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Construction and Optimization of Ecological Security Pattern in the Loess Plateau of China Based on the Minimum Cumulative Resistance (MCR) Model

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Abstract: With accelerating urbanization, the regional ecological security pattern (ESP) faces unprecedented threats. The situation is particularly serious in the Loess plateau of China (LPC) due to the fragile ecological environment and poor natural conditions. Constructing an ecological network and optimizing the ESP is significant for guiding regional development and maintaining the stability of the ecological process. This study constructed an ecological security network by integrating the minimum cumulative resistance (MCR) model and morphological spatial-pattern-analysis approach in LPC. Additionally, the optimization scheme of the regional ESP has also been proposed. Results show that the ecological source area is about 57,757.8 km^2, 9.13% of the total area, and is mainly distributed in the southeast of the study area. The spatial distribution of ecological sources shows specific agglomeration characteristics. The ecological security network constructed contains 24 main ecological corridors, 72 secondary ecological corridors, and 53 ecological nodes. Referring to the identified ecological sources area, corridors, nodes, and other core components, the "two barriers, five corridors, three zones and multipoint" ESP optimization scheme was presented. This research hopes to provide a valuable reference for constructing the ecological security network and optimizing ecological space in ecologically fragile areas of western China.

Keywords: ecological security pattern; minimum cumulative resistance model; ecological corridors; Loess plateau

1. Introduction

Ecological security commonly describes a state where the ecosystem structure and function are intact, healthy and stable, safeguards species and human habitats, protects wildlife migration, and provides adequate ecological services for human life and socioeconomic activities [1,2]. Meanwhile, ecological security also serves an essential role in protecting regional water resources, preserving biodiversity, and preventing natural disasters [3]. However, with the continuous acceleration of China's urbanization, the speed of urban expansion has been significantly accelerated with the continuous influx of the population. The ecological land has also been continuously squeezed, making the service function of the urban ecosystem face severe challenges [4,5]. The stability of the regional ecosystem is facing tremendous pressure. Some ecological and environmental problems are prominent, such as the loss of species habitats, the increased fragmentation of landscapes, reduced connectivity between habitat patches, water pollution, reduced biodiversity, etc. [6,7]. These ecoenvironmental problems have severely restricted the balanced development of the region and have indirectly promoted regional ecological protection to

become increasingly important [8]. Solving the conflict between the increasing demand for economic growth and regional ecological protection is gradually becoming one of the research hotspots of scholars.

Aiming at regional ecological and environmental problems and controlling ecological processes more effectively, the ecological security pattern (ESP) came into being. The ESP is a multiobjective, multilevel, and multicategory potential ecological spatial configuration pattern constructed to protect biodiversity and maintain the integrity of the ecosystem structure and ecological process [9]. It is an essential content of regional ecological security protection and has become one of China's three major strategies for land and space development and conservation [10]. Since its proposal in the 1990s, the ESP has become a research hotspot in ecology, environmental science, and urban planning worldwide. Scholars have done much research on constructing and optimizing the ESP. After years of exploration and practice, the ESP has evolved from the initial qualitative planning and quantitative pattern analysis to the rapid development of spatial data calculation, static pattern optimization, dynamic pattern simulation, and status trend analysis [11] [12,13]. In terms of its construction method, it can be summarized as a quantitative optimization method (such as an optimization technology method, system-dynamic model), spatial optimization method (such as ecology-based landscape pattern optimization model, ecological security network), and comprehensive optimization method (such as CLUE-S model, genetic algorithm, multi-agent model) [14,15]. Among them, constructing an ecological security network has become a meaningful way to establish an ESP and optimize the ecological space.

Establishing an ecological security network provides a new effective perspective to balance and optimize the urban ESP [3,16,17]. Constructing an ecological network is an important strategy to restore and maintain biological connectivity and habitat continuity [18]. It uses ecological sources and ecological corridors to restore the connections between fragmented habitat patches, forming an overall stable ecosystem function network, realizing ecological processes such as species inhabitation, reproduction, migration, and diffusion, and achieving the purpose of ensuring regional ecological security with a small amount of ecological land [19]. The essence of constructing an ecological security network is to solve the conflict between different functional lands. The research on ecological safety networks is abundant, covering many aspects such as maintaining ecological service function [20], protecting biodiversity [21], and improving the recreational environment and green infrastructure [22]. Some scholars have extended the related research on urban space governance based on identifying the ecological network space [23]. The commonly used methods for constructing an ESP can be divided into graph theory [24], circuit theory [25], the superposition method [26], the minimum cumulative resistance model [20], etc. Among them, the minimum cumulative resistance (MCR) model has become the mainstream method for building an ecological safety network due to its adaptability and scalability in analyzing various horizontal spatial expansions [3,27]. The model is based on the "source-sink" landscape theory, following the basic process of "identification of ecological sources-construction of ecological resistance surfaces-extraction of ecological nodes and corridors". Additionally, the process can be adjusted and expanded according to regional differences [25]. Through the continuous efforts of many scholars, the concept and theoretical basis of ecological security network construction based on the MCR model are clear, the construction mode is gradually maturing, and the application field is becoming wider and broader [2,28]. However, the practical problem is the serious disconnect between the ecological research of the MCR model and the planning results of the overall land-use and urban–rural planning. The lack of a strong linkage between the ESP and ecological space optimization makes it difficult for the construction of an ESP to play a guiding role in space optimization and management. Recently, some scholars have gradually introduced the evaluation results of ecological security into land-use planning and carried out land-use simulations with consideration of ecological security [29], urban expansion simulation [30], land-use conflict identification [31], etc. These studies are useful attempts to combine theoretical research and the practical application of ecological security organically. Generally,

relevant studies are still relatively few and have not formed a mature research paradigm. Especially in the Loess plateau of China (LPC), there are few explorations on ecological security research, and the research that links the research results with government planning is even rarer. Therefore, this study focuses on the LPC and constructs a region-wide ecological safety network to provide optimal solutions for government planning.

The construction of ecological civilization has been formulated as a strategic need for China. During the construction of national ecological civilization, the LPC should be given priority attention. The LPC is the most severe area of soil erosion and the most fragile ecological environment in China. Its severe soil erosion is considered the main source of sediment for the Yellow River. Over the years, many efforts have been implemented to improve the ecological environment of the LPC and have achieved certain impacts, such as the Grain for Green Project (GGP) and the Gully Land Consolidation Project (GLCP) [32]. However, resistance to constructing an ecological civilization has always existed in the region due to the unstable ecological framework and inadequate resource allocation. The ecological environment of the LPC directly affects the realization of China's sustainable development goals (SDGs) and regional synergistic development strategy [33]. Therefore, it is imperative to study the ESP of the LPC both in its theoretical and practical significance.

This paper focuses on the LPC as the study area. Specifically, the objectives of this work were to: (1) extract ecological source areas based on land-use patterns and the ecological-land-grade evaluation method; (2) construct the potential ecological network by using the MCR model; (3) propose optimization measures to build the ESP of the LPC. The innovation of this study consists of two aspects: firstly, the ecological safety network identification and optimization schema under the framework of "risk-network-pattern" is proposed, which is more reasonable and operable for the evaluation and optimization of ESP; secondly, the "point-line-surface" ESP optimization scheme for the whole LPC is constructed with a solid theoretical foundation, which can well integrate the theory into practical application. This research will provide a theoretical basis for the ecological civilization construction of the LPC and a reference for optimizing the ESP of other cities in ecologically fragile areas of China.

