Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 9476860, 17 pages
https://doi.org/10.1155/2022/9476860

Research Article

Mathematical Problems in Engineering Landscape Ecological Security Assessment and Ecological Pattern Optimization of Inland River Basins in Arid Regions: A Case Study in Tarim River Basin

Yuanrui Mu [1,2] and Wei Shen [1]

[1]*School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China*
[2]*No. 11 Geological Party, Xinjiang Bureau of Geology and Mineral Resources, Changji, Xinjiang 831100, China*

Correspondence should be addressed to Yuanrui Mu; 3001180140@cugb.edu.cn

Received 10 March 2022; Revised 2 April 2022; Accepted 7 April 2022; Published 2 May 2022

Academic Editor: Xuefeng Shao

Tarim River Basin (TRB), located at the Eurasia center, is a typical arid inland basin. It is critical to maintain the ecological security of TRB for the sustainable development of oases. With the inputs of four period land use data, the landscape ecological risk assessment model, the minimum cumulative resistance model, and network analysis were applied to analyze the landscape ecological security pattern and to optimize the landscape pattern. The results show that, during the period 1990–2020, (1) landscape ecological risks of TRB increased by 1.76%; (2) landscape ecological risks tend to agglomerate in space in each period. The clusters of high-high risk are mainly distributed in the central and eastern desert areas, while low-low risk clusters are mainly distributed in watersheds Oasis and mountains. (3) Ecological security pattern network of the basin becomes more complex and better. The optimized pattern, called Oasis Corridor Functional Area with one ring, two screens, two belts, ten corridors, and multicenter, is expected to provide reference for the ecological environment management and restoration.

1. Introduction

As an essential part of national security [1–5], ecological security is equally essential to political security, homeland security, military security, and economic security [6]. It has a strategic position and great significance, and it is also the key to achieving sustainable development [7, 8]. The concept of ecological security pattern and optimization originates from the West. In 1967, Mac Arthur and Wilson put forward the theory of island biogeography and "ecological network model" [9]. At present, based on different perspectives such as land use, landscape pattern, and ecological infrastructure construction, scholars have gradually developed from simple qualitative and quantitative pattern and planning analysis to more complex space research such as static pattern optimization, dynamic pattern simulation, and ecological state trend analysis [10]. The research methods mainly include multi-index comprehensive evaluation, minimum cumulative resistance model, scenario simulation, and landscape ecological index. Taken together, the index construction and methods of ecological security pattern research are still in further exploring. Most studies use the framework of "source-resistance surface-corridor" to construct the regional ecological security pattern [11]. In addition, most researchers regard the identification of ecological sources and ecological corridors as an important part of the construction of ecological security pattern, but the identification of strategic points is ignored.

Compared with other regional ecological risks, watershed ecological risk assessment has unique watershed characteristics [12]. In the current study, landscape analysis method is mainly used to analyze watershed ecological risk [13]. For example, Craig et al. [14] combined land use with landscape structure and used ecological threat index to evaluate the ecological risk status of Colorado River Basin; Yan et al. [15] constructed a watershed ecological risk assessment model according to the three indexes of landscape risk, vulnerability, and loss to evaluate the ecological risk of Taihu Lake Basin; Xu et al. [16] analyzed the temporal and spatial pattern of ecological security of coastal wetlands in Jiangsu by using landscape interference index and vulnerability index; Xie et al. [17] constructed an ecological risk assessment system based on landscape vulnerability, landscape structure index, and landscape component area to evaluate the ecological risk of Taihu Lake; Ma et al. [18] selected landscape indicators to quantitatively characterize the landscape pattern in medium and downstream of Shule River according to the degradation situation of the ecosystem; Ran et al. [19] applied an ecological risk assessment framework integrating landscape pattern characteristics and landscape vulnerability dynamics to analyze the spatiotemporal variations of landscape ecological risk in the Yangtze River Delta from 2000 to 2018. The above achievements provide the theoretical basis for watershed ecological planning, landscape structure adjustment and optimization, and social and economic sustainable development at home and abroad.

The Tarim River Basin (TRB) is the fifth largest in the world, and also the largest inland river basin in China. Its watershed runs around the Taklimakan Desert from west to east and through the Tarim Basin. It is a hybrid system with natural and social attributes, which compose of forests, grasslands, wetlands, deserts, and people living in the basin. It has typical characteristics such as good primitiveness and naturalness. The TRB is an essential part of the ecological barrier in northwest China in regulating the climate, conserving water sources, preventing desertification, protecting biodiversity, and maintaining the ecological balance. Due to the vulnerability of the ecological environment in arid areas and the sensitivity to external interference [20], the TRB has become one of the key areas for global change researches. Over the decades, global climate change and human activities have had a great impact on the ecological environment of the TRB. For example, the changes of Land Cover and landscape pattern, and drastic desertification, the shrinkage of wetland area, grassland degradation, reduction in biodiversity, and the ecological risks have attracted more and more attention. At present, the research on ecological risk assessment mainly focuses on some key areas in TRB [21–26], while the large-scale research on the whole TRB is still lacking. At the same time, for the optimization of landscape pattern, many studies focus on models and methods but lack the combination of landscape ecological security and pattern optimization and lack the evolution analysis on time series. This study grasps the watershed ecosystem pattern and ecological risk changes from a macro perspective. Taking the whole TRB as the research object, the paper uses the landscape ecological risk evaluation model to quantitatively evaluate the temporal and spatial distribution and change characteristics of landscape ecological risk and then designs the optimal layout scheme of ecological spatial structure in the TRB. It is expected to provide scientific reference for optimizing the ecological spatial structure of TRB, ensuring regional ecological security and promoting regional sustainable development.

2. Study Area and Data Source

2.1. Study Area. The TRB (71°39–93°45E, 34°20–43°39N) is located in the center of Eurasian continent and the south of Xinjiang. It borders the Pamir Plateau in the west, the Kunlun Mountains and Altun Mountains in the south, and Kuruktag Mountain in the east. The Taklimakan Desert is located in the middle of the basin. The area of TRB is about $1.02 * 106\,km^2$ [27], and it is the largest inland river basin in China (Figure 1). It has abundant natural resources but a fragile ecological environment [27–29]. The total length of the Tarim River is 2179 km. At present, only the Aksu River, Hotan River, Yarkant River, and Kaidu-Peacock River have surface hydraulic connections with the mainstream of the Tarim River [27]. Its runoff mainly comes from its source and snowmelt and glacial meltwater in the Tianshan and Kunlun Mountains [30, 31]. The basin is located in the hinterland of the Eurasian continent at mid-latitudes. The terrain of the basin is low in the middle and high around, inclined from west to East. TRB situates the inland with dry climate, scarce precipitation, and high evaporation. The average annual precipitation of TRB is 17.4–42.8 mm, and the annual average temperature is 10.6–11.5°C. And the climate type of TRB is a temperate arid continental climate [26]. The land use types are mainly sandy land, unused land, and grassland, and the ecological environment is extremely sensitive and fragile.

2.2. Data. The land use/land cover change data in 1990, 2000, 2010, and 2020 are from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn), with a spatial resolution of $30m \times 30\,m$. With ArcGIS 10.2, the secondary land types were reclassified into nine land-use types: cropland, forest, grassland, waterbody, sandy land, saline-alkali land, Gobi, and construction and unused land. The GDEMV2 digital elevation data was used, with a spatial resolution of $30m \times 30\,m$. It is collected from the Geospatial Data Cloud Platform of the Computer Network Information Center of the Chinese Academy of Sciences (https://www.gscloud.cn/). This study uses the Albers_Conic_Equal_Area projected coordinate system.

3. Method

The framework of this study is mainly divided into three parts (Figure 2) Firstly, the landscape indexes are used to dynamically evaluate the landscape ecological risk of TRB. The ecological sources are determined according to the InVEST model and landscape connectivity indexes, and the cumulative resistance surface is constructed combined with the results of landscape ecological risk assessment. Then, the ecological corridors are extracted through MCR model and circuit theory, the ecological nodes and ecological obstacles are identified, and the watershed ecological security pattern is constructed. Finally, according to the above research

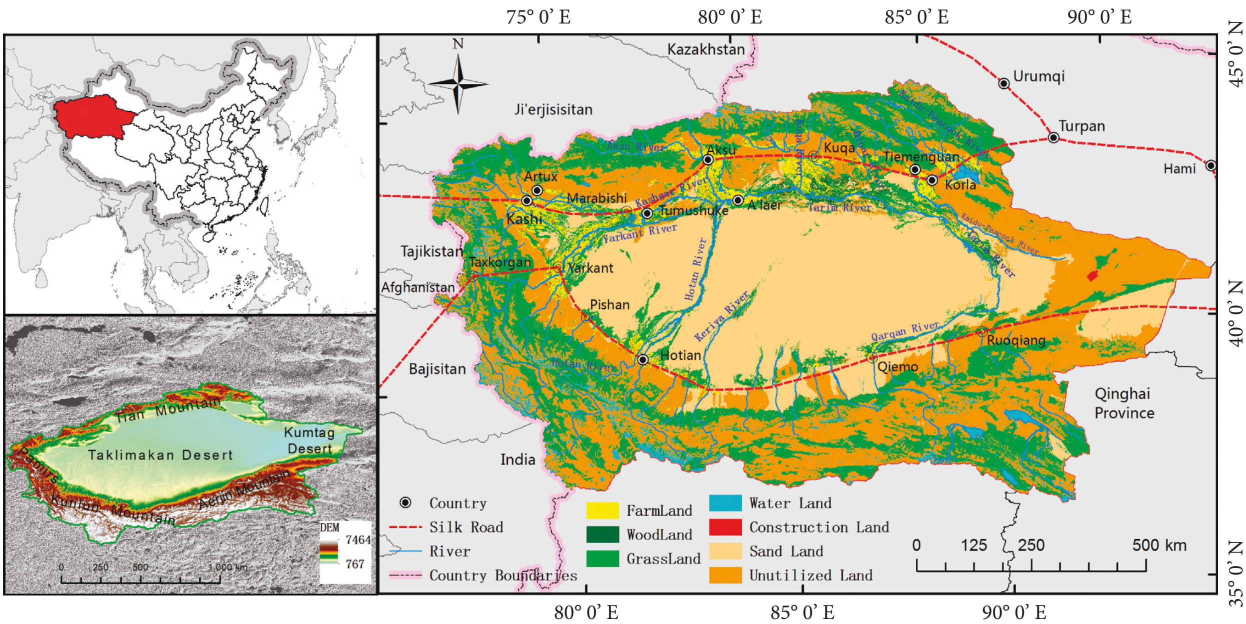

FIGURE 1: The location and land use/land cover of Tarim River Basin.

