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Ecological Security Pattern Construction in Loess Plateau Areas—A Case Study of Shanxi Province, China

Yongyong Fu [1], Wenjia Zhang [2], Feng Gao [1], Xu Bi [1], Ping Wang [1] and Xiaojun Wang [2,*]

[1] College of Resources and Environment, Shanxi University of Finance and Economics, Taiyuan 030006, China; yyong_fu@sxufe.edu.cn (Y.F.)
[2] College of Environment and Resource Science, Shanxi University, Taiyuan 030006, China
* Correspondence: xjwang@sxu.edu.cn; Tel.: +86-351-7010600

Abstract: Strong soil erosion and increasing human activities have made Loess Plateau areas ecologically fragile regions. Constructing the ecological security pattern (ESP) is imperative to maintain their ecosystem functions and sustainable development. However, it is still challenging to establish the ESP in such an unstable and scattered ecological environment. In this study, we take Shanxi Province, which suffers severe ecological problems in Loess Plateau areas, as an example to construct the ESP in a pattern of "source-resistance-corridor". The proposed methods include the following steps: (1) potential ecological sources are selected with important ecosystem functions based on contributions of soil and water conservation, habitat quality, and carbon storage; (2) ecological sources are determined by considering core areas at the landscape scale based on morphological spatial pattern analysis (MSPA) along with stability based on dynamic assessment on previous sources; (3) the comprehensive resistance surface is constructed by multiple resistance factors and remotely sensed nighttime light data; (4) ecological corridors are simulated and extracted based on circuit theory. As a result, the proposed ESP in our study area mainly includes 13,592 km^2 of ecological sources, 8519.64 km of ecological corridors, and 277 ecological nodes. Meanwhile, an ecological framework of "two axes, three belts, and three zones" was proposed based on the optimization and reorganization of ecological components within the ESP. Our research lays a methodological and practical foundation for regional ESP construction and sustainable development in Loess Plateau areas.

Keywords: ecological sources; ecosystem service function; circuit theory

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1. Introduction

Since 20th century, the invasion of human activities into ecosystems has been largely increasing in Loess Plateau regions, with the rapid and disordered occupation and mining of nature resources brought by the development of technology and urbanization [1,2]. This has caused a series of ecological and environmental problems, such as land degradation [3], soil erosion [4], and water pollution [5]. As a result, the structures and functions of ecosystem have been directly affected, leading to a shrinking of habitats and migration paths of animals in the ecological network [6]. Therefore, promoting the sustainable development of ecosystem has become a challenging issue in Loess Plateau regions.

To improve ecosystem services and protect ecological security, Kongjian Yu first proposed the research of the ecological security pattern (ESP) in 1990s [7]. Based on the landscape patterns and ecological processes, the ESP, which is an interconnected ecological network of diverse ecosystems, represents an effective approach for supporting biological species, preserving natural ecological processes, and maintaining regional ecological security [8–10]. It has gradually become a vital tool for identifying conservation and enhancing connectivity and management of these areas at the regional scale [11,12]. Currently, the pattern of "source-resistance-corridor" has formed and become a commonly used method, which mainly includes the identification of "Ecological sources", "Ecological resistance surface", and "Ecological corridors" [9,13].

The ecological sources, which represent conservations with important ecosystem service functions, are the foundations for establishing an ecological security pattern [14]. Currently, most studies directly select ecological source areas from a specific type of land use, such as patches of nature reserves, forests, or grassland [15,16]. However, such methods select ecological source areas from a static perspective, resulting in insufficient attention for the long-term status of the source areas. For example, economic forests can be easily selected as ecological source areas in such way, but most of them are vulnerable to natural disasters due to their inherent structural weakness [17]. Thus, the obtained source areas may have potential risks in terms of long-time stability. To solve such problems, we propose to select stable ecological resources by performing assessments based on long-term ecosystem service functions of each region. Meanwhile, some studies mainly focus on the ecological characteristics of the patches themselves [18,19]. They ignore the fact that each of the single patches is affected by the surrounding patches and has a specific function at the landscape scale. Therefore, some inappropriate land covers may be chosen as ecological sources without considering the relationship between patches and their surrounding environments. Thus, we tried to use the Morphological Spatial Pattern Analysis (MSPA) method to quantitatively identify core areas as the ecological sources at the landscape scale [20].

In the second stage, ecological resistance surface is constructed to simulate spatial resistance of species during migration between ecological sources [21]. Most researchers construct the resistance surface by directly assigning values based on land covers [22,23], which ignores the spatial heterogeneity brought by human activities. To solve such problems, our study adopts indicators that represent human activities and natural factors to evaluate the spatial resistance during migration. Specifically, six resistance factors were firstly selected to construct the primary resistance surface in our study, namely land use intensity, terrain undulation, NDVI, slope, distance from major roads (national and provincial roads), and population density. Then, nighttime lighting data was introduced to correct the primary resistance surface, obtaining the final and comprehensive resistance surface.