2. Materials and Methods

2.1. Study Area

The Loess plateau, located in the middle reaches of the Yellow River (Figure 1), northern China (33.68–41.29N, 100.86–114.53E), is one of the four major plateaus in China and also the largest loess deposit region in the world. The total area of the LPC is 6.32×10^5 km^2, approximately 6.6% of the total land area of China. Its geographical boundary extends to the Taihang Mountains in the east, Riyue Mountain and Wushao Mountain in the west, and Qinling Mountain in the south, covering parts of Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, and Henan provinces [33]. The LPC belongs to the transition zone of the humid monsoon climate to the inland arid climate, from southeast to northwest climate in the order of semihumid, semiarid, and arid climate. Controlled by the temperate continental climate, the seasonal differences in temperature and precipitation are distinct, and the average annual rainfall in the region ranges from 200 to 700 mm [34]. Affected by its geographical location and climate, the LPC has become the most serious area of soil erosion in China, even in the world, and has received extensive attention from ecological and geographical studies. Presently, a series of ecological problems such as soil erosion and desertification have placed additional burdens on the ecologically fragile LPC [35]. Related studies have shown that the average annual soil erosion rate was 3180 t km^{-2} yr^{-1} from 2000 to 2008 [36]. Meanwhile, with the continuous expansion of cultivated land and urban construction land area in this region [37], the ecological land area is generally in the trend of reduction, exposing the ecological environment of the region to risks.
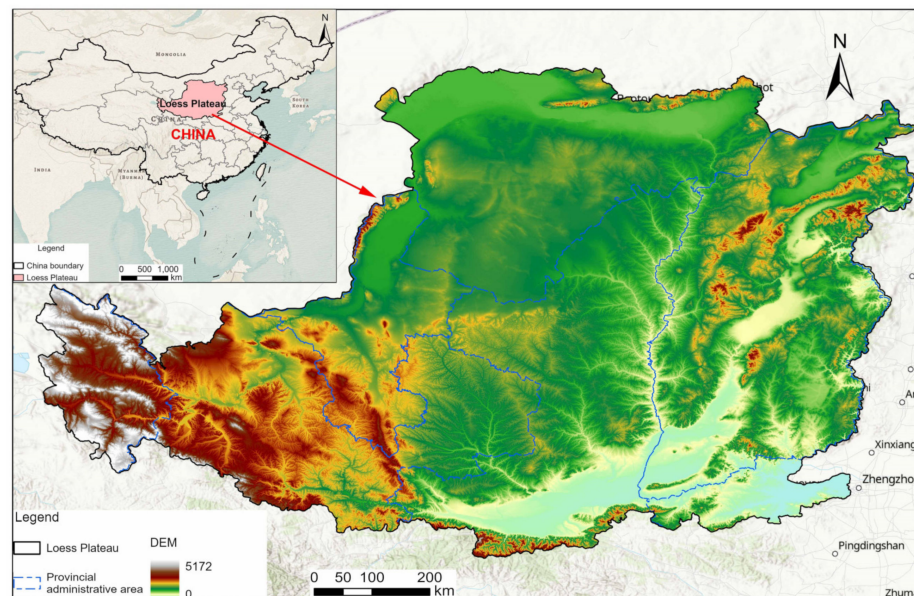
**Figure 1.** Location and topography of LPC.

2.2. Materials

Data from five primary datasets were involved in this study, including four spatial datasets, namely the land-use and land cover, the topography data, the Enhanced Vegetation Index (EVI) data and soil erosion data, and a text dataset, the weather station records dataset (Table 1). The land-use data was extracted from the Global Land Use/Land Cover Dataset 2020 provided by ESRI. The dataset was derived from ESA Sentinel-2 imagery with a resolution of 10m. The image interpretation method employed a popular deep-learning model and was trained using over 5 billion hand-labeled Sentinel-2 pixels worldwide. The confusion matrix validation results showed that the overall classification accuracy of this dataset was up to 86%, indicating the dataset was well-classified and could be employed in this research [38]. Depending on the actual research needs, land-use data was reclassified into six categories: arable land, forest land, grassland, construction land, water body, and other land. The EVI index was employed to describe the vegetation cover in the study area. Currently, EVI and NDVI are the most widely used indicators to reflect vegetation cover, and both indicators are derivatives of Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors [39]. Yet, NDVI is affected by atmospheric and soil conditions, making it susceptible to saturation and less sensitive to changes in vegetation cover [40]. The EVI was accordingly proposed to avoid these limitations. The EVI can effectively characterize biophysical/biochemical status and processes on the vegetation surface [41], minimizing canopy background variation and maintaining the distinction between lush vegetation cover. The EVI is superior to NDVI in its ability to reflect vegetation cover variability, which is an important consideration in selecting this index for this study. The coordinate system of all spatial data is transformed into the GCS_WGS_1984. To solve the problem caused by the inconsistent spatial resolution of raster data, all spatial data were resampled to a resolution of 250 m. Meteorological station data was converted into spatial data using the Kriging interpolation method.

Table 1. Details of data used in this study.

Data Name	Type	Resolution	Data Resource
EVI	Raster	250 m	https://modis.gsfc.nasa.gov/, accessed on 13 November 2022
Soil erosion data	Raster	1 km	http://www.geodata.cn/, accessed on 13 November 2022
Meteorological station data	Text	–	http://data.cma.cn/, accessed on 13 November 2022
DEM	Raster	30 m	https://lpdaac.usgs.gov/, accessed on 13 November 2022
Land-use data	Raster	10 m	https://www.arcgis.com/, accessed on 13 November 2022
Primary map data of LPC	Vector	–	1:250,000 national basic geographic database