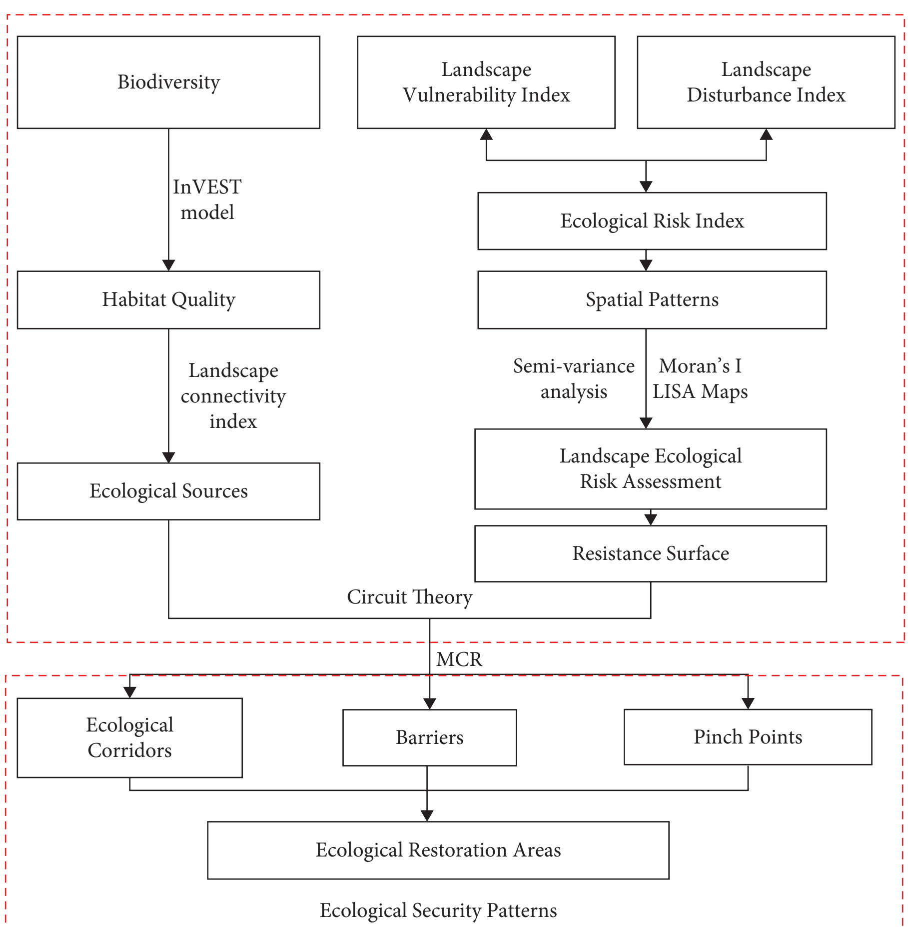

FIGURE 2: Framework of this study.

results, the measures and suggestions for the optimization of ecological security pattern are put forward. The specific framework is shown in Figure 2.

3.1. Construction of Landscape Ecological Risk Assessment Index System. The landscape pattern index highly condenses the information and is a simple quantitative index that expresses some aspects of its structural composition and spatial configuration. Based on previous research results [32, 33] and according to the relationship between the ecosystem landscape pattern and ecological risk, the landscape interference index, landscape fragmentation index, landscape separation index, landscape dominance index, landscape fragility index, and landscape loss index were used to establish the model of ecological risk index (Table 1). In order to spatially express the regional heterogeneity of landscape ecological risk [34, 35], a square grid of 10 km × 10 km was selected to divide the study area. The total number of risk areas is 5522. The ecological risk of each grid was calculated as the landscape ecological risk at the center point of each sample area.

3.2. Specialization of Landscape Ecological Risk. This study used ArcGIS10.2, GS + 9.0, spatial autocorrelation analysis, and semivariance analysis to represent the landscape ecological risk in the TRB spatially. Through the calculation of spatial weight and Moran's I index, the spatial autocorrelation of ecological risk in the study area is obtained, which reflects the distribution of adjacent ecological risk values in space. Spatial autocorrelation analysis can be divided into global correlation and local correlation [38, 39]. The best-fitting model was obtained by fitting the semivariogram to the point data through the geostatistical analysis module of ArcGIS [40–42]. We used the ordinary kriging interpolation method to get the spatial distribution map of ecological risk in four different periods.

(1) Global spatial autocorrelation (Moran's I). Global spatial autocorrelation is used to study the spatial correlation and regularity of variable attributes. The formula is as follows:

$$Moran'sI = \frac{N\sum_{i=1}\sum_{j=1}W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2\left(\sum_{i=1}^{n}\sum_{j=1}^{m}W_{ij}\right)}, \quad (1)$$

where N is the total number of sample areas in the study area; x_i and x_j, respectively, represent the observation value of a characteristic attribute x on the spatial unit ($i \neq j$) $\overline{x}$ is the mean value of x; W_{ij} is the spatial weight matrix.

(2) Local spatial autocorrelation. Local spatial autocorrelation can better show the spatial aggregation of ecological risk. It can show the spatial aggregation of ecological risk in the form of graphics, which can be divided into High-High, High-Low, Low-Low, and Low-High aggregation [43, 44]. The calculation formula is

$$I_i = \left(\frac{x_i - \overline{x}}{m}\right)\sum_{j=1}^{n}W_{ij}(x_i - \overline{x}), \quad (2)$$

where if the I_i value is positive, it indicates the spatial agglomeration of similar values (high or low values) around the regional unit, and if it is negative, it indicates the spatial agglomeration between dissimilar values.

(3) Semivariogram analysis method. In this paper, GS + 9.0 software is used to fit the semivariogram, establish the fitting model, and carry out the spatial analysis of eco-environmental security to reflect the changes of observed values at different distances [33, 45]. Then, the semivariogram can be expressed as

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z(x_i) - z(x_i + h)\right]^2, \quad (3)$$

where $\gamma(h)$represents the semivariogram, h is the step size, $N(h)$ represents the number of samples with interval h, and z(xi) and $z(x_i + h)$ represent the measured values at $z(x_i)$ and $z(x_i + h)$, respectively.

3.3. Habitat Quality Model. InVEST model was developed by Stanford University and the World Wide Fund for Nature in the United States. The original intention is to weigh the relationship between regional development and conservation. "Habitat Quality" in the model can be used as a reflection of habitat quality. It is a quantitative evaluation of habitat quality from the perspective of biodiversity [46, 47]. According to the InVEST model guide [48, 49] and the natural conditions of the TRB, this study set wetlands, woodlands, grasslands, and waters as habitats, and other lands as nonhabitats. Residential sites, roads, railways, and rural roads are considered threat sources for habitats. Based on reference values in the InVEST model guide and related literature [49–51], we set the various parameters. The habitat quality calculation formula is as follows:

$$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right], \quad (4)$$

where Q is the habitat quality of the grid x of land use type j, H is the habitat suitability of the land type j, D is the habitat degradation degree of the grid x of the land type j, k is the half-saturation constant, which is generally 0.50, and z is the default parameter, generally 2.50 [48, 52, 53].

3.4. Construction and Optimization of Ecological Security Pattern. In this study, the cumulative resistance surface of the landscape pattern was constructed according to the results of ecological source and landscape ecological risk assessment, and the minimum cumulative resistance model (MCR) and network analysis were used to establish ecological corridors, identify ecological nodes, and optimize the landscape pattern. The formula is as follows [26]:

Table 1: The methods of landscape pattern indices.

Index	Formula	Ecological meaning of landscape pattern index
Landscape fragment, Ci	$C_i = n_i/A_i$	Ci represents the fragmentation degree to which the landscape is segmented at a given time and nature, with higher values representing higher fragmentation of the landscape and greater human disturbance to the landscape. n_i is the number of patches of landscape type i, A_i is the total area of landscape type i.
Landscape separation, N_i	$N_i = A/2A_i\sqrt{n_i/A}$	N_i represents the degree of separation of patch distribution in the same landscape type, and the larger the value, the more complex the corresponding landscape spatial distribution and the higher the degree of fragmentation [36]. A is the total landscape area.
Landscape fractal dimension, F_i	$F_i = 2\ln(p_i/4)/\ln A_i$	F_i is a noninteger dimension value representing the geometric complexity of the patch or landscape mosaic. The value ranges from 1 to 2. The larger the value, the more complex the structure and change of the landscape patch. P_i is the perimeter of landscape type i.
Landscape interference, E_i	$E_i = aC_i + bN_i + cF_i$	E_i represents the effect of human interference on the area. The smaller the value, the better the survival of the creature. a, b, and c are the weights of the corresponding landscape indices, and $a + b + c = 1$, assign a, b, and c to 0.5, 0.3, and 0.2, respectively [37, 38].
Landscape fragility, V_i	Expert consultation and normalization	V_i represents the sensitivity of different landscape types to external disturbances, and the larger the value, the higher the ecological risk. According to the actual situation of the study area, the desert and Gobi are assigned a value of 7. The saline-alkali land is assigned a value of 6. The water area is assigned a value of 5. The cropland land is assigned a value of 4. The grassland is assigned a value of 3. The forest is assigned a value of 2. The urban land in the oasis in the arid area is the main area of human activities, the most stable, and is assigned a value of 1. Then, the landscape fragility is calculated using normalization.
Landscape loss degree, R_i	$R_i = E_i \times V_i$	R_i expresses the difference in the ecological loss suffered by various types of landscapes when disturbed, that is, the degree of loss of natural attributes. Through the comprehensive reflection of landscape disturbance index and landscape vulnerability index
Ecological risk index, ERI	$ERI = \sum_{i=1}^{N} A_{xi}/A_x \times R_i$	Based on the landscape disturbance index and vulnerability index, the spatial pattern was transformed into ecological risk variables by sampling method, and the ecological risk index of land use was constructed. N is the number of landscape types, A_{xi} is the area of the i-th type of landscape component in the x-th risk area, and A_x is the total area of the x-th risk area

$$MCR = f_{\min} \sum_{i=1}^{m} \sum_{j=1}^{n} D_{ij} W_i, \quad (5)$$

where MCR represents the cumulative value of the minimum resistance between ecological source j and any grid i; D_{ij} represents the distance from the i-th grid to the j-th ecological source on the landscape pattern resistance; W_i represents the resistance value of the first grid on the surface of landscape pattern resistance to the operation of ecological flows. This study used the Linkage Mapper module to build ecological corridors. We use the Linkage Mapper toolbox to construct ecological corridors in ArcGIS10.2 software.

(1) Identification of "ecological source" and the generation of resistance surface. In this study, the habitat quality model was used to identify the comprehensive ecological source of the TRB. Firstly, the patches with an area greater than 100 km were imported into Conefor Sensinode 2.6 Software. The threshold is set to 2000, and the connectivity probability is set to 0.5. Then, the three landscape indexes, including landscape coincidence probability (LCP), Integral index of connectivity (IIC), and Probability of connectivity (PC), could be calculated. Finally, the patches with patch importance of higher than 1 in the core area are identified as the ecological source. With the inputs of landscape ecological risk and the selected ecological sources, the cumulative resistance surface of the TRB was calculated by the cost distance tool. Using the natural breakpoint method, the ecological land in the study area is divided into five levels: ecological core area, ecological buffer area, ecological transition area, ecological optimization area, and ecological governance area.

(2) The establishment of ecological corridors. With the input of the selected "ecological source" and the cumulative resistance surface of the landscape pattern, this study mainly used the Linkage Mapper tool to calculate the minimum cost path between each ecological source and the rest of the ecological source. The minimum cost path is the ecological corridor. The ratio of the cost-weighted distance of the least-cost path to the path length is used to describe the relative resistance of moving along the path [54]. And the ratio of each corridor is divided into small resistance, medium resistance, and high resistance according to the natural breakpoint method.