Ecological corridors are constructed in the last stage, which provide important channels for circulation of material and energy in ecosystems [24,25]. Generally, the ecological corridors can be extracted by different methodological frameworks. The first is the minimum cumulative resistance (MCR) model, which is built based on graph theory and has been applied to extract ecological corridors in ESP. However, it directly calculates the shortest path in theory. Therefore, it fails to capture the difference in ecological potential between various sources. Specifically, it disregards the random migratory patterns exhibited by species [9,26]. Inspired by the similarity of species and random walk of electrons in physics, circuit theory was employed to simulate the migration process of species, especially for the construction of ESP and landscape connectivity [27–29]. According to the simulated current values, this theory can determine which pathway is reserved to enhance the connectivity of ecological networks. It thus integrates all possible pathways of migration. In this paradigm, ecological resistance is likened to impedance, and ecological flow is conceptualized as a random walk current [30], thus providing a more reasonable understanding of ecological corridor identification. Therefore, we explored and applied circuit theory to extract ecological corridors, ecological pinch points, and ecological obstacles in our study.

In Shanxi Province, located in the eastern part of the Loess Plateau in China, there are a variety of species and complex topographic and geological conditions which provide important ecosystem services. However, due to the severe soil erosion and environment pollution, the ecosystem in the study area is very fragile and scattered. In addition, high-intensity and large-scale mining activities have led to serious ecological damage [26]. Therefore, it is necessary to construct ESP to maintain ecosystem service functions and ensure ecological security in this region. The main objectives of our study are as follows: (1) identifying ecological source areas by exploring stability, important ecosystem services, and landscape relations of regions; (2) constructing a comprehensive resistance surface, which is constructed based on resistance factors that represent human activities and natural influence; (3) extracting ecological corridors and ecological nodes based on selected ecological resources and circuit theory.

2. Study Area

Shanxi Province (110°14′—114°33′ E, 34°34′—40°44′ N) is located in the eastern part of the Loess Plateau, with a total area of 156,000 km^2. Located in a mid-latitude inland region, it is in the temperate continental monsoon climate zone with four distinct seasons. As shown in Figure 1, the topography in Shanxi is relatively complex, including various landform types such as mountains, hills, plateaus, basins, and terraces. Mountains and hills account for more than two-thirds of the total area, and most of elevation is between 1000 and 2000 m. The main land use type is woodland, accounting for nearing 38.9% of the total area in 2019 and mainly distributed in the western and eastern mountains. Construction and farmland account for 31.0% of the total area, and are mainly distributed in the middle basins. In recent years, long-term and disordered mining activities have led to a series of ecological problems, such as environmental pollution, strong soil erosion, land degradation, and so on [31,32]. Therefore, facing the pressures from nature factors and human activities, it is urgent to build the ESP to maintain the ecosystem services and ecological security in this region.

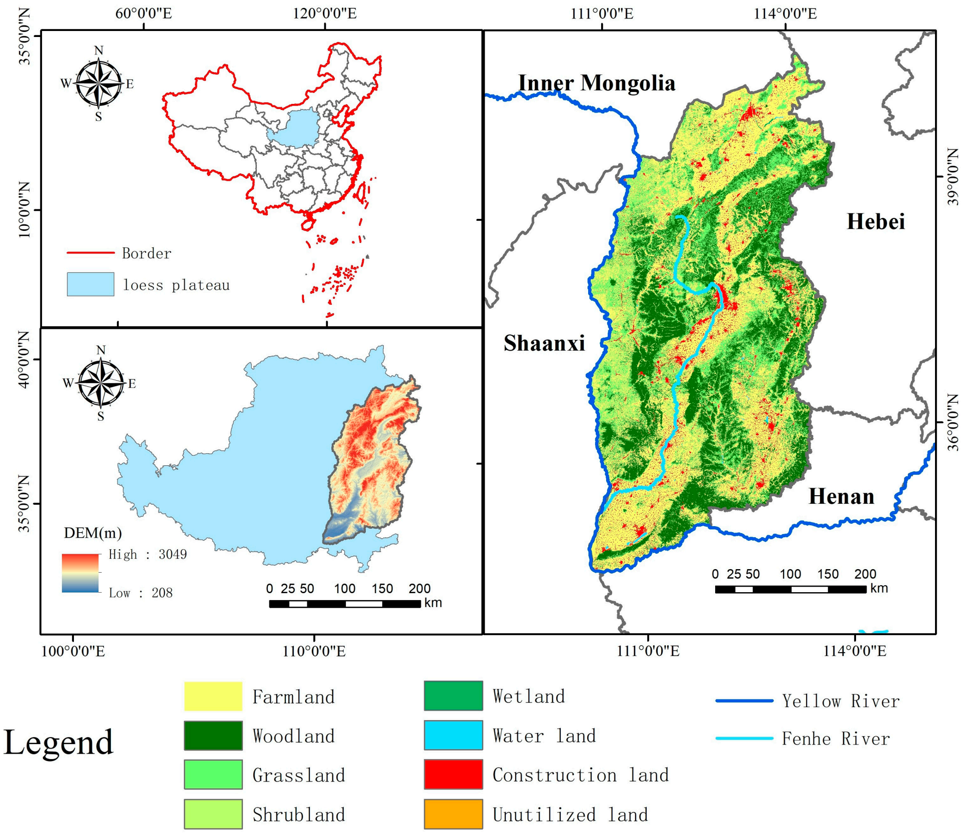

Figure 1. Geographical location of the study area.

3. Materials and Methods

As shown in Figure 2, following the pattern of "ecological source—resistance surface—corridor", we constructed the ESP based on three stages. In the first stage, we identified the ecological source area based on dynamic assessment of ecosystem service functions and the MSPA analysis. Secondly, we built the primary resistance surface based on seven commonly used resistance factors: land use, relief degree of land surface, slope, normalized vegetation index (NDVI), Digital Elevation Model (DEM), population density, and distance from the road. The comprehensive resistance surface was then constructed by correcting the primary resistance surface using nighttime light data. Finally, we employed the circuit theory to simulate and obtain the ecological corridors and nodes.