2.3. Methods

The workflow of this research is shown in Figure 2, and four steps are taken. The first step is to extract landscape classes in LPC using the morphological spatial pattern analysis (MSPA) approach, followed by ecological sources identification based on landscape connectivity evaluation. The third step is constructing the ecological network with the ecological corridors and nodes extracted by the MCR and gravity models. The last step is to optimize the ecological spatial security pattern based on the land-use data.
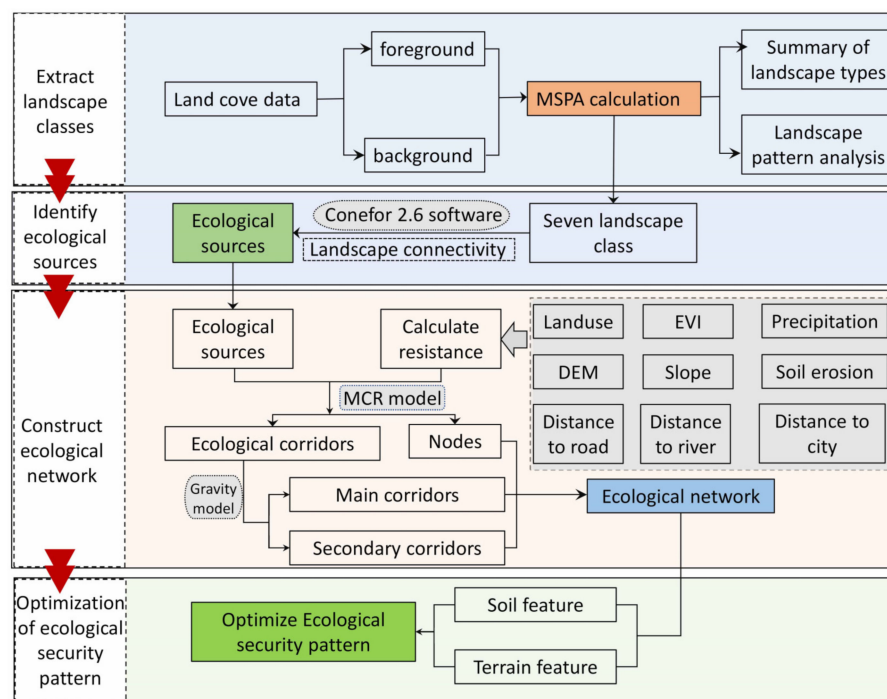
Figure 2. Research framework.

2.3.1. Identification of the Ecological Source

The ecological source area is the basis for the expansion and flow of ecological landscape elements and the core area for maintaining the stability of the ecosystem. It is usually the area of ecological land with the highest ecological quality [42]. In this study, the MSPA approach and the landscape connectivity were utilized to qualify land-use types and determine ecological sources.

(1)　MSPA Pattern Analysis

Morphological Spatial Pattern Analysis (MSPA) is an image-processing method developed by Soille and Vogt (2009) for mathematical morphological pattern computation of raster images [43]. The MSPA method was later widely introduced into landscape studies for structural connectivity analysis to facilitate accurate differentiation of landscape types and configurations [44]. The MSPA analysis method classifies land-use types into seven nonoverlapping landscape types, and each category has a different function for the

region's ecosystem (Table 2). In the MSPA method, the land-use data are first binarized into two types, foreground data and background data, followed by the geometric analysis of foreground data by GUIDOS (Graphic User Interface for the Description of image Objects and their Shapes) software to perform geometric analysis on the foreground data to determine the ecological sources. Referring to the importance criteria of land types in related studies [30], this work set forest land, grassland, and water bodies as foreground, cultivated land, construction land, and bare land as background data [25,45].

Table 2. MSPA pattern classes criteria.

Pattern Types	Description
Core	Habitat patches that are relatively important to the ecosystem and larger in size usually serve as ecological sources for the ecological network.
Perforation	The pixels located in the transition area between the foreground and background, which form the outer edge of the background.
Islet	Small, isolated, broken patches are disconnected from each other and do not contain core patches.
Edge	The transition area where the foreground and background intersect is located in the inner pixel of the foreground.
Bridge	Pixels in the foreground connect two or more separate core patches. Usually represents a corridor in an ecological network.
Loop	Foreground pixels connecting the same core area, serve as a shortcut for species to migrate within the same core area.
Branch	Foreground pixels connecting the core to other types (edge, bridge, loop, or perforation)

(2)　　Landscape connectivity

Ecological sources could be determined by evaluating the landscape connectivity between patches. Landscape connectivity describes the intensity of ecological flow between landscape patches and is an essential indicator for assessing the integrity of regional ecosystems [46]. Strong connectivity facilitates species migration and energy flow, contributing to biodiversity conservation, and stabilizing ecological processes. Landscape connectivity is commonly measured by the integral index of connectivity (IIC) and the probability of connectivity (PC), which defines connectivity by the likelihood of direct dispersal between two habitats and is the basis for assessing the strength, frequency, or flexibility of species migration [47]. Moreover, the percentage of importance (dI) is also widely utilized to measure the importance of a specific patch to the overall landscape connectivity. They are calculated by the following formula [48]:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \times a_j}{1 + nc_{ij}}}{A_L^2} \tag{1}$$

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

$$dI(\%) = \frac{I - I_{remove}}{I} \times 100\% \tag{3}$$

where n is the total number of ecological patches in the landscape; a_i and a_j are the areas of patches i and j; nc_{ij} is the number of connections between i and j; P^*_{ij} is the maximum connection probability that the species spread paths between patches i and j; A_L is the total area of the landscape; I is the landscape connectivity value; I_{remove} refers to the landscape connectivity value after a specific patch is deleted. These connective indexes were calculated using Conefor2.6 software, and ecological sources were selected based on these index results.

2.3.2. Resistance Surface Construction

The resistance surface can reflect the resistance value of species received when moving between different landscape units. The construction of the resistance surface is the foundation for the division of regional territorial space functions. The differences in environmental conditions and human activities will lead to regional differences in expanding ecological sources. Combining relevant research work and the actual situation of the study area, nine resistance factors (Table 3) were selected from three aspects of terrain factors, spatial location, and land surface cover to construct the resistance surface [49,50]. The weight of each resistance factor was determined using the expert scoring method (Delphi method) and referring to the previous research of Huang et al. (2020) [16,51]. The comprehensive resistance surface was obtained by weighted superposition of the resistance surface factors.

Table 3. The selected resistance factors and their classification criteria.

Resistance Factor	Level Classification	Value	Weight	Resistance Factor	Level Classification	Value	Weight
DEM (m)	0–500	1	0.08	EVI (%)	>70	1	0.10
	500–1500	2			50–70	2	
	1500–3500	3			20–50	3	
	>3500	4			0–20	4	
Slope (°)	<8°	1	0.08	Distance to road (km)	<3	1	0.06
	8–15°	2			3–10	2	
	15–25°	3			10–20	3	
	>25°	4			>20	4	
Land use	Water body, forest land, grassland	1	0.15	Distance to city (km)	>1.5	1	0.09
	Cultivated land	2			1–1.5	2	
	Built-up land	3			0.5–1	3	
	Bare land	4			<0.5	4	
Soil erosion	Slight erosion	1	0.18	Distance to river (km)	<1	1	0.14
	Moderate erosion	2			1–3	2	
	Severe erosion	3			3–5	3	
	Extremely severe erosion	4			>5	4	
Precipitation (mm)	>600	1	0.12				
	400–600	2					
	200–400	3					
	0–200	4					

2.3.3. Extraction of Ecological Corridors and Nodes

The ecological corridor is the direct channel of material and energy exchange between ecological sources, usually linear or zonal distribution in the ecological environment [52]. On the minimum cumulative resistance surface, the corridor is the lowest resistance valley between two adjacent ecological source areas and the most easily connected low-resistance channel [16]. The ecological nodes are the weakest places of ecological function in the corridor. As the crucial points for vegetation cover and water source protection, they are important for maintaining the integrity, continuity, and ecological functions of the regional landscape ecological structure. In this study, ecological nodes are defined as the geometric centers of ecological sources and the intersection of ecological corridors [2]. The ecological corridors in the study area were identified using the minimum cumulative resistance model (MCR). The MCR model was first proposed by Knaapen in 1992 and has been widely used in species protection and landscape pattern analysis [12,53]. Cumulative resistance refers to the total cost of resistance required for a species to pass through patches with different resistance values from the source to the destination, reflecting the potential possibility and trend of species diffusion [54]. The model comprehensively considers the source, space distance, and basement surface factors. Its formula is as follows [55]:

$$MCR = fmin \sum_{j=n}^{i=m} D_{ij}R_j \tag{4}$$

where *MCR* is the minimum cumulative resistance; *Dij* is the spatial distance from source *i* to destination *j*; R_j is the resistance value of landscape unit *j*; *fmin* represents the positive correlation between minimum cumulative resistance and ecological process; *n* is the total number of landscape units. The resistance value directly shows the difficulty of species migration. The smaller the resistance value, the easier it is for the species to pass through different landscapes from the "source" to reach the destination; on the contrary, the more difficult it is for species to migrate [56].