(3) Identify ecological "pinch points" and ecological barrier points. Ecological "pinch points" refer to areas that play an important role in ecological

protection. The identification of ecological "pinch points" is to ground one node (ecological source ground), input the same current electrical to other nodes (ecological source ground), and obtain the cumulative current electrical of each pixel through the iterative operation. The point with the high value of cumulative current electrical is the ecological "pinch point" [54, 55]. Ecological "pinch points" have high current electrical density and irreplaceability [56]. This study identifies "pinch points" in ecological corridors through the Pinchpoint Mapper module in Linkage Mapper toolbox. Ecological barrier points refer to areas where the movement of species between habitat patches is hindered. Removing these areas can increase the connectivity between ecological sources [57], and ecological restoration should be carried out in these areas. We use the Barrier Mapper module of Linkage Mapper toolbox to identify the barrier points in the ecological corridor.

(4) Optimizing the layout of ecological spatial structure in the TRB. According to the construction of the ecological security pattern in the TRB, identify the main components of the ecological security pattern and analyze their spatial and temporal distribution characteristics. Based on reference to the "green-heart corridor group network" ecological space structure optimization combination mode proposed by Yang Tianrong et al. [58] and the "corridor group network" ecological space structure optimization combination mode proposed by Guo Rongchao et al. [59], this study optimizes and reorganizes the ecological security pattern of the TRB. Based on the identified ecological source areas, relying on topographical features to build an ecological safety protection zone and dividing the ecological function zones of the TRB, we use central river systems, roads, and intersource corridors to connect functional areas to build a regional ecological corridor network system. Through the optimization and reorganization of "point-line-surface" ecological spatial structural elements such as oasis areas, ecological pinch points, and corridor networks [60], an ecological spatial structure system with multilevel and complex "oasis corridor group network" is constructed in the arid inland river basin.

4. Results

4.1. The Spatial-Temporal Evolution of Landscape Ecological Risk in the TRB. This study used the index model to fit the ecological risk and generated a four-phase landscape ecological risk distribution map (Figure 3). Using the natural breakpoint method, the ecological risk value is divided into five grades: low risk ($ERI < 0.028$), relatively low risk ($0.028 \leq ERI < 0.032$), medium risk ($0.032 \leq ERI < 0.036$), relatively high risk ($0.036 \leq ERI < 0.040$), and high risk ($ERI \geq 0.040$). The results showed that the landscape ecological risks at the four phrase in the TRB had similar structure and distribution characteristics. In the composition of risk levels, high-risk areas occupy the highest proportion of area, followed by relatively high-risk areas, and the ratio of the low-risk areas is the smallest. The spatial distribution of risk levels generally follows a pattern of high in the central and eastern regions and low in the surrounding areas.

Spatially, high-risk areas are mainly distributed in the central and eastern parts of the Tarim Basin and the transition zone between mountains and oases. These regions are sandy land, Gobi, and saline-alkali land with high landscape sensitivity and vulnerability. The landscape type is single, and the external world's resistance is weak, resulting in a high landscape ecological risk. The relatively low-risk areas are distributed in the southern slope of the Tianshan Mountains, the Pamir-Kunlun Mountains-Aljin Mountains, and the alluvial plains in the middle and lower reaches of the river. The landscape in this area is mostly grassland, cultivated land, and swampy land. The low-risk areas are distributed in the southern slope of the Tianshan Mountains, the Pamir-Kunlun Mountains, and the Altun Mountains. This area is rich in water resources and has diverse landscape types, mainly grasslands, waters, and woodlands. And there is little human disturbance, so the landscape ecological risk level is low.

As the trend of ecological risk, the statistics of the area of each ecological risk level in the four periods (Table 2) show that the degree of ecological risk overall increases. The ecological risk of TRB is mainly of a high ecological risk level, accounting for more than 30%. The trend of ecological risk area in the four periods is as follows: the area of high and relatively high-risk levels has increased at the cost of decreasing the areas of the low, relatively low, and medium risk level. Among them, the areas of high-risk areas and relatively high-risk areas increased by 3.77% and 0.22%, respectively. The high areas were mainly distributed in the transition zone of desert margins, cities, and oasis margins. The interweaving changes of cropland, construction land, grassland, saline-alkali land, and sandy land reduce the landscape continuity and increase the landscape fragmentation, resulting in an increasing trend of landscape ecological risks. From 2010 to 2020, the areas of relatively low, medium, and high ecological risk levels increased, and the areas of low and high-risk levels decreased significantly. And the share of the low ecological risk level decreased from 9.37% to 8.24%. The area of low and high-risk levels is mainly transferred to the relatively low and relatively high-risk areas. With the implementation of environmental protection policies and policies in the Tianshan Mountains, Pamir-Kunlun Mountains, and Altun Mountains, many mines have been shut down, the forest and grassland areas have increased significantly, and the ecological risk has been reduced. The oasis area around the Tarim River continues to develop with urbanization, increasing ecological level. In the future, we should focus on strengthening the ecological protection, planning, and construction of the oasis area around the Tarim River and the transition zone at the edge of the desert with medium and above ecological risk levels.

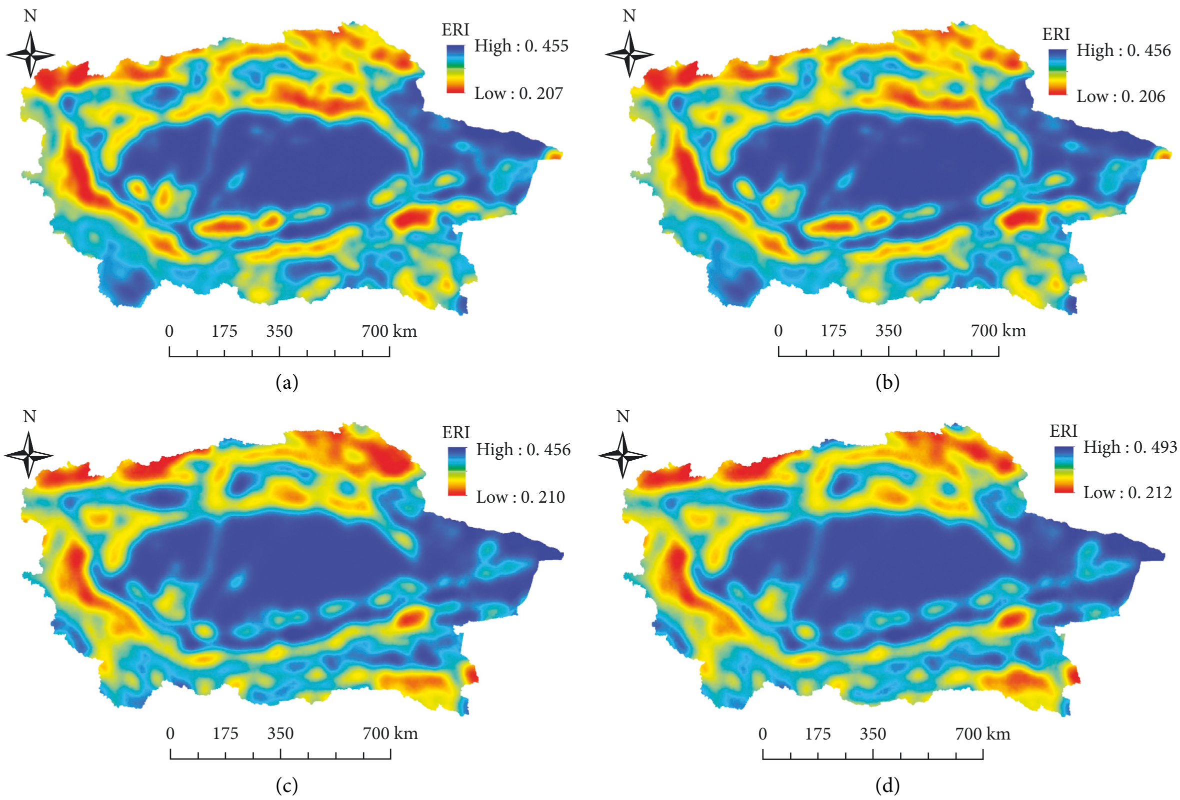

FIGURE 3: The spatial distribution of landscape ecological risks in the Tarim River Basin in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

TABLE 2: The ratio of each ecological risk level in TRB in four periods.

Risk level	Area/km^2				Change ratio/%		
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020
Low risk	105490.74	102003.28	96890.42	85162.72	−3.42	−5.28	−13.77
Relatively low risk	153342.37	151718.48	142635.10	144424.86	−1.07	−6.37	1.24
Medium risk	204713.05	206221.62	180941.32	192709.24	0.73	−13.97	6.11
Relatively high risk	231268.06	229987.72	229288.61	233568.51	−0.56	−0.30	1.83
Hight risk	338523.99	343407.11	383582.75	377472.88	1.42	10.47	−1.62

4.2. Spatial Autocorrelation of Landscape Ecological Risk in the TRB. Figure 4 shows that the distribution of landscape ecological risks in the TRB is highly coupled with the regional geographical environment, and the degree of agglomeration of human activities corresponds to the degree of spatial agglomeration of risks. The landscape ecological risk in the TRB is dominated by High-High (H-H) and Low-Low (L-L) clustering patterns, showing significantly spatial clustering characteristics. The areas with H-H in the TRB are mainly concentrated in the central part of the study area (Taklimakan Desert), the eastern part (Kumtage Desert), and the transition zone between mountains and oases. The related landscape types are mainly sandy land, saline-alkali land, and the Gobi. The L-L agglomeration areas are mainly distributed in the southern Tianshan Mountains, Kunlun Mountains, Altun Mountains, and oasis areas in the TRB, and the landscape types are dominated by grasslands, waters, and woodlands. From 1990 to 2010, the distribution of H-H areas in the southern and eastern part of the watershed in the contact zone between desert and Oasis gradually expanded. The area of L-L gradually shrank and the change of the L-L are mainly in oases such as Korla City and Hotan County. This is mainly due to the expansion of human activities and the small-scale land reclamation in the Oasis middle-agricultural area, which results in the increase of landscape fragmentation and the reduction of the L-L area. From 2010 to 2020, the H-H areas gradually shrunk, and the L-L areas gradually expanded.