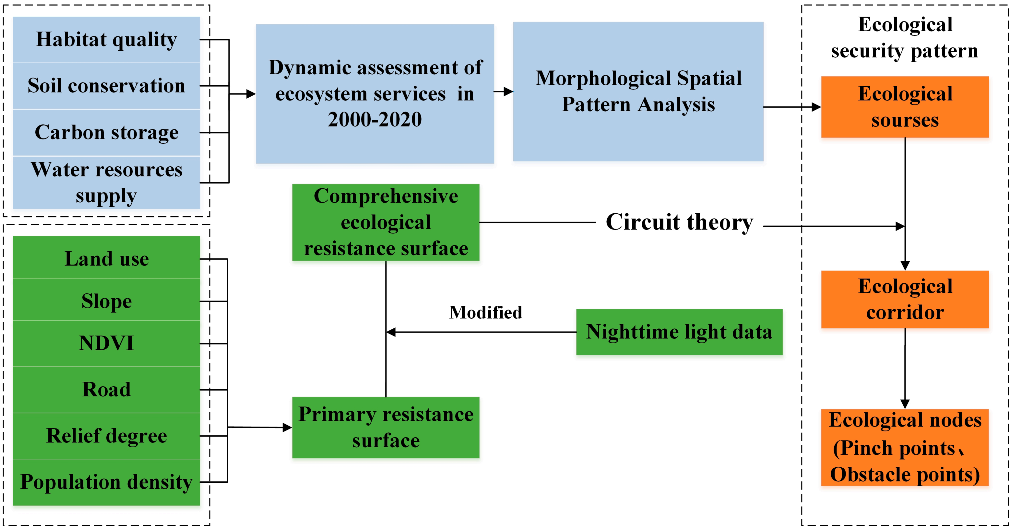

Figure 2. Overall framework of the study, including the identification of ecological sources, corridor, and nodes.

3.1. Data Source and Preprocessing

As shown in Table 1, the data used in this study includes a raster dataset captured from human activities and natural factors. The natural factors are mainly represented by DEM with a spatial resolution of 30 m, annual rainfall data, evapotranspiration data, and NDVI in 2000, 2010, and 2020. Human activities are mainly reflected by land use, population, and the road traffic data in 2000, 2010, and 2020. During the pre-processing stage, the resolution of all the data is resampled to 30 m and the coordinate system of the data is converted to WGS_1984_UTM_49N.

Table 1. Data description. DEM represents the Digital Elevation Model. NDVI represents the Normalized Difference Vegetation Index.

Data Type	Resolution	Data Source
DEM	30 m	Geospatial data cloud (http://www.gscloud.cn, accessed on 15 May 2024)
Average annual rainfall	30 m	Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (https://imde.cas.cn, accessed on 15 May 2024)
Evapotranspiration	30 m	Global Change Scientific Research Data publishing System (http://www.geodoi.ac.cn, accessed on 15 May 2024)
NDVI	30 m	China Ecosystem Assessment and Ecological Security Database (https://www.ecosystem.csdb.cn/index.jsp, accessed on 15 May 2024)
Land use	30 m	GLOBELAND 30 (http://www.globallandcover.com, accessed on 15 May 2024)
Road traffic	30 m	Open Street Map (http://www.openstreetmap.org, accessed on 15 May 2024)
Population density	1 km	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn, accessed on 15 May 2024)
Nighttime light data	1 km	National Centers for Environmental Information (https://www.ngdc.noaa.gov, accessed on 15 May 2024)

3.2. Identification of Ecological Sources

Ecological sources serve as the "source" of species, which plays an important role in the survival and flourishing of species. To select ideal ecological sources, we firstly extract areas with important ecosystem services as the potential selection, which provide important services in supporting natural systems and human activities [33]. In our study, four kinds of ecosystem service functions including habitat quality, soil conservation, water conservation, and carbon storage were firstly evaluated in Shanxi Province from 2000 to 2020. Then, seven types of landscape forms were obtained at the regional scale by using the MSPA model. Compared with other landscape forms, the core areas are the broad and contiguous patches at the landscape scale, which offer an ideal ecological environment for species survival. Thus, the stable core patches over 20 years were selected as the final source areas.

3.2.1. Assessment of Ecosystem Service Functions

In our study, we used the InVEST model (Version 3.6.0), which is generally divided into many modules, for the analysis of ecological suitability. Due to the unique combination of climatic, topographic, and land cover attributes, specifically the semi-arid conditions, intricate terrain, vast loess regions, and intense coal mining activities, the study area faces significant challenges, including water scarcity, soil erosion, and a decline in biodiversity. Therefore, we performed assessments based on four corresponding ecosystem service functions, and the setting of parameters was mainly determined from a summary of the current literature [26,34–37]. After that, the equal-weighted summation method was used to obtain the comprehensive evaluation results, and the commonly used natural breakpoint method was employed to classify the evaluation results into three levels, namely key, important, and general regions.