The ecological corridors were constructed by the cost–distance module in the ArcGIS platform based on the identified ecological source results and the constructed resistance surfaces. To differentiate the importance level of ecological corridors, ecological corridors were divided into two categories: the main ecological corridors and the secondary ecological corridors. The importance of ecological corridors is evaluated based on the intensity of interactions between ecological sources and target areas. The larger the interaction between the source and the target area, the more important the corridor is [57]. Generally, the connectivity and transfer efficiency of main ecological corridors are higher than those of secondary ecological corridors [28]. The quantification of the interaction intensity can be calculated using the gravity model. The calculation formula is as follows:

$$G_{ij} = \frac{L_{max}^2 \ln(S_i S_j)}{L_{ij}^2 P_i P_j} \tag{5}$$

where G_{ij} is the interaction intensify between ecological source *i* and *j*, L_{max} is the maximum cumulative resistance of all corridors in the study area, S_i and S_j are the patch areas of sources *i* and *j*, and $P_i P_j$ is the resistance value between sources *i* and *j*.

3. Results

3.1. Results of Landscape Patterns Using MSPA and Ecological Source

The spatial distribution of landscape types and the statistical results were derived based on the MSPA approach (Figure 3, Table 4). As can be seen, nearly half of the study area (47.51%) was classified as core, mainly in the central part of the LPC, in a clustered state. The large core area is accompanied by a long edge, resulting in the edge area being second only to the core area (4.5%). As structural corridors in the ecosystem, the bridge connects different cores, a function vital to ecological connectivity, and it accounts for 0.68% of the total area. The perforation is affected by the edge effect, and the area is also large, accounting for 2.7% of the study area. The loop, islet, and branch areas are relatively small, at 1.28%, 0.82%, and 0.52% of the total area, respectively. A further distinctive feature is that, except for the core area, the spatial distribution of other landscape types is relatively dispersed, indicating a relatively high fragmentation of the landscape.

Within the concept of ecological source, only areas of ecological land with the best habitat quality are appropriate; hence, patches in the top 20% of landscape connectivity were selected as ecological sources for this study. Under this principle, 38 ecological source areas were identified, with an area of 57,757.8 km², accounting for 9.13% of the LPC (Figure 4). The spatial distribution of the ecological sources shows certain characteristics of agglomerative distribution. Still, the overall distribution is relatively discrete, mainly concentrated in the eastern and southern parts of the LPC, which belong to the Shaanxi and Shanxi provinces. These areas are mainly situated in the Guanzhong Plain, which has low topography, abundant water resources, and a relatively good ecological environment. These areas are the core zones to construct the ESP of the study area, and the land-use conflict between ecological sources and other land-use categories should be strictly controlled. The ecological sources are poorly distributed in the north and northwest region, which is already close to the Mawwusu Desert area, with its dry climate, sparse vegetation, harsh ecological conditions, and fragile ecosystems. Generally, the spatial variability of ecological sources is significant in the LPC.
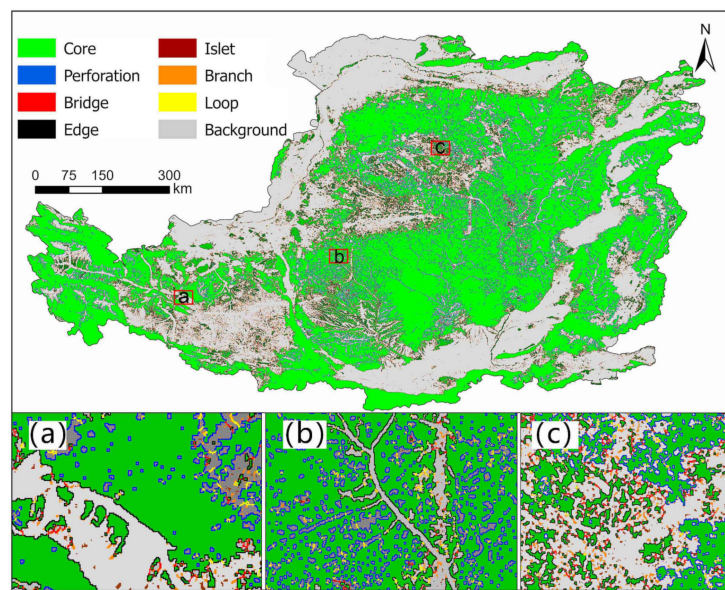
Figure 3. Spatial distribution of landscape pattern in LPC based on MSPA. (**a**) sample view of the edge; (**b**) sample view of the perforation; (**c**) sample view of the bridge.

**Table 4.** Statistical areas of each landscape type.

Landscape Type	Area ($\times 10^4$ km^2)	Accounting for Forestry Area (%)	Accounting for the Study Area (%)
Core	30.8	81.91%	47.51%
Islet	0.53	1.41%	0.82%
Perforation	1.75	4.66%	2.70%
Edge	2.92	7.75%	4.50%
Bridge	0.44	1.18%	0.68%
Loop	0.83	2.20%	1.28%
Branch	0.33	0.89%	0.52%
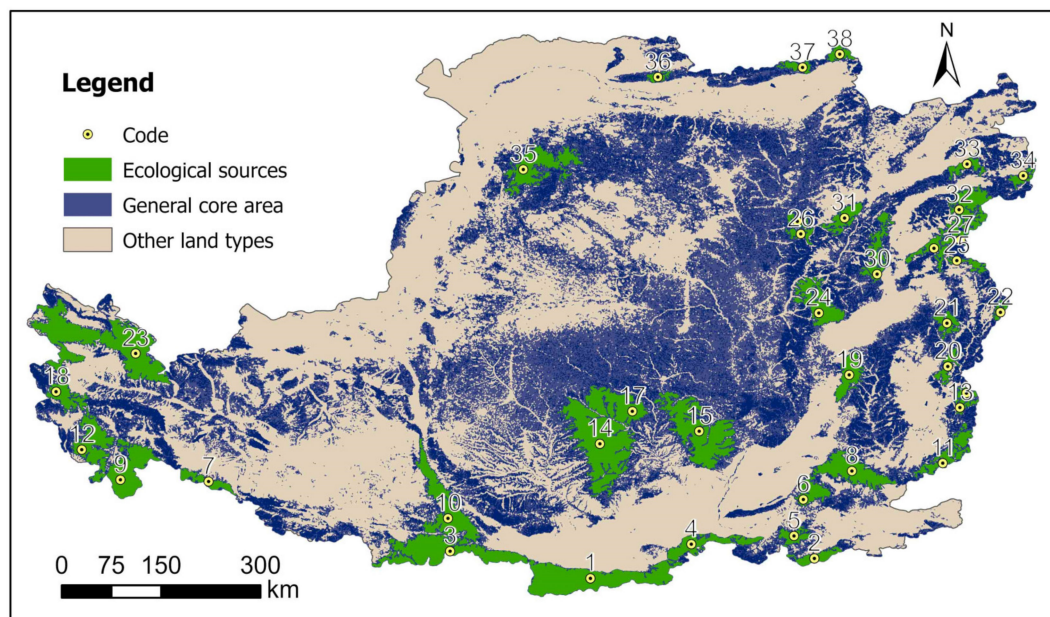
Figure 4. Results of the core patch importance assessment.