4.3. Optimization of Landscape Ecological Pattern

4.3.1. Spatial-Temporal Dynamic of Habitat Quality in the TRB. Figure 5 showed that industrial and mining construction land, desert, saline-alkali land, Gobi, and bare land are the main distribution areas with low habitat quality in the study area. The Taklimakan Desert in the middle and the Kumtag Desert in the east have the largest low habitat quality. At the same time, there is an excellent correlation between the distribution of habitat quality and topographic

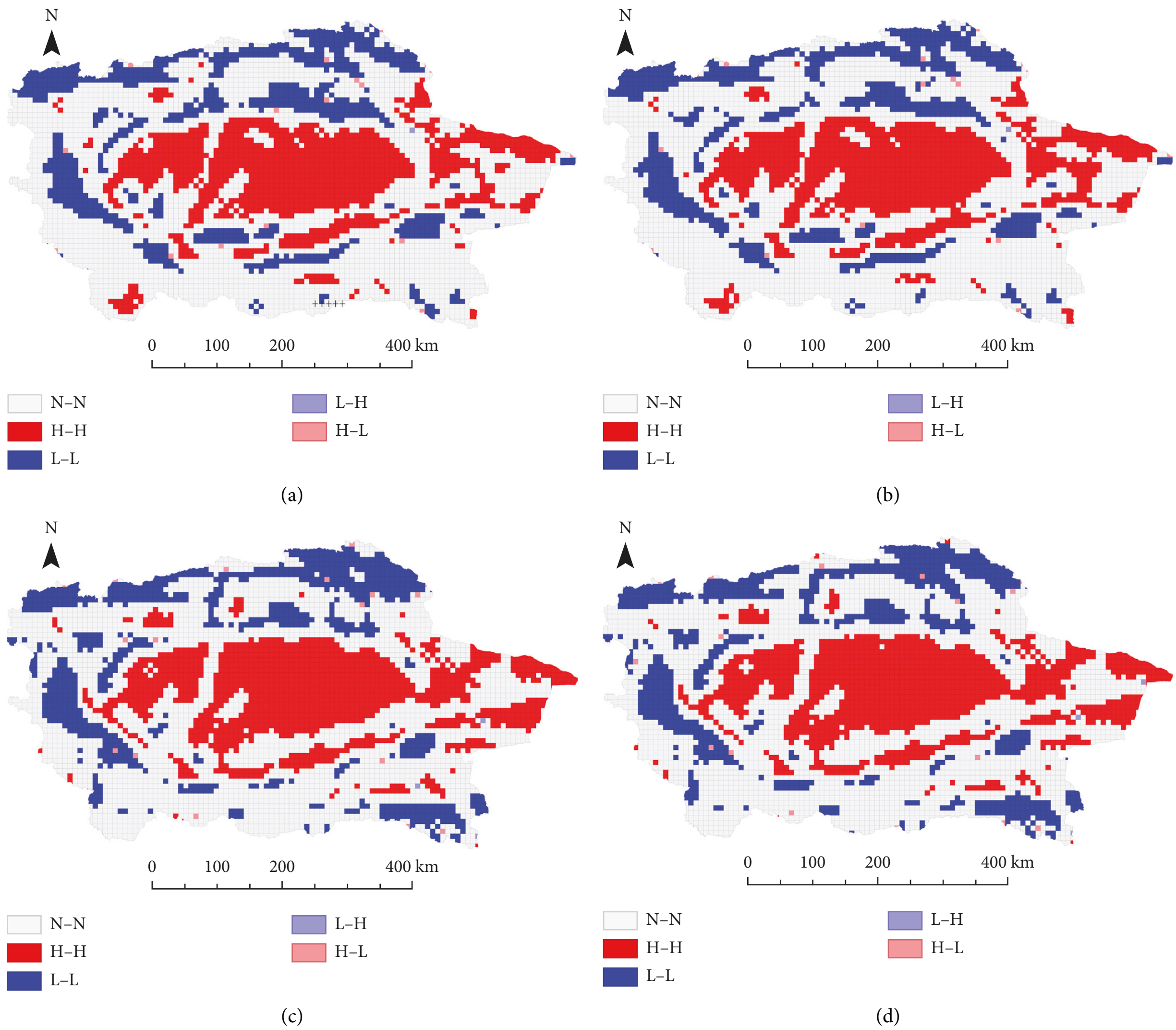

Figure 4: Local spatial autocorrelation clustering map of landscape ecological risks in the Tarim River Basin in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

conditions. The areas with low habitat quality mostly have low altitudes, where desert areas are widely distributed. And the mountains and oasis areas with high altitudes and high vegetation coverage are mostly the areas with suitable habitat quality. Spatially, Figure 4 shows that the areas with high habitat quality in the four periods are distributed in the oases and mountainous areas, and the landscape types are mainly grasslands, oases, and shelter forests on the edge of the desert. The areas with low habitat quality are concentrated in the sandy land and saline-alkali land in the central and eastern parts, construction land such as towns and villages in the oases, and the Gobi area in the transition zone between the oases and the piedmont, which is largely different from the areas with high habitat quality.

In terms of trend, the average habitat quality of the TRB was 0.3751, 0.3736, 0.3686, and 0.3694 in the four periods, respectively. And the habitat quality overall decreased. From 1990 to 2000, many croplands was reclaimed, resulting in a gradual reduction in the area of wetlands and grasslands, and the patches became more and more fragmented. During the period 2000–2010, with the rapid urban development, construction land expanded significantly, and the extension of urban outlines took up a large amount of cropland, grassland, and woodland. In addition, grasslands were degraded to unused land on the edge of deserts, resulting in a sharp drop in habitat quality. In mountainous areas such as the Tianshan Mountains and the Kunlun Mountains, the habitat quality level is greatly affected by natural factors, and the change of habitat quality in this area was small. From 2010 to 2020, the habitat quality increased slightly. During this period, the water body area increased from 27970.69 km^2 to 27213.10 km^2. The reduction rate of forest and grassland areas decreased from 2.21% in 2010 to 1.40% in 2020. The area converted from cropland land to forest and grassland is 2282.94 km^2. These indicate that the continuous popularization of the water-saving drip irrigation model in the Oasis, the transformation of the land use pattern, and the implementation of the “ecological water delivery” and “returning farmland to forests and grasslands” has improved the ecological environment of the TRB.

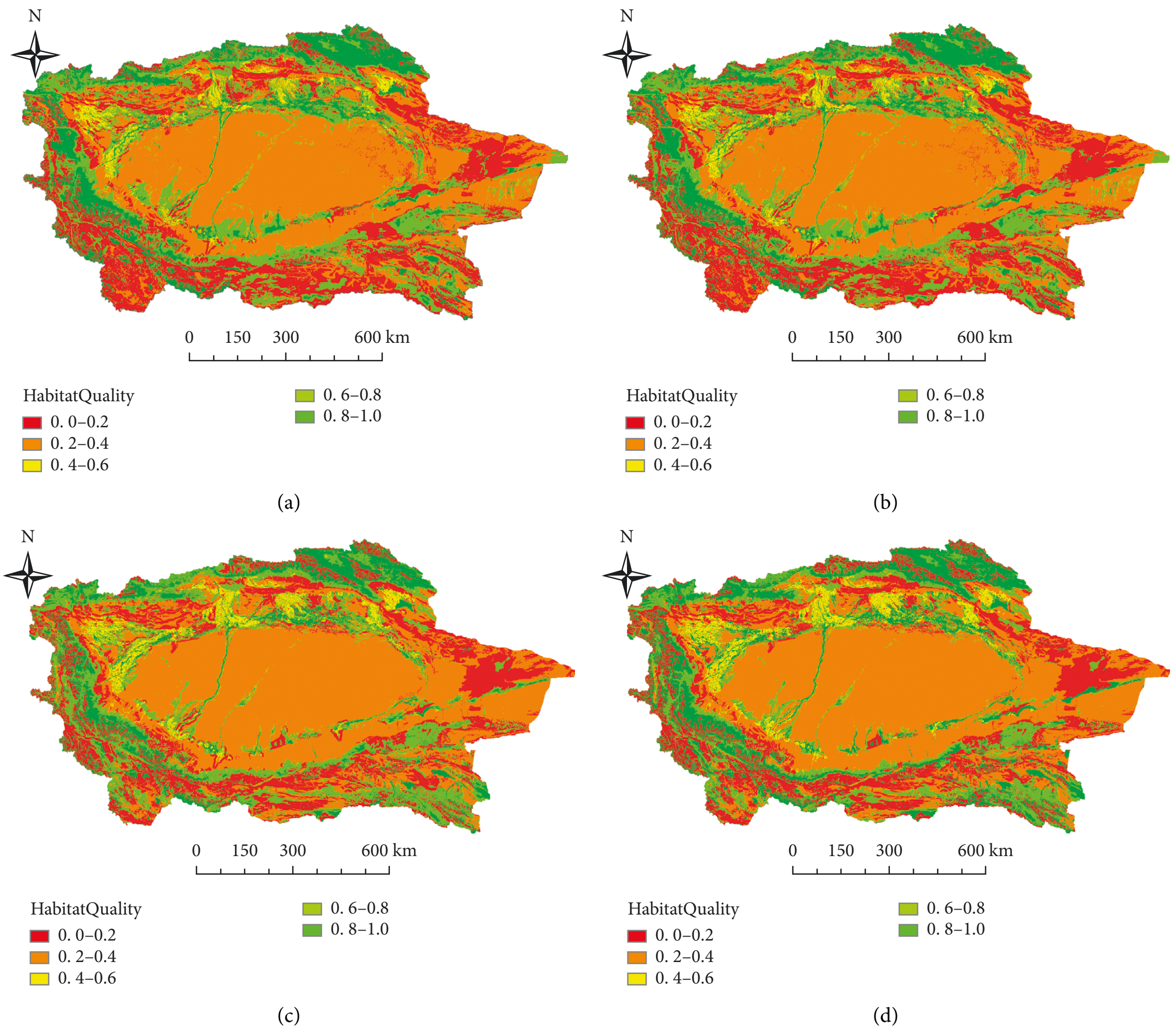

FIGURE 5: The spatial distribution of habitat quality in the Tarim River Basin in the four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

4.3.2. Spatial-Temporal Characteristics of Ecological Sources. The ecological source area is generally an area with high habitat quality, which positively affects the ecological environment. Based on the evaluation results of the habitat quality of the TRB, the distribution of ecological sources was identified (Figure 6). From 1990 to 2020, the area of ecological sources in the TRB increased overall. The ecological sources are mainly distributed in the southern slope of the Tianshan Mountains, the Pamir-Kunlun Mountains- Altun Mountains, and the watershed oasis area. The Tianshan Mountains and the Pamir-Kunlun Mountains-Altun Mountains water conservation areas are the primary areas for ecological security in the TRB and the ecological bottom line for urbanization development and resource and environmental development and construction. Development and construction activities must be strictly prohibited in the above regions. From 1990 to 2000, the ecological source areas of the mainstream of the Tarim River, the Kashgar River, and the Yarkant River decreased, which was related to the unreasonable use of water resources in the middle and lower reaches of the basin, which resulted in the cut-off of the river. By 2010, the area of ecological sources increased significantly, and the source area accounted for 10.86% of the study area, which was related to the policies of ecological water delivery and returning farmland to forests and grasslands in the middle reaches. By 2020, the areas of ecological sources increase significantly, accounting for 11.32% of the study area. Under a series of environmental management measures, the connectivity of green landscape patches continues to increase, and the degree of aggregation between patches increases.

4.3.3. Construction of Comprehensive Ecological Security Pattern. Based on the establishment of the cumulative resistance surface of the landscape pattern in the TRB, the ecological corridors and ecological nodes were identified, respectively, and they were superimposed and combined to construct the ecological security pattern of the TRB (Figures 7–9). Overall, from 1990 to 2020, the area of ecological land in the TRB increased, the ecological quality gradually began to improve, and the ecological security pattern network system became more complex and better.