(1) Assessment of the habitat quality. Habitat quality represents the ecosystem's ability to provide resources and carriers for the sustainable development of species, which is a key function in maintaining biodiversity. In the module of habitat quality, we take areas with high ecological suitability, such as water, woodland, and grassland, as ecological land, and areas that are greatly affected by human activities, such as cultivated land and urban construction land, are selected as threat sources. The formula is as follows:

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

Q_{xj} is the habitat quality represented by x pixel of j-type land; H_j is the habitat suitability of j-type land. D_{xj} is the threat level of grid pixel x in j; z is a constant parameter setting as 2.5; k is a half-saturated constant setting as 0.5.

(2) Evaluation of the function of soil conservation. Soil conservation is the function by which the ecosystem uses its structure and process to reduce soil erosion caused by water erosion. The soil conservation service model of the RUSLE equation was used to estimate the water and soil conservation function of ecosystem. The formula is as follows:

$$\mathrm{SC} = \mathrm{Ap} - \mathrm{Ar} = R \times K \times L \times S - R \times K \times L \times S \times C \times P, \quad (2)$$

SC is soil retention, $t/(hm^2 \cdot a)$; Ap is potential soil erosion, $t/(hm^2 \cdot a)$; Ar is the actual soil erosion, $t/(hm^2 \cdot a)$. R is the precipitation erosivity factor, $MJ \cdot mm/(hm^2 \cdot h \cdot a)$; K is the soil erodibility factor, $t \cdot ha \cdot h/(ha \cdot MJ \cdot mm)$; LS is topographic relief m; C is vegetation cover factor; P is the soil and water conservation measure factor.

(3) Assessment of the function of water conservation. Water conservation refers to the interception and accumulation of precipitation of the ecosystem, which uses its ability to interact with the water, and the realization of water circulation through evaporation. In

this paper, water conservation can be evaluated by the water consumption balance method, i.e., precipitation minus evapotranspiration and surface runoff. The formula is as follows:

$$\mathrm{TQ} = \sum_{i=1}^{j} (P_i - R_i - ET_i) \times A_i \times 10^3, \tag{3}$$

TQ is the total amount of water conservation; P_i is the annual average precipitation; R_i is the annual average runoff; ET_i is evaporation; A_i is landscape type area; i is the type of ecosystem in the study area; j is the number of ecosystems.

(4) Evaluation of the function of carbon storage. In this paper, the carbon sequestration module is used to evaluate the function of carbon storage. Based on the distribution and average carbon density of different land use types, the carbon storage was calculated. The formula is as follows:

$$C = C_{above} + C_{soil} + C_{dead} + C_{below}, \tag{4}$$

C is the total carbon storage; C_{above} is aboveground carbon storage; C_{soil} is soil carbon storage. C_{dead} is dead carbon storage; C_{below} is the underground carbon storage.

3.2.2. Morphological Spatial Pattern Analysis

MSPA is a mathematical morphology-based image processing method which can divide raster images into seven categories: core area, island, pore, edge area, bridge area, ring island, and branch line [38,39]. Among them, the core region has an ideal ecological environment and can be used as a primary ecological source area. To obtain such landscapes in our study, we perform analysis based on the comprehensive evaluation results of ecosystem service value. We set the key region as the prospect analysis data of the MSPA model and the other regions as the background analysis data. Finally, based on the analysis results in 2000, 2010, and 2020, the stable patches were extracted as the final sources.

3.3. Construction of Ecological Resistance Surface

3.3.1. Primary Ecological Resistance Surface

Ecological resistance surface describes the spatial resistance encountered by species during the migration between ecological patches [40]. Many methodologies are available for constructing such a surface. Referring to prior research methodologies [41–44], this study opted for both human activities and natural elements as key factors in shaping the resistance surface. Notably, human activities emerged as the primary determinant, while natural elements served as corrective factors. Specifically, our study mainly selected six resistance factors to construct the primary ecological resistance surface, namely land use intensity, topographic relief, NDVI, slope, distance from main roads, and population density, in order to evaluate the difficulty of movement. As shown in Table 2, following previous studies, these factors were assigned weight values ranging from 1 to 9. A higher resistance coefficient means greater resistance value during migration.

Table 2. Resistance factors, coefficient, and weight in Shanxi Province.

Resistance Factor	Resistance Class	Coefficient	Weight
Land use intensity	Cultivated land	5	0.4
	Forest	1	
	Grassland and water	3	
	Construction land	9	
	Unutilized land	3	

Table 2. *Cont.*

Resistance Factor	Resistance Class	Coefficient	Weight
Slope (°)	<8 8~15 15~25 25~35 >35	1 3 5 7 9	0.1
NDVI	<0 0~0.1 0.1~0.2 0.2~0.3 >0.3	1 3 5 7 9	0.25
Degree of relief (°)	<8 8~15 15~25 25~50 >50	1 3 5 7 9	0.15
Population density (person/km^2)	<80 80~200 200~500 500~900 >900	1 3 5 7 9	0.13
Distance from the road (m)	<1000 1000~2000 2000~3000 3000~4000 >4000	9 7 5 3 1	0.12

3.3.2. Correction of the Primary Resistance Surface

As urban expansion and economic activities tend to invade ecological land and other types of land, spatial heterogeneity happens in such regions. To alleviate such influence, we adopt nighttime lighting data, which can reflect the extent and intensity of human activities, to revise the resistance surface of different types of land use [45,46]. The formula is as follows:

$$R' = \frac{L_i}{L_a} \times R \quad (5)$$

R' is the comprehensive resistance surface corrected by nighttime lighting data; L_i is the night light index corresponding to raster pixel i; L_a is the average night light index corresponding to land use of a; R is the resistance surface corresponding to land use type before modification.