3.2. Ecological Network Structure Analysis Based on the MCR Model

Resistance surfaces were constructed based on the selected resistance factors (Figure 5), and then the comprehensive resistance surface was obtained by spatially weighted superposition of these resistance surfaces. The ecological corridors between ecological sources were constructed using the MCR model based on the comprehensive resistance surface. Since too many ecological corridors are not conducive to establishing targeted protection measures, redundant and duplicate corridors were eliminated. Finally, 96 ecological corridors with a total length of 9382.46 km were identified among 38 ecological sources. The gravity model was employed to construct the interaction matrix among the ecological source, and the corridors with interactions intensifying greater than 100 were extracted as important corridors, while the remaining were graded as secondary ecological corridors.
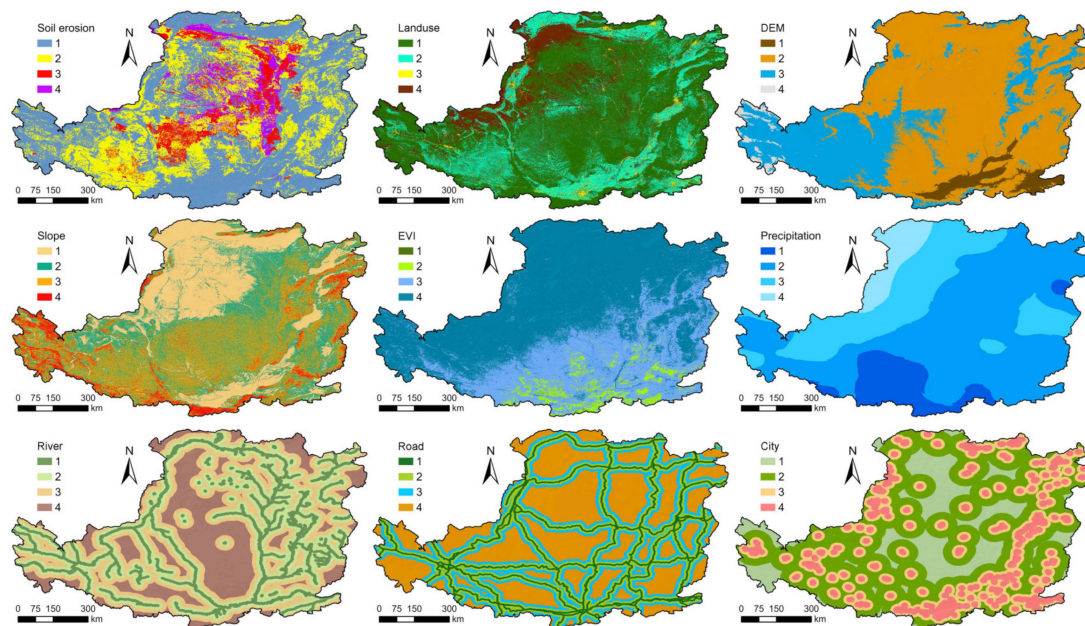
Figure 5. Resistance factors of the MCR model.

The interaction matrix identified 24 important ecological corridors with a total length of 2352.28 km and 72 secondary ecological corridors with a total length of 7030.18 km, which form the basic framework of the ecological safety network in the study area (Figure 6). There are overlapped parts with natural corridors (such as rivers, roads, etc.) and corridors that do not exist in reality among the identified ecological corridors. Moreover, 53 ecological nodes were also recognized, including 38 centroids of ecological sources and 15 intersections of important ecological corridors. These ecological nodes serve as transit links between ecological sources and provide transient functions for biological migration, an essential component of the ecological safety network.

From the overall perspective, the ecological corridor network covers a wide extent, except in the northern and northwestern parts of the study area, where the number of ecological corridors and nodes is small, and the ecological connectivity is weak. The scattered distribution of ecological sources significantly reduced the spatial connectivity in each region, resulting in regional differences in the interdiffusion of species migration and energy flow in the study area. Regarding the spatial distribution of corridors and ecological nodes, the spatial connectivity between ecological sources in the southeastern parts is stronger, as the density of corridors and ecological nodes is significantly higher than in the east. Since species encounter less resistance to migration and dispersal between the southeastern sources and have greater potential for material and energy exchange, they have become the primary distribution areas of important corridors and should be emphasized for conservation.
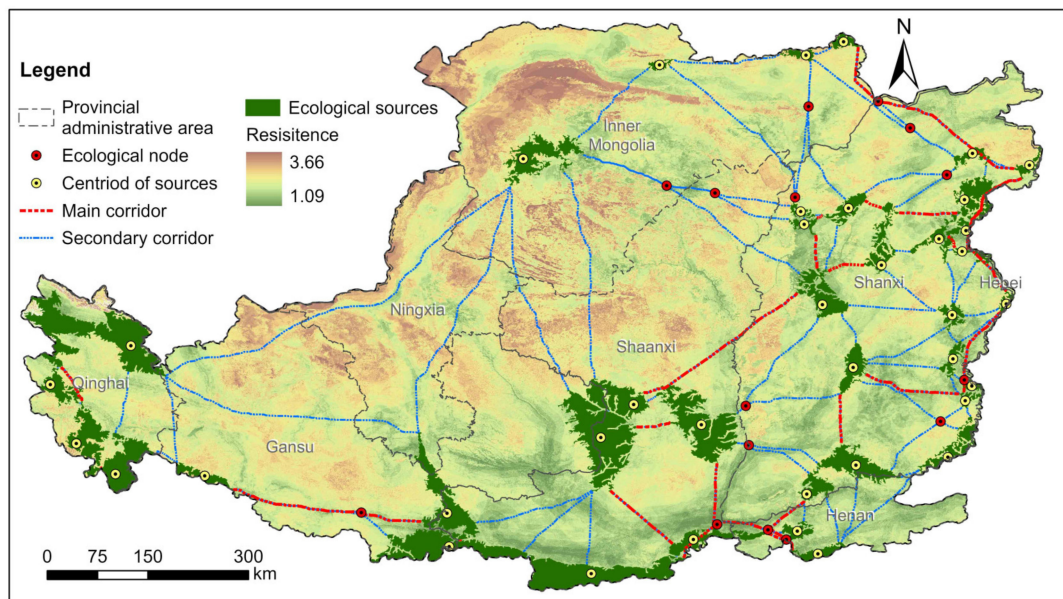
Figure 6. Construction results of ecological network structure in LPC.