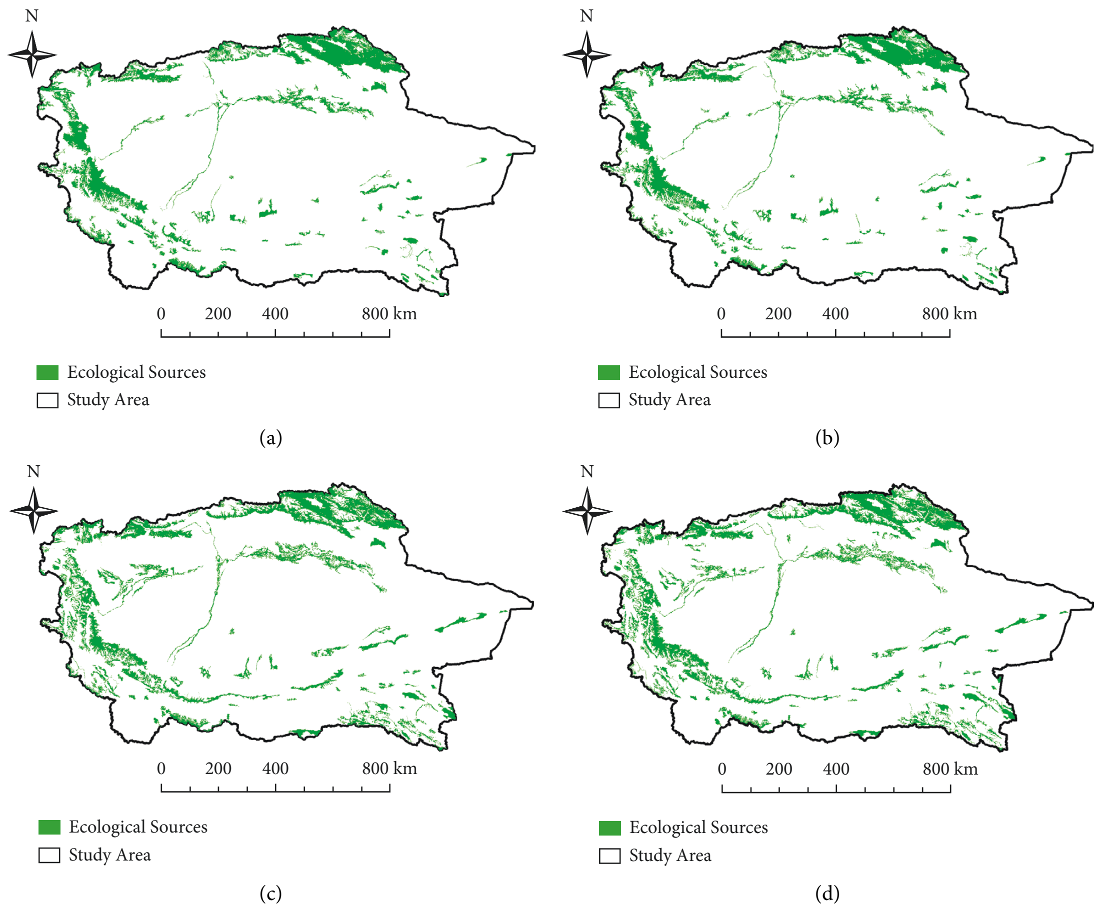

Figure 6: The spatial and temporal distribution of ecological sources in Tarim River Basin in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

In 1990, the ecological security pattern identified 58 ecological strategic nodes, 18 ecological barrier points, and 240 corridors (21 large resistance corridors, 142 medium resistance corridors, and 77 small resistance corridors). The ecological strategic nodes are mainly distributed at the intersection of corridors, the ecological barrier points are mainly distributed in the transition zone between oases and mountains, and the ecological corridors surround the entire TRB. In 2000, there were 56 ecological strategic nodes, 20 ecological barrier points, and 241 ecological corridors (23 large resistance corridors, 126 medium resistance corridors, and 92 small resistance corridors). The ecological corridor mainly has two rings connecting the primary "source" areas. The middle ring is distributed along the mainstream of the Tarim River, and the outer ring is distributed along the Tianshan Mountains-Pamirs -Kunlun Mountains-Altun Mountains. The medium-resistance corridors are longitudinally connected to the transverse corridors, and some of the transverse corridors are connected to a small part of the source and intersect with the corridors. In 2010, the ecological security pattern had 53 ecological strategic nodes, 18 ecological barrier points, and 292 ecological corridors (26 large resistance corridors, 138 medium resistance corridors, and 128 small resistance corridors). Compared with 2000, the number of corridors increases, the connectivity and network connection between sources are stronger, and the horizontal and vertical corridors in the watershed's middle and lower reaches are intertwined, strengthening the connection between regions. In 2020, 70 ecological nodes, 21 ecological barrier points, and 337 ecological corridors (40 high-resistance corridors, 179 medium-resistance corridors, and 118 low-resistance corridors) were extracted. The main line of the corridor is still along with the distribution of the mainstream of the Tarim River and its tributaries, and the ecological source area has increased. And the number of ecological corridors between the Kashgar River in the west and the Qarqan River in the east has increased significantly.

Figure 9 also showed that the spatial distribution of corridors in the TRB is significantly different. The central and eastern deserts of the basin lack ecological sources and are not connected by corridors. And the number of corridors between patches around the Tarim River is large, the network density is high, and the connectivity is strong. The ecological sources in the northern Tianshan Mountains, the western Pamir Plateau, the southern Kunlun Mountains-Altun Mountains, and the Oasis have small resistance and a large number of low-resistance corridors, but the ecological sources are separated by deserts and Gobi, and the resistance is relative. And the distribution of small-area ecological sources acts as a "stepping stone," connecting the various

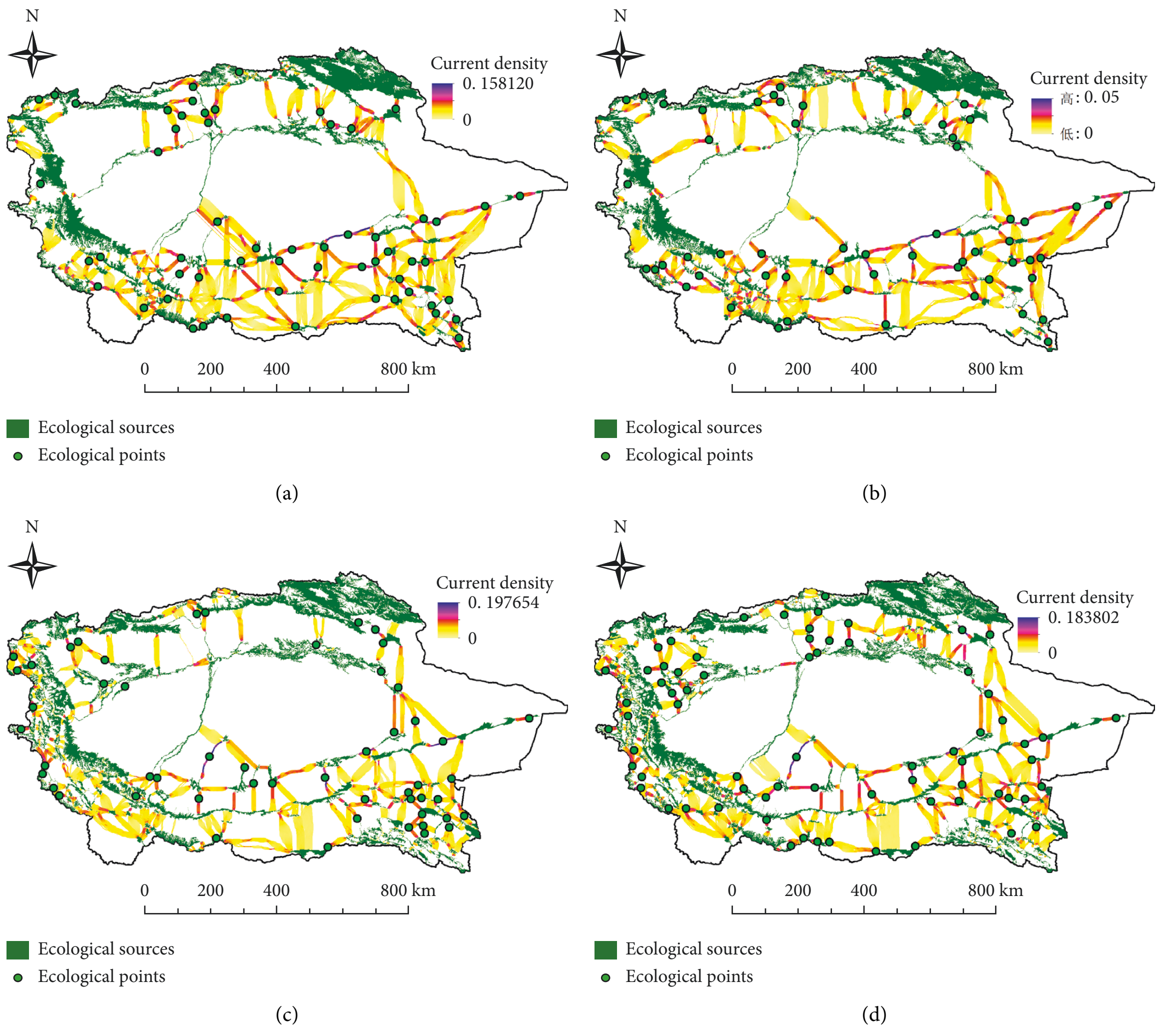

Figure 7: The spatial distribution of ecological nodes in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

ecological sources to generate multiple high-resistance ecological corridors, which together constitute the optimal corridor network in the TRB. From 2010 to 2020, the number of ecological nodes and corridors increased significantly, especially the high-resistance corridors, which are mainly concentrated in the transitional areas between the upper and middle, and lower reaches of the Tarim River, and are the key areas for soil and water conservation. The obstacle points in the study area are mostly distributed in the high-resistance ecological corridor. From the comparison with Figure 8, it can be found that most of the barrier points are construction land and road land, and they all appear in the area where natural and artificial ecosystems blend. A few barrier points appear in areas with frequent human activities, which are mostly urban residential land. The ecological corridors in these areas are relatively short and narrow, and as the resistance value of the obstacle points increases, the ecological corridors may be directly cut off. Therefore, the improvement and restoration of obstacle points are the focus of ecological pattern network optimization and promote the complexity of the ecological security pattern network system.