3.4. Construction of Ecological Networks Based on Circuit Theory

As the channels for circulation of material and energy in the ecosystem, ecological corridors play a key role in the ecosystem. Circuit theory uses the random walk of electrons to simulate the migration of species at the landscape scale, which can be used to identify possible movement paths [47,48]. Specifically, it regards individual species or gene flow as electrons, uses the concept of landscape resistance surface to replace electrical resistance, and regards the ecological sources as nodes to replace electrodes [49]. When current is flowing from one ecological source to another, the current values within intervening grids serve as probability that a random walker would traverse those grids to reach the destination. For each pair of sources, a current of 1 A is loaded, and grids with different resistances along the path will experience different currents. As a result, a better path that is more advantageous for migration shows greater conductivity of electricity. Therefore, the connectivity between two nodes can be reflected by electrical current.

Meanwhile, the ecological pinch and obstacle points, which are crucial areas for the ecological restoration, are simulated using the Linkage Mapper module. Ecological pinch points represent the "necessary path" in the process of migration [50]. All the pinch points are presented with high current density in corridors, which play an important role in maintaining network connectivity. The destruction and degradation of this area would significantly reduce the connectivity of the ecological network.

Ecological obstacle points are the key areas that impede the flow of species between ecological sources [29]. To identify ecological obstacle points, the moving window method is employed to calculate the current value after clearing the obstacle areas. As the cumulative current recovery value can reflect the spatial resistance of species migrating in the area, areas with large cumulative recovery value are identified as ecological obstacle points.

In our study, based on the comprehensive resistance surface and circuit theory, the Linkage pathway tool in Linkage Mapper software and Circuitscape (version 4.0.5) were used to extract the ecological corridor [51].

4. Results

4.1. Identification of Ecological Sources

Based on dynamic assessment of ecosystem service functions and MSPA analysis, the stable core patches were extracted as primary ecological sources. Then, we obtained 115 patches by removing patches with an area less than 30 km^2 from the primary sources.

As shown in Figure 3, most of the ecological sources are distributed in the mountain regions, such as mountains at the western and eastern areas. These areas have abundant precipitation, relatively warm and humid climate, high vegetation coverage, and minimal impact of human activities. In contrast, the ecological sources are less frequently distributed in areas with large scale of arable and construction areas, where significant ecological environment damage happens, such as the northern sandstorm areas, central basins, and western loess hilly areas. As for the northern regions, these areas generally have less precipitation, low vegetation coverage, and mining activities. In the middle regions, there are a large number of cities and farmlands distributed in the central basins, which are significantly affected by human activities. Studies also show that economic development, urbanization construction, and coal energy structure have led to high-intensity land use, environmental pollution, and ecological environment damage [31,52,53].

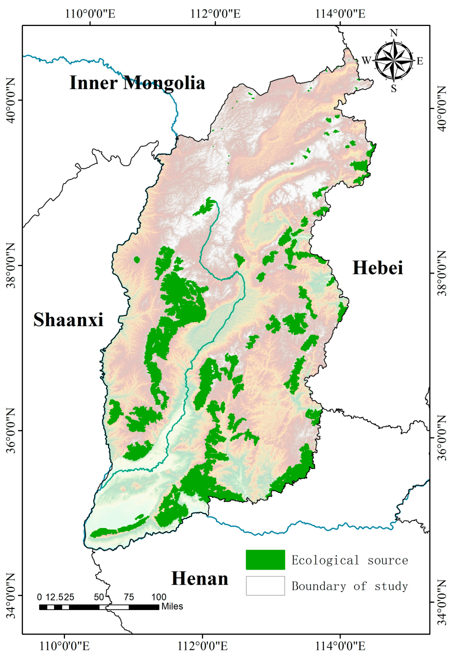

Figure 3. Spatial distribution of the ecological sources.

4.2. Construction of Resistance Surface in Plateau Areas

Shanxi Province is a typical region in the Loess Plateau, which suffers severe ecological problems from nature factors and human activities. First, due to the special geological and climatic conditions, it has severe soil erosion and a fragile ecological background [54,55]. Besides, as most of the mineral resources are distributed within the mountain areas in the whole province, high-intensity and large-scale mining have caused serious damage to the ecological environment [31]. Therefore, it is necessary to select resistance factors that match the regional characteristics and establish an indicator system based on its specific ecological conditions.

As shown in Figure 4a–f, our study selects six factors to construct the primary resistance surface: land use, slope, Normalized Difference Vegetation Index (NDVI), undulation, population density, and distance from roads. However, urban expansion and economic activities generally have a significant influence on other types of land, resulting in spatial heterogeneity even within the same type of land use [56]. To solve this problem, we proposed to use the nighttime lighting data, which is the light captured by satellites at night, to simulate and correct such influence on the resistance surface. As can be seen from Figure 4g,h, the most active human activities are successfully heightened, which also significantly eliminate the salt-and-pepper effects.