Quantifying the regional variability of ecological sources shows that 31.32% of the ecological sources are located in Shaanxi province, followed by Shanxi province (25.30%), and the area of these two central regions is 37,317.31 km^2, accounting for 56.62% of the total ecological source area (Figure 7). In contrast, less than 5% of the ecological source area is located in Ningxia, Henan, and Hebei provinces. Regarding the ecological corridor, 37.70% of the total corridors are located in Ningxia province, followed by Shanxi province (25.44%). The length of these two central regions is 5442.77 km^2, accounting for 63.14% of the total corridor length. Despite having the longest ecological corridors in Ningxia province, they are all secondary ecological corridors. Important ecological corridors are mainly located in Shanxi (49.47%) and Shaanxi (21.08%) provinces, reaching 70.58%, with a length of 1659.38 km. It is clearly observed that the density of ecological nodes and corridors is much higher in the southeast than in the northeast, with a significant imbalance. Moreover, severe soil erosion and low vegetation cover in the northwest cause the energy flow, material exchange, and species migration between ecological sources in the eastern area to be relatively limited. Therefore, there is an urgent need to optimize the regional space based on the current ecological corridor network and enhance the connectivity of ecological resources in these regional spaces.
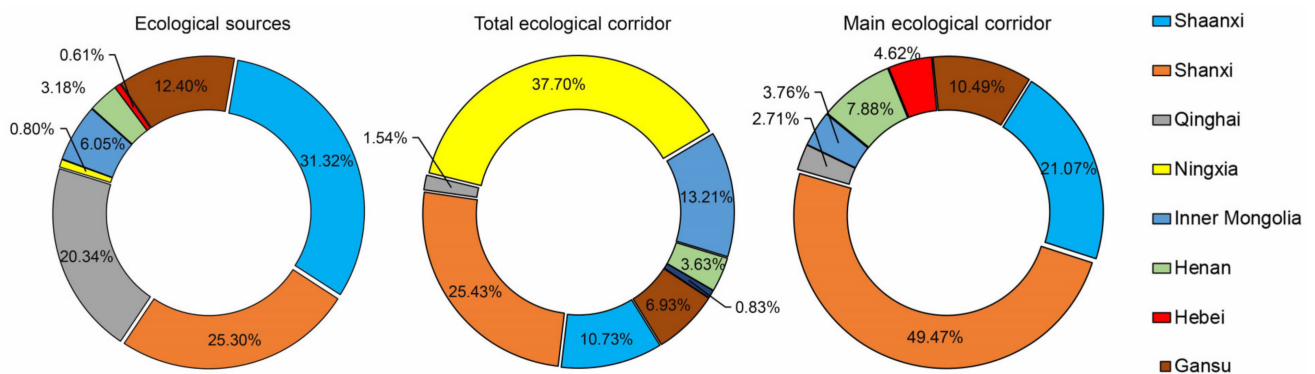

Figure 7. Ecological sources and corridors in each administrative area of LPC.

3.3. Optimization Scheme of Ecological Spatial Security Pattern in LPC

As an important reference for regional ecological management, regional ESP can guide regional ecological restoration and serve as an important basis for overall urban planning and various special plans. This study comprehensively considers the ecological sources, corridors, and ecological nodes of the LPC, attaches importance to the connection function of ecological corridors to ecological sources, strengthens the strategic transfer function of ecological nodes, and builds a "two barriers, five corridors, three zones and multipoint" ESP (Figure 8). This pattern contains a multilevel, networked, and functionally complementary ecological spatial structure to maximize the ecological effects of the accumulation, association, and diffusion of ecological resources in different regions. Among them, 'two barriers' refer to the Yellow River barrier in the northern part and the Yellow-wei River barrier in the southern region; these two barriers are based on the existing rivers and form a relatively enclosed area to maintain ecological balance. The two natural barriers block the radiation of external ecological influences, whilst the rivers, as important water sources, also positively impact the circulation of materials and energy flows in the surrounding area. The "five corridors" are constructed concerning the spatial distribution of corridors extracted from the MCR model and consist of four north–south and one east–west corridor. These corridors are essential axes linking the different functional subregions. The staggered spatial distribution ensures the continuity of energy flow and material exchange while complementing and continuing the ecological functions of ecological nodes and improving the connectivity of the ecological pattern. The "three zones" include two soil and water conservation functional zones (according to the soil erosion intensity), which suffer from loose soils, abundant rainfall, sparse surface vegetation, and are prone to erosion, and the ecological function core zone in the central part of the LPC. These three areas are targeted and focused for the protection of vulnerable regions. "Multipoint" are mostly identified ecological nodes. These ecological nodes are constructed to enhance the connectivity of species transfer and energy circulation paths. Compared with the original ecological landscape pattern, the optimized ESP was significantly improved in network closure, line–point rate, and connectivity rate.
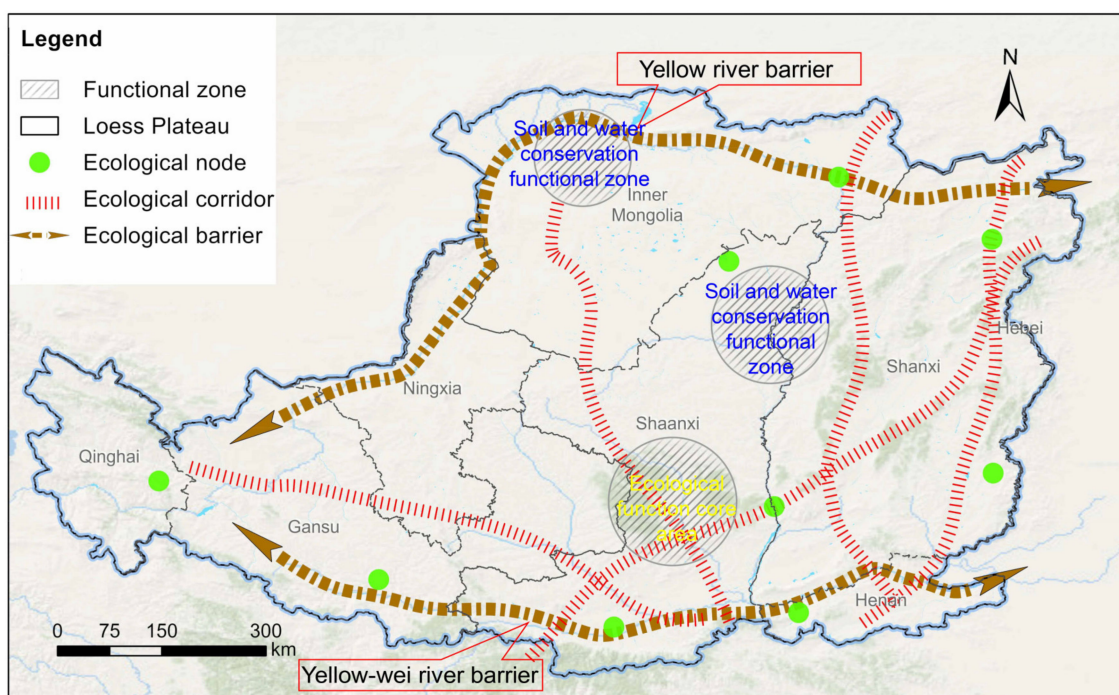