4.3.4. Optimal Layout Design of the Ecological Spatial Structure. Based on the analysis of the background characteristics of ecological security in the TRB and related policy orientations, the elements of the TRB are optimized and reorganized. The oasis ecological source through the watershed is the ecological green center; other land uses are the matrix elements. The corridor is the ecological low resistance area between the main ecological source areas. The ecological high resistance area is the restoration zone, and the transition zone between the Oasis and mountainous areas is the key ecological restoration belt. The areas between the Oasis and desert (Gobi) are ecological protection belts, and the area outside the ecological protection belt is the main governance area. And the Tianshan Mountains and Kunlun Mountains-Altun Mountain ecological barriers are the ecological functional area, which is mainly for water conservation and ecological diversity maintenance. These will eventually form an oasis ecological ring in the Tarim Basin with green hearts embellishing the matrix, connecting five major water system corridors in each functional area. And a compound ecological spatial structure optimization system with “one ecological ring, two ecological barriers, two

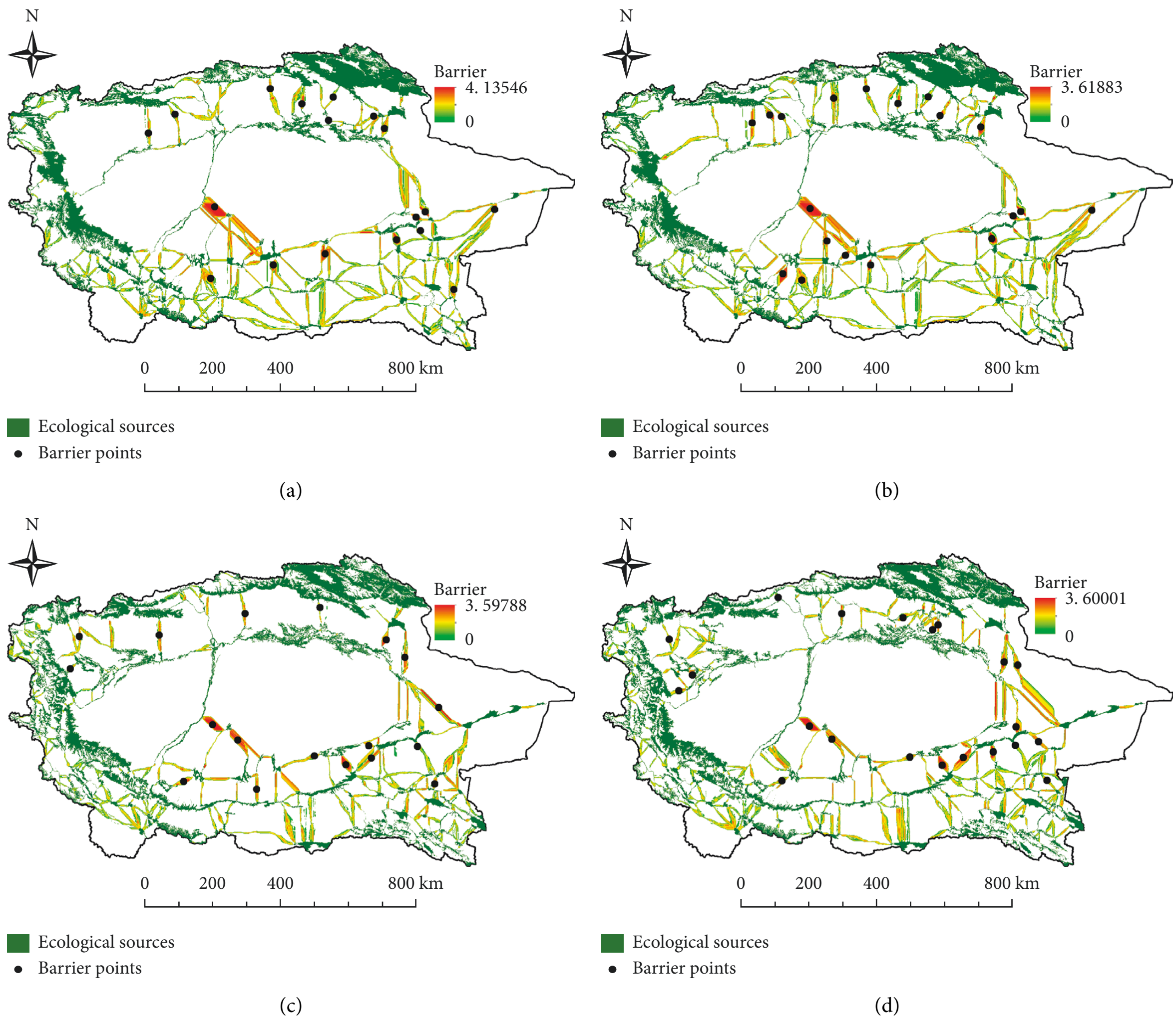

Figure 8: The spatial distribution of barrier points in Tarim River Basin in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

restoration belts, and ten ecological corridors” will be conducted (Figure 10).

5. Discussion

5.1. Suggestions for Ecological Space Structure Optimization in the TRB

(1) Build an oasis ecological restoration belt and a windbreak and sand fixation protective belt to strengthen the ecological environment quality of the “two districts.” To ensure the orderly development of the nine oasis areas and prevent sandstorms and soil erosion, protective belts are constructed in highly vulnerable areas between desert areas and oasis areas, mountain areas, and oasis areas to prevent desertification, salinization, and grassland degradation. The Kunlun-Altun Mountain North Slope Restoration Zone and the Tianshan South Slope Ecological Restoration Zone are located in the transition zone between the mountainous area and the oasis area, which are of great importance for soil and water conservation. The governance optimization area in the desert area in the central TRB and the water source conservation ecological functional area in Tianshan Mountain and Pamir-Kunlun-Altun Mountain are two critical areas in the ecological optimization layout. The water conservation areas in the north and south are the water sources of the entire TRB. To ensure the normal development of the oasis area, enclosure protection should be strengthened to ensure water conservation. The optimized management area is mainly in deserts with the worst habitat quality, which is the biggest threat to the development of the oasis area. The management measures include adopting ecological measures to fix the sand, implementing water-saving irrigation measures, and planting desert vegetation.

(2) Coordinate the relationship between “oases” and build a water systems and road corridors network. The oasis ecological ring along the Tarim Basin connects the nine oases (Akesu Oasis, Kuqa Oasis, Kashgar Oasis, Yarkant Oasis, Korla Oasis, Hotan Oasis, Yanqi Oasis, Ruoqiang Oasis, and Qiemo Oasis), which is an essential corridor for preventing

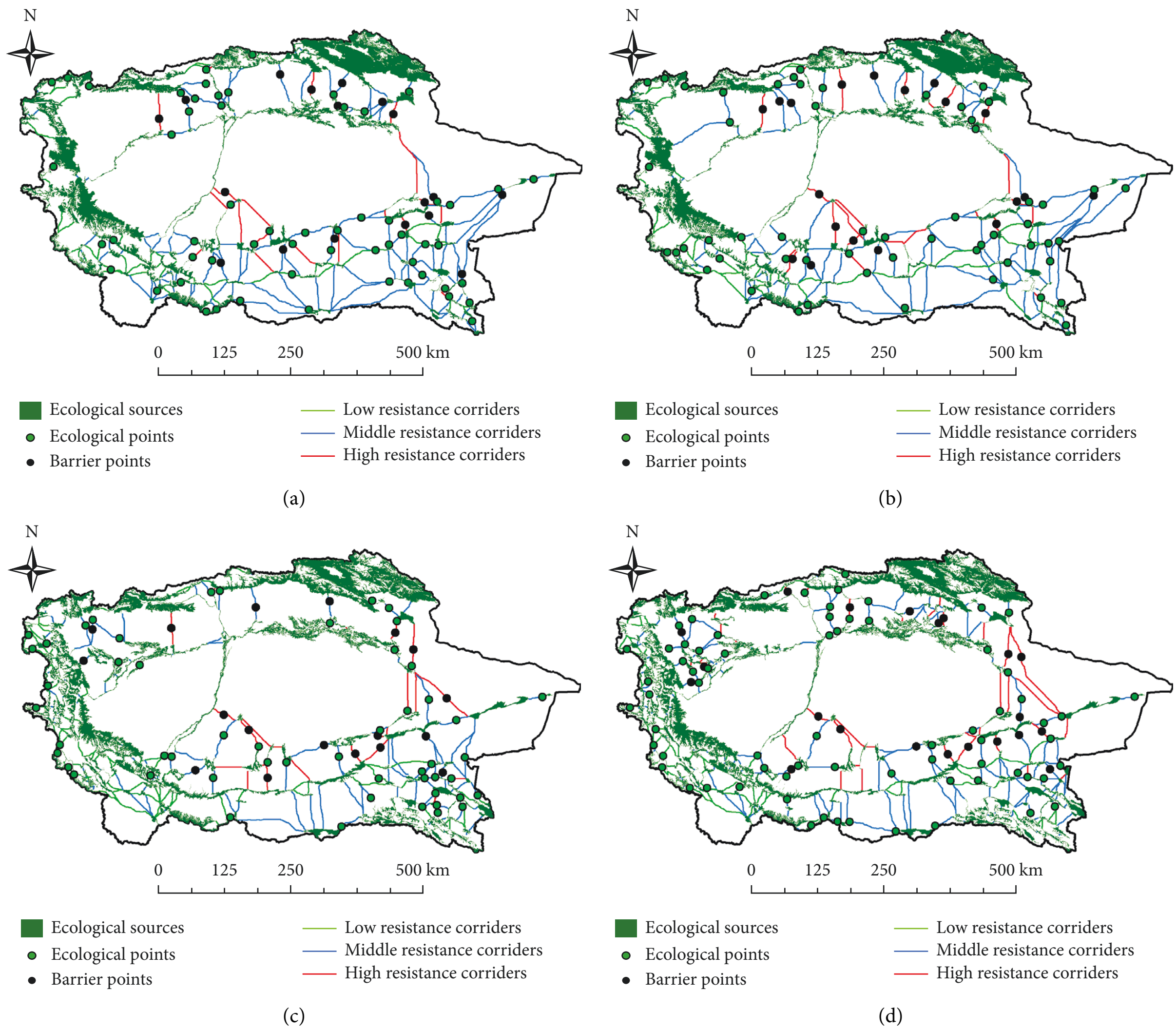

Figure 9: Comprehensive ecological security pattern changes in spatial and temporal in Tarim River Basin in four periods. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

and controlling desert expansion and maintaining the stability and security of Oasis. Based on the oasis ecological ring of the Tarim Basin, the main ecological corridor consists of water systems (Aksu River, Weigan River, Kashgar River, Qarqan River, Kaidu-Peacock River, Hotan River, Yarkant River, and the mainstream of Tarim River) and the main roads. Increase the connectivity between oasis areas through a ring and ecological corridor, which is more conducive to oasis development. The complementarity of the ring and ecological corridor will jointly promote the development of the ecological environment in the TRB and build a more complete ecological security pattern network system. Strengthen the protection of ecological nodes and water sources, maintain critical ecological areas, and promote energy flow, ecological flow, and diffusion between species. Further, conserve water resources, maintain biodiversity, and optimize and adjust the relationship between humans and land in the oasis area.

(3) Create a “one-ring, multipoint” urban agglomeration to coordinate ecological and economically sustainable development. The Tarim Basin Oasis Ecological Ring is the core area of the “Belt and Road” initiative, the China-Pakistan Economic Corridor (CPEC), and an important Silk Road passage. Therefore, it is also the economic circle of the Tarim Basin. Build four major urban agglomerations (Kashgar, Hetian, Korla, and Aksu) along the economic circle of Tarim Basin, play the radiation and driving role of the oasis city group, build a green ecological security barrier, and form a more secure, stable, and green sustainable national space.