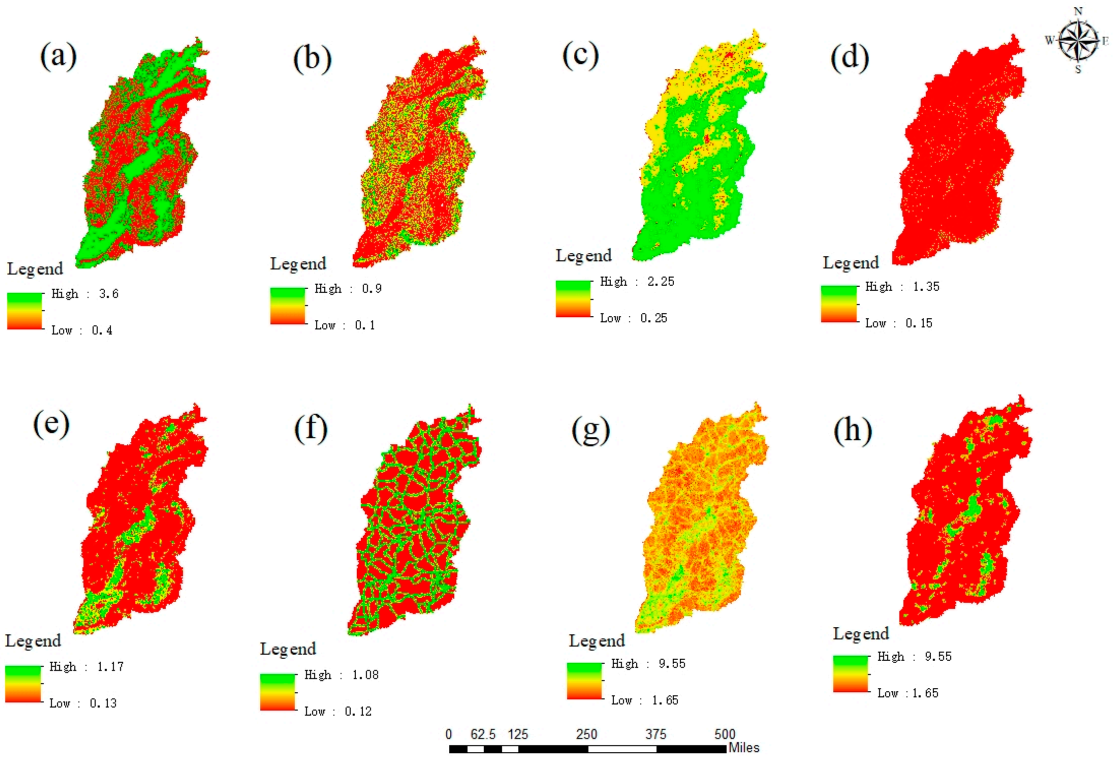

Figure 4. Ecological Resistance Surface in Shanxi Province: (**a**) land use resistance value; (**b**) slope resistance value; (**c**) NDVI resistance value; (**d**) undulation resistance value; (**e**) population density resistance value; (**f**) distance from the road resistance value; (**g**) primary resistance value; (**h**) comprehensive resistance value.

4.3. Mapping of Ecological Corridor

To fully explore the potential paths of species during migration, we extracted ecological corridors based on circuit theory. As a result, we extracted 252 ecological corridors with a total length of 8519.64 km. As shown in Figure 5, most of the ecological corridors are distributed in the eastern and northern parts of Shanxi Province.

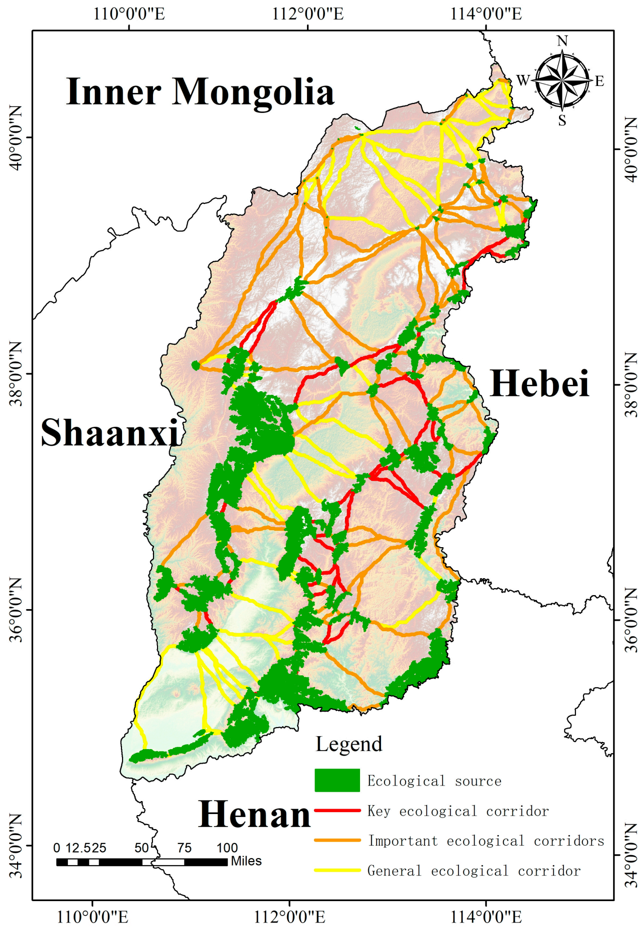

Figure 5. Spatial distribution of the ecological corridors.

