and divided it into the main corridor and the bridge corridor based on the resistance value and the spatial location of the corridor. The main corridor is the central corridor that connects different sources in the ecological network, while the bridge corridor is an important corridor that connects different subsystems and promotes the exchange of energy and material between various subsystems. Some of the potential corridors were also selected as planned corridors to form a corridor network system in order to ensure that the entire ecological network was a closed network.

3.2.3. Ecological Node Identification

The "ridge line" of the resistance surface was extracted through hydrological analysis, where a total of 536 ecological stepping-stones were identified in combination with the intersection of ecological corridors. The land use types where the ecological stepping-stones are located include grassland, woodland, water body, and cultivated land. They are mainly grassland and woodland, based on the land use land cover data from 2018. Combining the characteristics of the study area and considering the rationality of the spatial distance and node layout, we eliminated the ecological stepping-stones that are relatively close in space and difficult to protect. Finally, the locations of 73 ecological stepping-stones were obtained.

The ecological breakpoint was determined to be the intersection of the road network and the ecological corridor. So, a total of 1821 ecological breakpoints were identified. Some were eliminated based on the characteristics of the study area, as well as the spatial distance and the ecological safety matrix where the ecological breakpoint is located. Finally, 47 ecological breakpoints were identified and classified according to the different functional corridors.

3.2.4. Results of Ecological Network

On the basis of the above, this research constructed a composite ecological safety network that was composed of points (stepping-stones and ecological breakpoints), lines (ecological corridors), and areas (ecological sources and safety zones) intertwined and organically combined as shown in Figure 8 and Table 8. Taking into account the distance between different ecological elements and the needs of land spatial planning, on the basis of relevant research, the whole region is divided into seven ecological subsystems, which provides theoretical support for the final realization of regional ecological governance and ecological control [69–71].