**Figure 8.** Optimization scheme for ESP of LPC.

4. Discussion

4.1. Construction of Resistance Surface Factors and Ecological Corridors

Ecological resistance surface can reflect the resistance value of species moving in the landscape, mainly affected by the land-use type, the surrounding environment, and human activities [58]. However, in the construction of resistance surfaces, natural factors often get a larger weight because of their greater impact on the landscape spatial pattern and are easy to quantify. The effect of human activities on the ecological environment is often reduced to a certain factor, which is not analyzed separately, which leads to its importance being weakened. Some important human activity factors are ignored because they are difficult to quantify, such as policy factors (basic farmland protection policies, Green for Grain Project, etc.). Policy factors have no less impact on the ESP than natural factors. Still, they are difficult to quantify, so they are not considered in most studies or replaced by an approximate quantifiable factor. Another limitation is that the current evaluation index system selects factors such as the distance to artificial structures (such as built-up areas and roads) and other factors when selecting human activity impact factors. However, some indicators representing the intensity of human social and economic activities are abandoned because they are difficult to be spatialized [49]. In addition, artificial structures are constantly changing, but the data update delay makes the selected human activity factors unable to fully reflect human activities' real impact. Moreover, some human activity factors are inaccurate due to the limitations of quantitative methods, such as population aggregation. The differences in the degree of population aggregation cause different environmental pressures. When expressing the degree of population aggregation, the index of population density is usually adopted, divided by the total population in an administrative area by the total administrative area. This calculation method makes the population density difference between administrative divisions. Still, the population density within the same administrative division is the same, which cannot reflect the difference in population aggregation. The influence of this calculation error will increase with the increase of the research scale. For some human activity factors that can only be qualitative, a popular quantification method is expert scoring. This method has a greater subjective influence, and the results cannot be objective. These reasons listed above make it difficult for human activities to be considered when constructing resistance surfaces. Some scholars are constantly attempting to put forward new indicators to reflect the intensity of human activities. Sun incorporates the impact of human activities on nature into the evaluation index system to reflect the impact of human activities; this method could effectively reflect the interrelationship between the natural ecosystem and socioeconomic system under complex conditions [59]. Dai introduces the Duranton and Overman index (DO index) of industrial agglomeration based on the detailed spatial information of enterprises to represent the intensity of human economic activity, which provides a new alternative index for quantifying human activity factors [28]. These research works are providing exploration for more accurate resistance surface construction processes.

The ecological corridor constructed in this study based on the MCR model is the optimal pathway for species migration and energy flow under ideal conditions. However, species and energy may not follow an artificially defined pathway in the actual situation and may even wander randomly. In this case, the effectiveness of the ecological corridors identified by the MCR model is greatly diminished. The functional evaluation of networks based on circuit theory is a good supplement to existing models [21]. The theory treats the generated ecological resistance surface as a resistive and analyses the possible migration routes of species dispersal along a given distance (truncate distance) throughout the ecological process by modeling the movement of electric currents across the resistive surface [60]. Comparing the species-dispersal probability under circuit theory and the minimum-cost pathway (Figure 9) under the MCR model reveals that, unlike the MCR model, which provides an optimal solution from ecological source site to site, the circuit theory model offers more possible pathways for species migration and energy flow. Therefore, a more comprehensive framework for a regional ecological safety network containing

point–line–multiline–surface could be constructed by combining the MCR model with the circuit theory model in subsequent studies.
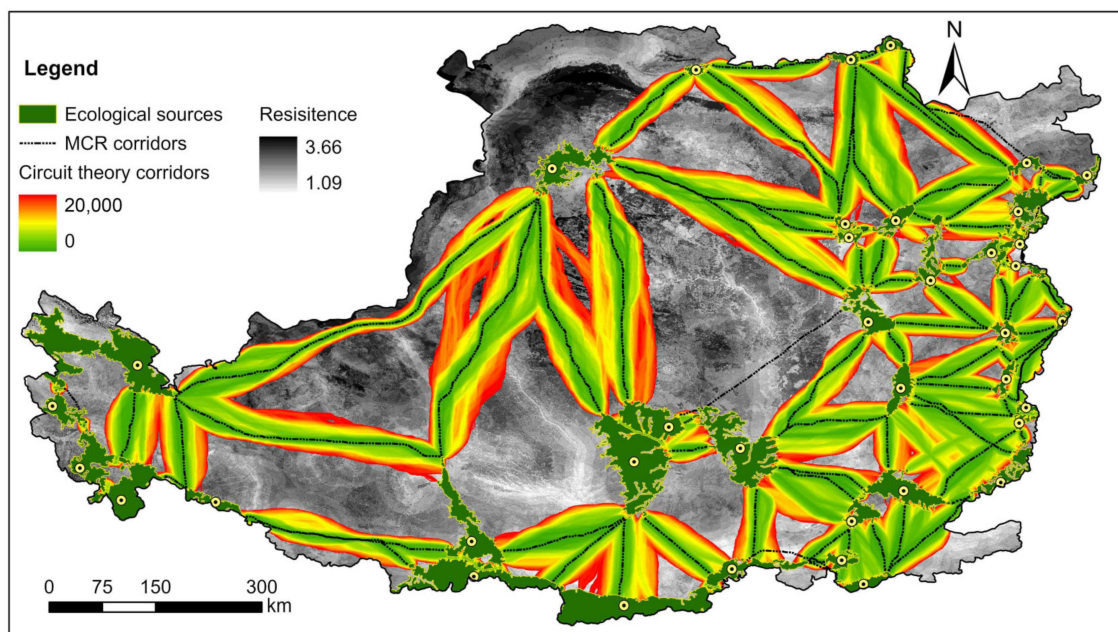

Figure 9. Comparison of ecological corridors constructed by the MCR model and circuit theory.

4.2. Influencing Factors of Regional Differences in ESP

Many factors are affecting the pattern of ecological security. In addition to the human activities discussed above, it is closely related to various ecological processes. Understanding the impact of changes in the pattern of ecological security on ecological processes is an important research topic in landscape ecology [61]. The key components of ESP play an important role in maintaining and controlling some ecological processes and forming landscape patterns. At the same time, ecological processes, in turn, affect the overall ESP, which is an interactive process. The ESP may restrict various ecological processes (such as biological and ecological processes, including species distribution and migration, soil erosion and land degradation, etc.). The impact of increased human activity and accelerated urbanization on the regional ecology is particularly evident in the changes to ecological processes, such as GGP (Figure 10). Policy-driven human activities change the ecological environment more rapidly than its natural evolutionary processes and promote (inhibit) ecological processes more intensely than its natural state. Since human activity directly affects the ecosystem structure of the target area, changing its landscape pattern; on the other hand, it alters material cycles and energy flows, thereby affecting the regional ecological process [62].