To further analysis the connectivity of ecological corridors, we reclassified the ecological corridors into three classes based on the natural breakpoint method. As a result, we obtained 71 key ecological corridors with a total length of 1183.28 km, 109 important ecological corridors with a total length of 4005.02 km, and 72 general ecological corridors with a total length of 3331.34 km. As shown in Figure 5, the key ecological corridors are mainly distributed in mountain areas for short-distance connection, such as the western and eastern areas. The land covers in these areas are dominated by forest and grassland, which provide strong connectivity between corridors. Compared with key ecological corridors, important ecological corridors have relatively larger resistance values, which are mainly distributed in mountain areas for long-distance connections. Such corridors have larger resistance values caused by natural factors, such as long distances, high altitudes, or steep terrain between ecological sources. Meanwhile, general corridors are mainly distributed in population concentration area, such as the middle basin areas. These areas have the largest scale of arable and construction land, which have the greatest resistance compared to others. Therefore, their connectivity is relatively weak, and further restoration is needed to improve their connectivity.

4.4. Mapping of Ecological Nodes

As shown in Figure 6, we first obtained the cumulative current density distribution map of the study area. Places with high current density in corridors, which means most species would select such paths for migration, were labeled as pinch point areas. Following such ideas, we identified a total of 166 areas as the ecological pinch points.

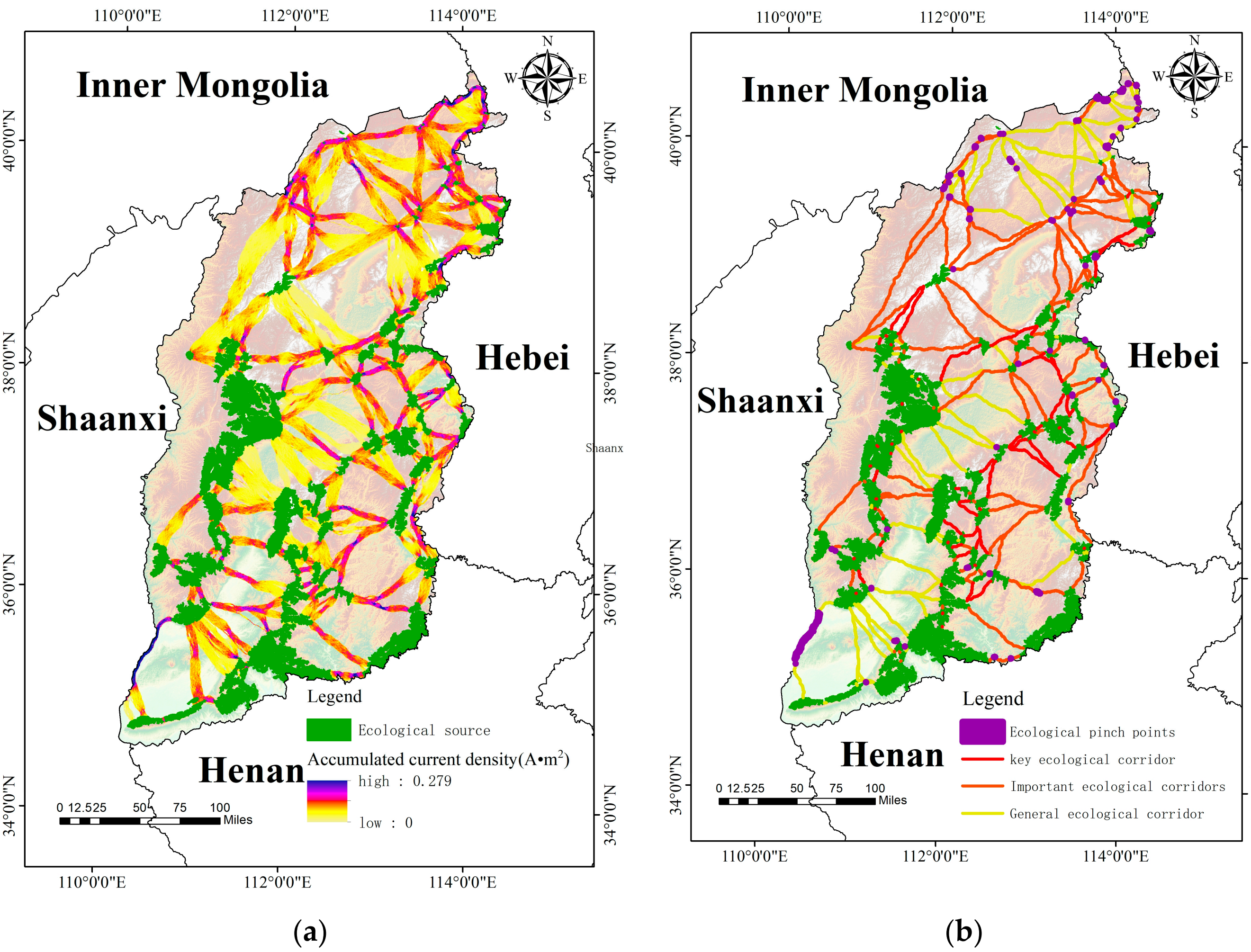

Figure 6. Spatial distribution of cumulative current density (**a**) and ecological pinch point (**b**).

Among them, a total of 78, 56, and 32 ecological pinch points are within key, important, and general ecological corridors, respectively. Most of the ecological pinch points are distributed in mountain regions, as the large scale of forest and grassland landscape in these areas is conducive for migration. Meanwhile, some of the ecological pinch distribution areas are crossing points of migration paths, such as the points in northern areas, making it a key area for migration. As most species have relatively small resistance values during migration in the pinch points, these should be protected first.

Meanwhile, we used seven search radii of 300, 500, 700, 900, 1100, 1300, and 1500 m to calculate the maximum improvement score of each pixel. As shown in Figure 7, places with large cumulative recovery value are identified as ecological obstacle points. A total of 111 ecological obstacle points were identified.