(4) Actively respond to government planning and optimize ecological space structure. The overall layout of Xinjiang’s space plan (2021–2035) proposes that the upstream areas need to strengthen enclosure protection and continue building the Tianshan Mountains and Pamir-Kunlun-Altun Mountains water conservation forest. And in the middle and

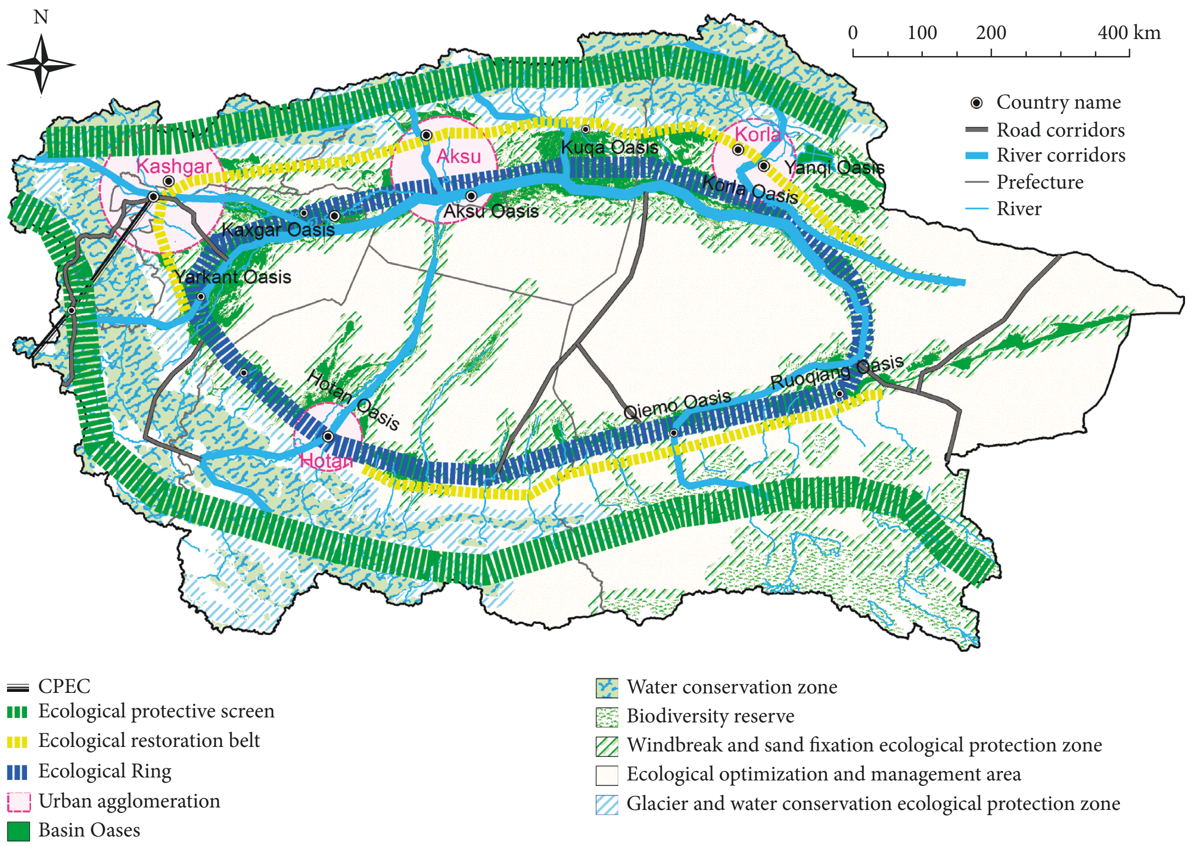

Figure 10: The design of the optimized layout of ecological space structure.

lower reaches, we should strengthen water conservation, renovate the water-saving system, and conduct the oasis shelter forest system. These are all for constructing the water conservation area in the Tianshan Mountains and Pamir-Kunlun Mountains, corridor basin oasis functional area, the interactive functional area between desert and Oasis, and desert area. Based on the relevant policies and planning, this study reconstructs the spatial boundary in the form of space, realizes the spatial governance from the perspective of space, scientifically and rationally divides the spatial structure of the watershed, and promotes the sustainable development of the region.

5.2. The Uncertainty of the Methods. Uncertainty analysis of landscape ecological risk assessment: the choice of indexes, the determination of the relationship between indexes and ecological risk, and the combination of indexes to obtain the comprehensive results of ecological risk may lead to the uncertainty of the results. For example, the assignment of vulnerability in landscape ecological risk reflects the relative vulnerability of landscape types in the study area. The differences in landscape ecological classification also lead to the low general applicability of vulnerability assignment. Therefore, how to improve the accuracy of vulnerability index assignment or construct new vulnerability index and adopt more scientific methods to study landscape ecological security needs to be further improved. In addition, this study uses the landscape index to construct the ecological security evaluation model. From the perspective of landscape spatial structure to analyze the temporal and spatial changes of watershed ecological security, there is a lack of consideration of watershed socio-economic factors, and the results are relative.

The selection of ecological sources may affect the results of ecological corridors identification. Some small or scattered ecological sources may be ignored in the analysis, but they may play an important role in regulating the regional environment. Therefore, we should pay attention to the uncertainty in landscape ecological risk assessment, so as to provide accurate scientific basis for relevant ecological environment decision-making.

6. Conclusion

As a typical watershed of Inland Arid area, TRB has a fragile Desert-Oasis ecosystem, which is highly sensitive to human activities. Watershed landscape management is a major challenge for the government. How to realize the sustainable development of the watershed? In this study, the temporal and spatial dynamic changes of ecological security are analyzed by constructing a landscape ecological risk assessment model in TRB from 1990 to 2020. Secondly, the spatial autocorrelation analysis of landscape ecological risk is carried out to determine its spatial clustering characteristics. Using the MCR model and circuit theory, this paper constructs the landscape ecological security pattern of TRB from

1990 to 2020, defines the ecological function areas, ecological corridors, and ecological points, and realizes the combination of spatiotemporal dynamic evaluation and optimization of regional ecological security. The main research results are summarized as follows: the landscape ecological risk shows an upward trend from 1990 to 2020. The areas with high ecological risk are the desert areas in the middle and east of the study area, the transition zone between piedmont area and oasis. There is a significant aggregation phenomenon of landscape ecological risk in TRB. Taking the results of landscape ecological risk assessment and the ecological sources selected through Habitat Quality and landscape connectivity as the basis for the generation of landscape pattern resistance surface, this paper constructs the landscape ecological security pattern of the basin and optimizes the ecological spatial structure of arid inland rivers. The distribution pattern is "one ring, two screens, two belts, ten corridors, and multiple centers," so as to ensure the continuity of ecological processes in the study area. The corresponding optimization suggestions are put forward: the key corridors connecting the nine oases around the TRB. Urban development should consider the current ecological resources and corridors to prevent landscape fragmentation, strengthen the improvement and restoration of ecological obstacles, and formulate the spatial planning of the Kunlun-Altun Mountain North Slope Restoration Zone and the Tianshan South Slope Ecological Restoration Zone. This study can provide a scientific basis for the Ecological Planning and Urban Master Planning of inland basins in arid area in the future. With future research, human factors should be added to the dynamic change of landscape security pattern, especially in the analysis of the relationship between national policies, watershed planning, socioeconomic statistics, and land use. In addition, according to the research on the contradiction between water resources protection and economic development in arid areas, it needs to be further explored to build a practical ecological security model to realize ecological and economic development.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] J. X. Gao, "Ecological security is an important part of national security," *Qiushi*, vol. 24, pp. 43-44, 2015.

[2] D. Geneletti, E. Beinat, C. F. Chung, A. G. Fabbri, and H. J. Scholten, "Accounting for uncertainty factors in biodiversity impact assessment: lessons from a case study," *Environmental Impact Assessment Review*, vol. 23, no. 4, pp. 471–487, 2003.

[3] Q. Huang, R. Wang, Z. Ren, J. Li, and H. Zhang, "Regional ecological security assessment based on long periods of ecological footprint analysis," *Resources, Conservation and Recycling*, vol. 51, no. 1, pp. 24–41, 2007.

[4] 叶. Ye Xin, 邹. Zou Changxin, 刘. Liu Guohua, 林. Lin Naifeng, and 徐. Xu Mengjia, "Main research contents and advances in the ecological security pattern," *Acta Ecologica Sinica*, vol. 38, no. 10, pp. 3382–3392, 2018.

[5] C. Bingshuai, D. L. Xu, H. S. Dou et al., "Index system of ecological security of inland lakes in cold arid region: a case study of Hulun Lake, China," *Acta Ecologica Sinica*, vol. 41, no. 8, pp. 2996–3006, 2021.

[6] N. Bonheur and B. D. Lane, "Natural resources management for human security in Cambodia's Tonle Sap Biosphere Reserve," *Environmental Science & Policy*, vol. 5, no. 1, pp. 33–41, 2002.

[7] C. X. Zou and W. S. Shen, "Research progress of ecological security Rural," *Eco-Environment*, vol. 19, no. 1, pp. 56–59, 2003.

[8] X. Chen and C. H. Zhou, "Review of the studies on ecological security," *Progress in Geography*, vol. 24, no. 6, pp. 8–20, 2005.

[9] R. H. Mac Arthur and E. O. Wilson, *The Theory of Island Biogeography*, Princeton University Press, Princeton, 1967.

[10] J. Peng, H. J. Zhao, Y. X. Liu, and J. S. Wu, "Research progress and prospect on regional ecological security pattern construction," *Geographical Research*, vol. 36, no. 3, pp. 407–419, 2017.

[11] J. H. Pan and Y. Wang, "Ecological security evaluation and ecological pattern optimization in Taolai River Basin based on CVOR and circuit theory," *Acta Ecologica Sinica*, vol. 41, no. 7, pp. 2582–2595, 2021.

[12] W. Q. Zhao, Z. H. Yang, W. C. Su, and K. Li, "Ecological risk assessment and management of watershed based on landscape pattern change——a case study of the Chishui river basin in Guizhou," *Resources and Environment in the Yangtze Basin*, vol. 26, no. 8, pp. 1218–1227, 2017.

[13] R. F. Wang and Z. R. Nan, "Applied research on the risk assessment of the Heihe River Basin based on the theory of landscape ecology," *Journal of Safety and Environment*, vol. 13, no. 6, pp. 133–137, 2013.

[14] P. Craig P, P. Kristen L, W. Joanna B, and D. Julian, "Development and assessment of a landscape-scale ecological threat index for the Lower Colorado River Basin," *Ecological Indicators*, vol. 11, no. 2, pp. 304–310, 2011.

[15] 许. Xu Yan, 高. Gao Junfeng, and 郭. Guo Jianke, "The ecological risk assessment of Taihu Lake watershed," *Acta Ecologica Sinica*, vol. 33, no. 9, pp. 2896–2906, 2013.

[16] C. Xu, L. Pu, M. Zhu et al., "Ecological security and ecosystem services in response to land use change in the coastal area of Jiangsu, China," *Sustainability*, vol. 8, no. 8, p. 816, 2016.

[17] X. P. Xie, Z. C. Chen, F. Wang, M. W. Bai, and W. Y. Xu, "Ecological risk assessment of Taihu Lake basin based on landscape pattern," *Chinese Journal of Applied Ecology*, vol. 28, no. 10, pp. 3369–3377, 2017.