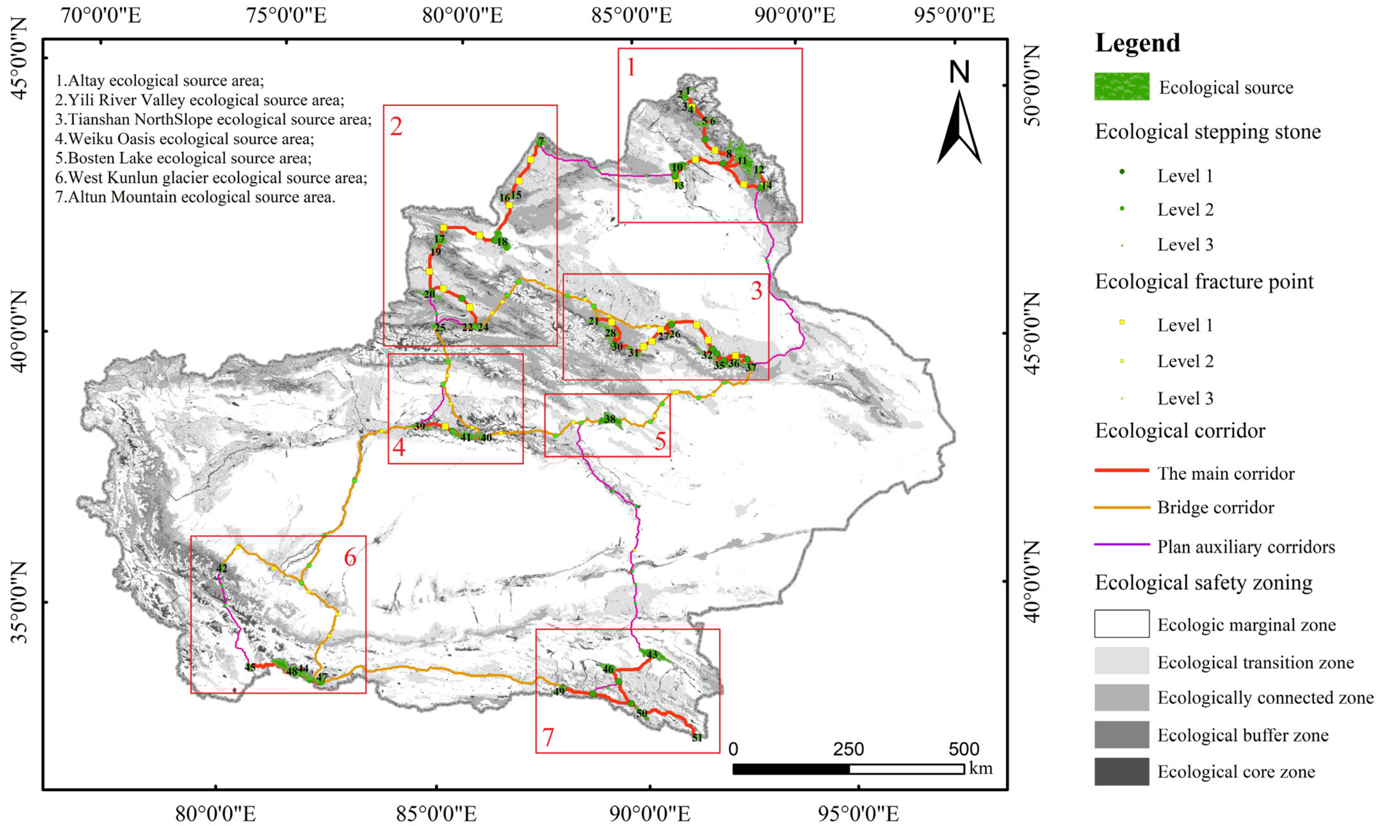

Figure 8. The ecological network of Xinjiang.

Table 8. Statistics of ecological network elements.

Ecological Source Area	Source		Corridor						Ecological Node					
			The Main Corridor		Bridge Corridor		Planning Auxiliary Corridor		Stepping-Stone			Ecological Fracture Point		
	Number	Area/km^2	Number	Length/km	Number	Length/km	Number	Length/km	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
1. Altay ecological source area	13	3031.23	16	696.69	0	0.00	1	558.01	5	0	5	6	0	0
2. Yili River Valley ecological source area	11	2008.83	11	771.53	1	145.47	3	519.33	5	4	3	8	3	0
3. Tianshan North Slope ecological source area	13	1401.18	23	728.75	5	1012.46	0	0.00	11	2	1	8	6	0
4. Weiku Oasis ecological source area	3	688.60	5	216.25	2	694.86	1	133.54	3	3	0	1	5	0
5. Bosten Lake ecological source area	1	737.57	0	0.00	2	319.19	1	656.88	0	4	1	0	4	0
6. West Kunlun glacier ecological source area	5	1324.23	5	242.04	3	1138.70	1	265.33	4	6	2	0	5	0
7. Altun Mountain ecological source area	5	1625.05	6	577.74	0	0.00	1	68.94	5	1	8	0	0	1
Total	51	10,816.68	66	3233.01	13	3310.68	8	2202.04	33	20	20	23	23	1

The core area of the ecological subsystem is centered around the Tianshan Mountains according to the spatial distribution of each subsystem and the complexity of the network. The most complex system is in the northern slope of the Tianshan Mountains, with 13 ecological source areas that are distributed in strips along the Tianshan Mountains. There are 28 corridors, 14 ecological stepping-stones, and 14 ecological fracture points. This region has a complex ecological landscape, and the distribution of ecological patches is relatively scattered. It is also the area where human activities are most concentrated in Xinjiang, resulting in a high contradiction between humans and the land, and thus it faces greater ecological risks. The Altay Ecological Source Area has 14 ecological source sites, 17 ecological corridors, 15 ecological stepping-stones, and 15 ecological breakpoints. The main type is forest land. The source areas are relatively densely distributed, and they are far away from human activities for easy protection. The Ili River Valley Ecological Source Area has 11 ecological sources, 15 corridors, 12 ecological stepping-stones, and 11 ecological breakpoints. However, the entire ecological source has a large north–south span. In the process of protection, the maintenance and transformation of ecological nodes should be strengthened to promote the connectivity of the ecological landscape. The Bosten Lake Ecological Source Area is mainly centered on Bosten Lake, and the protection of the water source should be strengthened. Meanwhile, certain restrictions on the surrounding human activities should be imposed. The Weiku Oasis Ecological Source Area has three ecological sources, eight ecological corridors, six ecological stepping-stones, and six ecological breakpoints. The source areas are mainly forestland, which is relatively densely distributed. As it is located on the edge of the desert, there is a strong risk of desertification. The West Kunlun Glacier and Altun Mountain Ecological Source Area are relatively far away from the human activity area, and the ecological foundation level is relatively high. At the same time, they are within the scope of the nature reserve and have been properly protected.