The ESP research method based on the MCR model adopted in this study provides a new method for revealing how the landscape pattern controls the ecological process. In addition, the MCR method has essential application value in species resource management, biodiversity conservation, and landscape ecological planning. In other studies [63–65], evaluating the ESP by considering ecological processes (e.g., natural hazards, biodiversity maintenance, and carbon sequestration) is also an important approach to constructing the ESP. Notably, this approach should consider regional differentiation, as the dominant ecological processes differ in different regions. Under this approach, the more comprehensive and objective the ecological processes considered when evaluating the regional ESP, the more reasonable and accurate the evaluation results will be.
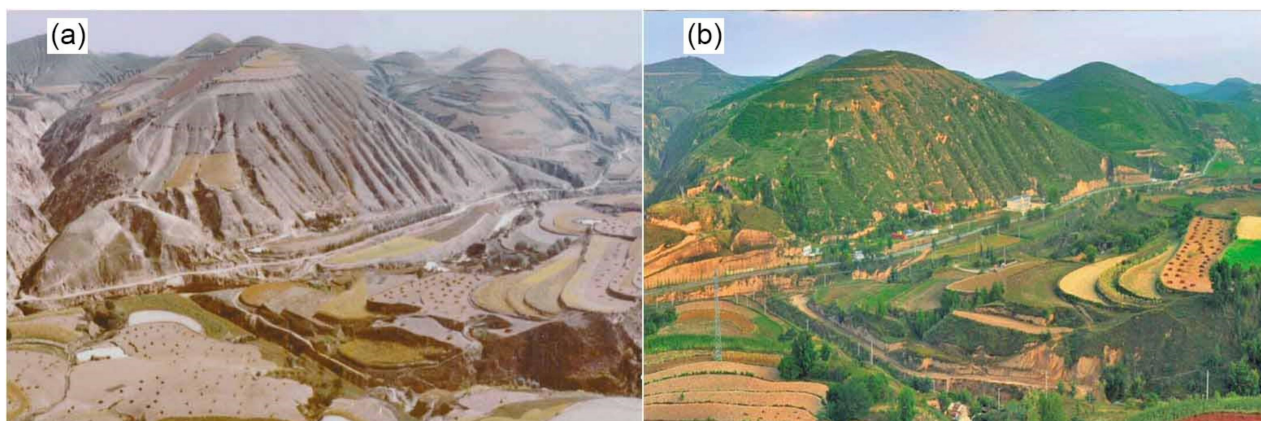
Figure 10. Comparison before and after the policy of GGP in LPC. (**a**) before GCP (1984) in Wuqi County, Shaanxi Province; (**b**) after GCP (2017) in Wuqi County, Shaanxi Province.

Moreover, the current construction of the ESP mainly takes a holistic and global perspective for resistance surface factors selection and ecological sources identification, and the advantage of this approach involves extensive biodiversity conservation and comprehensive spatial distribution. However, the point should be emphasized that ESP is supposed to include more sub-patterns, including species-specific or ecological-process-specific ESP construction [66]. The resistance surface factors and ecological sources considered in the construction of this kind of ESP under specific objectives are often different from the typical ESP construction, since the diversity of species and the complexity of ecological processes determine that the impact factors and environmental conditions are distinct, and corresponding solutions should be set for specific protection objectives.

4.3. Limitations and Future Research Directions

Unlike the strategic ecological protection strategy, constructing an ESP can subdivide the protection object into a point–line–surface structure. The protection object is divided into different priority levels for targeted protection, which is more conducive to effectively implementing protection measures. The ESP constructed in this work clearly shows the key ecological elements and weak areas of the LPC. It can provide a scientific basis for planning regional ecological civilization construction and delineating ecological red lines. However, there are still some limitations in this study. Specifically, it is the impact of the scale effect. The scale effect is an inherent property of landscape patterns and processes, including three levels of time, spatial extent, and data resolution [67]. In terms of the time level, this research constructed the ESP of the LPC based on the land-use/land cover data at a single time node. However, the ecological safety network is in a dynamic process along with the change in land-use and land cover. The evaluation of the ESP at a single time node can help to comprehend the spatial distribution of ecological risks in the region. Still, for regional managers and decision-makers, the dynamic evolution process and characteristics of the urban ESP are more valuable. Hence, the evaluation of the regional ESP based on different time nodes should be emphasized in further studies. At the spatial extent level, ESP construction methods and considerations differ for global, regional, or small watershed unit scales, since variability in landscape phenomena and processes occurs as spatial extent change [68]. Moreover, according to the first law of geography, everything is related to other things, and the relationship between adjacent things will be closer [69]. The smaller the spatial extent, the fewer the species and the simpler the ecological processes. With the gradual expansion of spatial extent, the number of species increases along with the complexity of ecological processes, and the spatial heterogeneity of ecological processes becomes more obvious. Therefore, the influence of the scale effect at the spatial extent also needs to be considered when constructing the regional ESP. The impact of data resolution mainly refers to the size of the raster data grid. Theoretically, the higher the data resolution,

the more detailed the evaluation results. However, more detailed information from high-resolution data is accompanied by an increase in computational load, and high-resolution data can lead to fragmented evaluation results to a large spatial extent. For this study, the 250-m resolution data are sufficient to express the ecological security of the LPC and can meet the needs of this study.

5. Conclusions

The contradiction between economic growth and environmental protection in land-use has existed for a long time. Effective coordination of the contradiction between the two is an important measure to maintain the healthy and stable development of the region. This work identified the ecological sources area and constructed an integrated ecological network based on the MCR model and the MSPA method. On this basis, the ESP optimization plan of the LPC is proposed. The methodology employed in this research is not restricted to specific regions and has good generalizability and can be implemented in other regions with complete basic material. It should be noted that regional variability leads to different factors affecting ecological processes and patterns, and local adaptation and comprehensive consideration are needed when selecting resistance surface construction factors. The main conclusions of this study are as follows:

(1) The dominant landscape type in the LPC is core (47.51%); among the core area, 57,757.8 km^2 was identified as ecological sources due to its high landscape connectivity, and the spatial distribution shows a certain regional agglomeration effect.

(2) Twenty-four main ecological corridors, seventy-two secondary ecological corridors, and fifty-three ecological nodes are extracted based on the MCR model. Most corridors and nodes are in the southeastern area of LPC, reflecting the efficient species migration and energy flow in this region. The opposite situation is that the spatial connectivity in the northern and northwestern parts of the study area is weak due to the low density of corridors and fewer ecological nodes.

(3) Based on the identified ecological sources, corridors, and nodes, combined with the current status of land-use in the study area, soil erosion status, and other attributes, a "two barriers, five corridors, three zones, and multipoint" ESP optimization scheme was proposed to provide a reference for land space planning and ecological environment governance.

Author Contributions: Conceptualization, H.W. and L.X.; data curation, software, H.Z. and J.C.; writing—original draft, H.W. and P.L.; writing—review and editing, L.X. and H.J.; funding acquisition, L.X. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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