[18] L. Ma, J. Bo, X. Li, F. Fang, and W. Cheng, "Identifying key landscape pattern indices influencing the ecological security of inland river basin: the middle and lower reaches of Shule River Basin as an example," *The Science of the Total Environment*, vol. 674, pp. 424–438, 2019.

[19] P. Ran, S. Hu, A. E. Frazier, S. Qu, D. Yu, and L. Tong, "Exploring changes in landscape ecological risk in the Yangtze River Economic Belt from a spatiotemporal perspective," *Ecological Indicators*, vol. 137, Article ID 108744, 2022.

[20] Y. J. Wang, *Study on the Influence of the Change of Water Resources and its Impact on Ecological Security in the Arid: An Example of Ebinur Lake Basin in Xinjiang*, Xinjiang University, Ürümqi, China, 2018.

[21] Y. N. Chen, W. C. Cui, W. H. Li, Y. P. Chen, and H. F. Zhang, "Utilization of water resources and ecological protection in the Tarim River," *Acta Geographica Sinica*, vol. 58, no. 2, pp. 215–177, 2003.

[22] Z. J. Kong, M. J. Deng, H. B. Ling, G. Y. Wang, S. W. Xu, and Z. R. Wang, "Ecological security assessment and ecological restoration countermeasures in the dry-up area of the lower Tarim River," *Arid Zone Research*, vol. 38, no. 4, pp. 1128–1139, 2021.

[23] Z. M. Yang and X. P. Liu, "Ecological carrying capacity monitoring and security pattern construction in the Aksu River Basin, Xinjiang," *Arid Land Geography*, vol. 44, no. 5, pp. 1489–1499, 2021.

[24] J. H. Qi, *The Research on Oasis Ecological Evolution of Shule River Basin*, Zhenzhou University, Zhengzhou, China, 2014.

[25] Z. Z. He, H. W. Wang, S. T. Yang, B. Fang, Z. Y. Zhang, and X. Y. Liu, "Spatial-temporal differentiation and pattern optimization of landscape ecological security in the Ugan-Kuqa river oasis," *Acta Ecologica Sinica*, vol. 39, no. 15, pp. 5473–5482, 2019.

[26] N. N. Shi, Y. Han, Q. Wang et al., "Risk assessment of sandstorm diffusion and landscape pattern optimization in southern Xinjiang," *Acta Geographica Sinica*, vol. 76, no. 1, pp. 73–86, 2021.

[27] P. Zhang, "Research on the Coupling System of Society,e-coenvironment and Water in Tarim River basin," China Institute of Water Resources and Hydropower Research, PHD Thesis, 2019.

[28] X. Y. Zhang, "Study on Computing Methods and its Application of Dynamic Carrying Capacity of Water Resources under the Climate Change," Zhengzhou University, PHD Thesis, 2015.

[29] M. J. Deng, Z. L. Fan, H. L. Xu, and H. Y. Zhou, "Ecological function regionalization of Tarim River basin," *Arid Land Geography*, vol. 40, no. 4, pp. 705–717, 2017.

[30] L. Q. Xue, J. Wang, and G. H. Wei, "Dynamic evaluation of the ecological vulnerability based on PSR modeling for the Tarim River Basin in Xinjiang," *Journal of Hohai University(Natural Sciences)*, vol. 47, no. 1, pp. 13–19, 2019.

[31] 楚. 徐. 罗. 孙. Chu Zhi, C. C. Xu, Y. X. Luo, and Q. Sun, "Land use simulation and ecological benefit evaluation in the Tarim River basin based on ecological protection red line management," *Acta Ecologica Sinica*, vol. 41, no. 18, pp. 1–13, 2021.

[32] X. B. Zhang, P. J. Shi, J. Luo, H. L. Liu, and W. Wei, "The ecological risk assessment of arid inland river basin at the landscape scale;A case study on shiyang river basin," *Journal of Natural Resources*, vol. 29, no. 3, pp. 410–419, 2014.

[33] Y. Zhao, Z. J. Luo, Y. T. Li, J. Y. Guo, X. H. Lai, and J. Song, "Study of the spatial-temporal variation of landscape ecological risk in the upper reaches of the Ganjiang River Basin based on the"production-living-ecological space"," *Acta Ecologica Sinica*, vol. 39, no. 13, pp. 4676–4686, 2019.

[34] N. Rangel-Buitrago, W. J. Neal, and V. N. de Jonge, "Risk assessment as tool for coastal erosion management," *Ocean & Coastal Management*, vol. 186, Article ID 105099, 2020.

[35] X. Y. Chen Xinyi, G. Z. Xie, and J. P. Zhang, "Landscape ecological risk assessment of land use changes in the coastal area of Haikou City in the past 30 years," *Acta Ecologica Sinica*, vol. 41, no. 3, pp. 975–986, 2021.

[36] J. Peng, Y. Wang, Y. Zhang, J. Wu, W. Li, and Y. Li, "Evaluating the effectiveness of landscape metrics in quantifying spatial patterns," *Ecological Indicators*, vol. 10, no. 2, pp. 217–223, 2010.

[37] W. Zhang, W. J. Chang, Z. C. Zhu, and Z. Hui, "Landscape ecological risk assessment of Chinese coastal cities based on land use change," *Applied Geography*, vol. 117, Article ID 102174, 2020.

[38] Y. Xiong, M. Wang, H. P. Yuan, C. Y. Du, and H. P. Wu, "Landscape ecological risk assessment and its spatio-temporal evolution in Dongting Lake area," *Ecology and Environmental Sciences*, vol. 29, no. 7, pp. 1292–1301, 2020.

[39] L. Xue, B. Zhu, Y. Wu et al., "Dynamic projection of ecological risk in the Manas River basin based on terrain gradients," *The Science of the Total Environment*, vol. 653, pp. 283–293, 2019.

[40] X. Jin, Y. Jin, and X. Mao, "Ecological risk assessment of cities on the Tibetan Plateau based on land use/land cover changes - case study of Delingha City," *Ecological Indicators*, vol. 101, pp. 185–191, 2019.

[41] J. Wang, W. Bai, and G. Tian, "Spatiotemporal characteristics of landscape ecological risks on the Tibetan Plateau," 资源科学, vol. 42, no. 9, pp. 1739–1749, 2020.

[42] J. Wang, X. L. Zhang, and H. R. Du, "Spatial pattern evolvement and characteristics of the economy in Xinjiang at the county level," *Progress in Geography*, vol. 30, no. 4, pp. 471–478, 2011.

[43] C. S. Ye and Y. F. Feng, "Ecological risk assessment for Pearl River Delta based on land use change," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 19, pp. 224–232, 2013.

[44] H. Shi, Z. P. Yang, F. Han, T. G. Shi, and F. M. Luan, "Characteristics of temporal-spatial differences in landscape ecological security and the driving mechanism in Tianchi scenic zone of Xinjiang," *Progress in Geography*, vol. 32, no. 3, pp. 475–485, 2013.

[45] R. J. Yao, J. S. Yang, and G. M. Liu, "Spatial variability of soil salinity and moisture and their estimations by cokriging method: a case study in characteristic field of Yellow River Delta," *Journal of Soil and Water Conservation*, vol. 20, no. 5, pp. 133–138, 2006.

[46] X. Zhang, J. Zhou, G. Li, C. Chen, M. Li, and J. Luo, "Spatial pattern reconstruction of regional habitat quality based on the simulation of land use changes from 1975 to 2010," *Journal of Geographical Sciences*, vol. 30, no. 4, pp. 601–620, 2020.

[47] L. Rahimi, B. Malekmohammadi, and A. R. Yavari, "Assessing and modeling the impacts of wetland land cover changes on water provision and habitat quality ecosystem services," *Natural Resources Research*, vol. 29, no. 6, pp. 3701–3718, 2020.

[48] H. T. Tallis, T. Ricketts, and A. Guerry, *InVEST 2.5.6 User's Guide*, The Natural Capital Project, Stanford, 2013.

[49] J. Gong, Y. Xie, E. Cao, Q. Huang, and H. Li, "Integration of InVEST-habitat quality model with landscape pattern indexes to assess mountain plant biodiversity change: a case study of Bailongjiang watershed in Gansu Province," *Journal of Geographical Sciences*, vol. 29, no. 7, pp. 1193–1210, 2019.

[50] Y. Wang, J. X. Gao, Y. Jin et al., "Habitat quality of farming-pastoral ecotone in bairin right banner,inner Mongolia based on land use change and InVEST model from 2005 to 2015," *Journal of Ecology and Rural Environment*, vol. 36, no. 5, pp. 654–662, 2020.

[51] Y. Y. Gu, X. F. Huang, C. X. Zou, X. Ye, N. F. Lin, and W. M. Zhang, "Monitoring habitat quality changes in yuanjiangyuan nature reserve based on landsat images,"

Journal of Ecology and Rural Environment, vol. 35, no. 6, pp. 764–772, 2019.
[52] Y. J. Liang and L. J. Liu, "Simulating land-use change and its effect on biodiversity conservation in a watershed in northwest China," *Ecosystem Health and Sustainability*, vol. 3, no. 5, pp. 13–23, 2017.
[53] Q. Sun, L. Zhang, X. L. Ding, J. Hu, Z. W. Li, and J. J. Zhu, "Slope deformation prior to Zhouqu, China landslide from InSAR time series analysis," *Remote Sensing of Environment*, vol. 156, pp. 45–57, 2015.
[54] L. L. Song and M. Z. Qin, "Identification of ecological corridors and its importance by integrating circuit theory," *Chinese Journal of Applied Ecology*, vol. 27, no. 10, pp. 3344–3352, 2016.
[55] 付. 刘. 刘. Fu Fengjie, Z. H. Liu, and H. Liu, "Identifying key areas of ecosystem restoration for territorial space based on ecological security pattern: a case study in Hezhou City," *Acta Ecologica Sinica*, vol. 41, no. 9, pp. 3406–3414, 2021.
[56] L. Y. Huang, S. H. Liu, Y. Fang, and L. Zou, "Construction of Wuhan's ecological security pattern under the quality-risk-requirement framework," *Chinese Journal of Applied Ecology*, vol. 30, no. 2, pp. 615–626, 2019.
[57] B. H. McRae, S. A. Hall, P. Beier, and D. M. Theobald, "Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits," *Plos One*, vol. 7, no. 12, Article ID e52604, 2012.
[58] T. R. Yang, W. H. Kuang, W. D. Liu, A. L. Liu, and T. Pan, "Optimizing the layout of eco-spatial structure in Guanzhong urban agglomeration based on the ecological security pattern," *Geographical Research*, vol. 36, no. 3, pp. 441–452, 2017.
[59] R. C. Guo, S. H. Song, and C. H. Miao, "Optimizing and upgrading of structure and function in urban agglomerations region: a case study of zhongyuan urban agglomeration," *Scientia Geographica Sinica*, vol. 31, no. 3, pp. 322–328, 2011.
[60] 杨. 王. 魏. 杨. 郭. Yang Liangjie, J. Wang, W. Wei, Y. C. Yang, and Z. C. Guo, "Ecological security pattern construction and optimization in arid inland river basin: a case study of shiyang river basin," *Acta Ecologica Sinica*, vol. 40, no. 17, pp. 5915–5927, 2020.