4. Discussion

4.1. The Development of Ecological Network Construction in Xinjiang

The regional ecological environment construction is a continuous and dynamic process. Under the fragile ecological environment of Xinjiang, the spatial pattern of ecological elements will change to a certain extent with the development of regional economy, society, and human activities. The strategy of optimizing the layout of ecological security in the future will also be biased due to land policy and environmental changes. In future research, the construction of an ecological security pattern should be further in line with the development and utilization, as well as the planning and control of the land and space [7,8]. According to the requirements of the construction of the ecological security pattern of land and space, it is necessary to fully consider whether the existing ecological "source" land can meet the needs of maintaining regional ecological security and construction, as well as adhere to the protection and restoration measures and new construction measures of "source" land in the process of ecological zoning development and construction [72]. At the same time, we should also pay attention to the greening construction along the corridor to improve its damage protection ability, maintain and enhance the function of the ecological corridor, and make it a more stable ecosystem component [73,74].

4.2. Applicability of Research Methods

This paper uses some classical methods in ecology to discuss the basic situation of Xinjiang's ecological security pattern and build an ecological network. These estimation methods can effectively reveal and highlight the practical contradictions and development needs of regional ecological security. The "Source-corridor-resistance surface" model is a classic model of ecological network construction. The difference is that researchers often focus on the choice of source. The urban ecological network of Nanchang is built based on the green space [1]; the urban ecological network of Wuhan was built based on the threat of the urban road network [75]; the ecological network of the central urban area of Harbin was built based on the urban landscape pattern [76]; a networked evaluation was made by the ecological environment in the upper reaches of the Yellow River based on the intersection of agriculture and animal husbandry [22]; and the construction of an ecological network was explored in Xinjiang based on land use cover [29]. There are some similarities in methods between this study and other studies. The difference is that this study does not focus on single factor evaluation in the selection of source areas but constructs a composite ecological security pattern based on habitat quality, soil and water conservation, and ecosystem service value, which makes it more appropriate and more scientific in its content. In addition, there is still a lack of relevant research on the Xinjiang ecological network; therefore, this study can supplement the prior research.

4.3. Limitations and Prospects

In general, there are some shortcomings in this study, such as only few relevant regional studies being reported, and some model parameters referring to similar adjacent regions or adopting pan-regional parameters. At the same time, limited by the vast area of research and the complex internal environment, we only carried out analysis at the macro scale when conducting relevant research, and some natural environment differences at the micro scale were inevitably overlooked. In addition, when constructing the ecological security pattern, it is insufficient to determine the regional ecological security level solely based on the ecosystem service's function. Ideally, the natural conditions and development needs of the regional ecological environment should also be considered in ecological environment and landscape planning. This is essential in order to enhance the regional ecosystem's stability, and the rates of success of the land space strategy implementations. In future research, we will try to perform analyses based on smaller scales to supplement and verify the overall results, and improve the scientific quality and applicability of relevant research. In the next step, we will strive to achieve the goal of hierarchical and refined ecological management by obtaining more comprehensive, refined, and targeted data, and by conducting ecological network construction research on local small areas with typical characteristics and large differences in the region.

5. Conclusions and Recommendations

The construction of an ecological network reduces the difficulty of ecological governance and restoration. By controlling key ecological sources, corridors, and key nodes, the objects of ecological protection are more targeted, and the scientific nature of ecological management and control is enhanced. It involves an expansion and optimization of the existing ecological safety management in the region, which helps to promote the sustainable ecological development of Xinjiang more effectively. The conclusions of this study are as follows:

(1) The spatial differentiation of the ecological security pattern of a single element is basically consistent with the comprehensive ecological security pattern. The ecological security level of the study area is mainly ecological fringe, and the overall ecological conditions are bad, mostly in a continuous large area of desert, showing very obvious characteristics of arid areas. The ecological land is extremely fragmented and mainly distributed in the mountains and waters which are far away from human activities, with obvious spatial differences and low ecological security level.

(2) The ecological network framework in Xinjiang has the structural characteristics of an uneven distribution of "source", broken corridor structure, and a low degree of networking. The ecological corridor is spatially oriented from north to south and runs through the whole study area. Based on the prominent contradiction between humans and land, this study combines the regional physical and geographical characteristics and the overall development plan. The ecological space layout system of "7 ecological subsystems, 51 source areas, 87 ecological corridors, and 33 ecological nodes" has been constructed.

In view of the results from the construction of the network, the combination of the ecological protection principles, and the theory of system control, we proposed the following protection strategies:

(1) Protect the core source area. The core source areas in Xinjiang's ecological network are mainly composed of forest land and water bodies, and they are concentrated

in mountainous areas and large water bodies. The mountainous areas have large terrain undulations and precipitation, and thus often have a greater risk of soil erosion. These areas are closer to the dense areas of human activities. Thus, these ecological networks face a greater risk of destruction. Therefore, proper maintenance of the ecological land around the source area is essential. Management should convert more farmland to forest and grassland, strengthen the protection of existing forest land, and promote tree planting in risk areas. In addition, decision makers should reduce the interference of human activities in the source area by restricting the development of national land space or opening up the edge buffer zone of the source area. Moreover, management should prevent urban sprawl and cultivated land occupation around the ecological source area to improve the landscape conditions of other ecological land, and to artificially cultivate and optimize ecological patches with great potential. By doing so, they should be able to increase the number of potential sources, and, at the same time, promote the improvement of the landscape conditions of existing sources.

(2) Build ecological corridors. The construction of ecological corridors should be divided into different levels and focused. The focus of management and control should be concentrated on the four subsystems on both sides of the Tianshan Mountains. The construction of corridors should make full use of the current land types, and ensure that all sources can be directly or indirectly connected.

(3) Improve the layout of ecological nodes. The current ecological nodes mainly involve maintenance, and the control nodes, such as the ecological stepping-stones at the intersection of corridors or near the source, should be strengthened. The stability should be enhanced by planting drought-tolerant vegetation, expanding the area, and improving the status of land use. The graded ecological stepping-stones adopt different construction strategies, which can be appropriately increased or decreased by judging the economic benefits of node construction.

(4) Regulate the ecological subsystem. From the perspective of the current ecological subsystem, the ecological source areas of Altay, Altun Mountain, and West Kunlun Glacier are far away from the spaces for human activities. So, the risk of damage is low. Since other ecological source areas are clustered around the human activity space with a greater risk of damage, they must be protected. Different administrative strategies should be adopted to realize the linkage between different ecological source areas. For example, the Altay ecological source area is mainly forestland, so it is necessary to pay attention to water and soil conservation and strengthen the stability of the forest ecosystem through vegetation restoration and controlled development. The Bosten Lake ecological source area is dominated by large water bodies, so attention should be paid to water source protection and controlled agricultural irrigation. In terms of ecological network governance, Yin et al. [77] conducted in-depth research on the status quo of the ecological network in Hunan Province from the perspective of territorial and spatial planning and provincial cooperation. Gu et al. [78] put forward the supervision of ecological element cybernetics theory for the ecological network of nature reserves in Fujian Province. In actual ecological management, we must fully consider the regional ecological background and ecological needs and then formulate targeted protection strategies.

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