The ecological obstacle points are mainly distributed at middle basin areas. Most of the identified areas are covered with urban construction and cultivated land, which indicates that human activities pose greater pressure on ecological protection in these areas and threaten the migration of species. Furthermore, more than one half of the ecological obstacles are located at general ecological corridors, indicating that these obstacles become a key factor for transforming important ecological corridors to key ecological corridors.

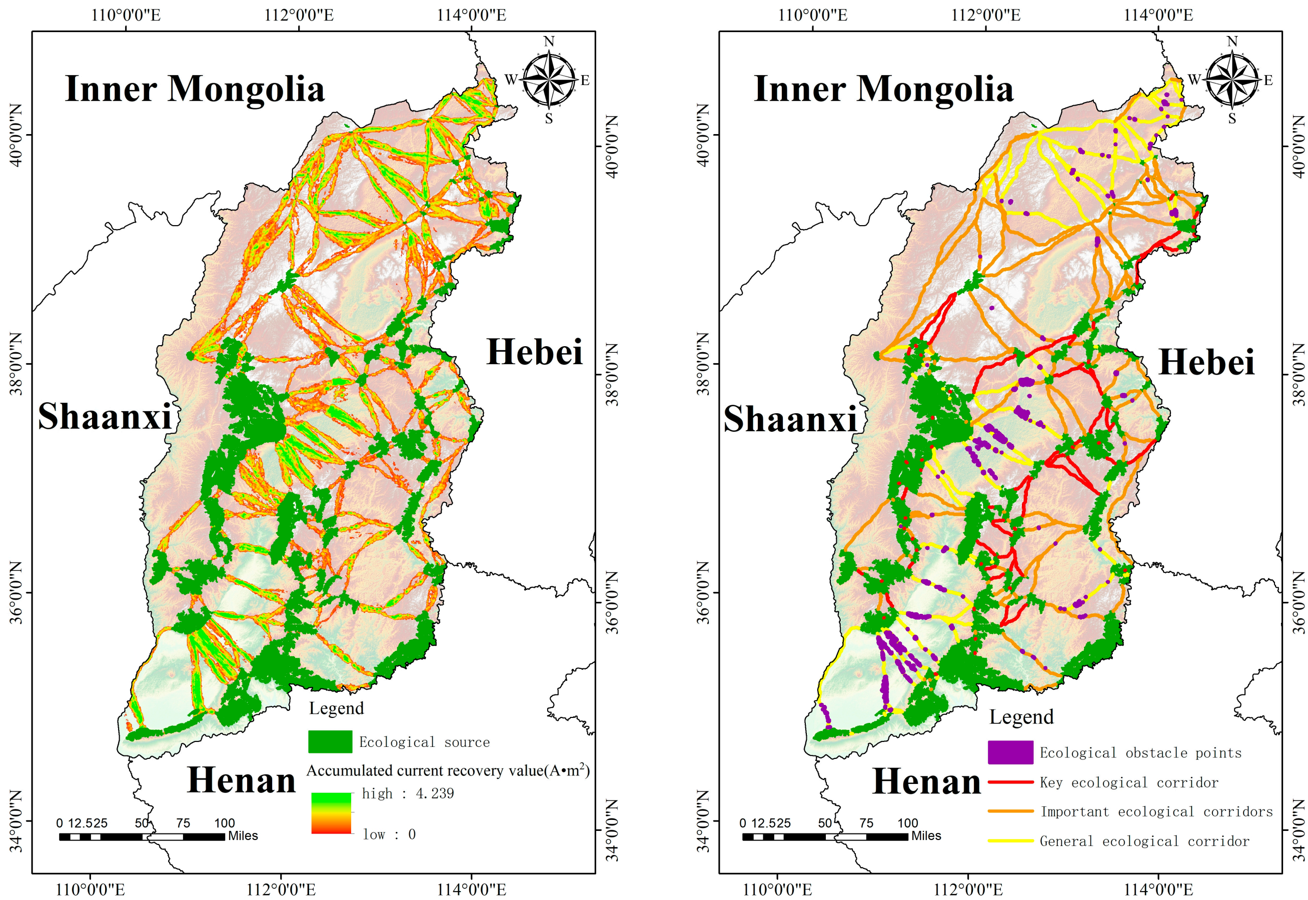

Figure 7. Spatial distribution of the cumulative current recovery value and the ecological obstacle points.

5. Discussion

5.1. Identification of Ecological Sources in Plateau Areas

Ecological source areas generally serve as providers of import ecosystem service and habitats for species and should be presented as a relatively stable environment. To identify ecological sources, previous studies mainly use the following methods: (1) manually selecting land covers with forests, grasslands, or existing nature reserves as ecological source areas [15,16]; (2) selecting areas with important ecological service functions in a certain year as ecological sources [42,57,58].

However, the loess plateau area suffers severe soil erosion and low coverage of vegetation, resulting in thousands of ravines and broken terrain on the Loess Plateau [4,59,60]. Therefore, the identified source areas from a static perspective may lack sufficient stability, resulting in insufficient attention to the long-term status of the loess plateau areas. In addition, previous research mainly focuses on the ecological system service of the single patches, resulting in insufficient attention to the relationship between patches and the surrounding environment. To solve such problems, our study first obtained the comprehensive evaluation results (Figure 8). Then, we used the commonly used natural breakpoint method to classify the evaluation results into three levels, namely key, important, and general regions.

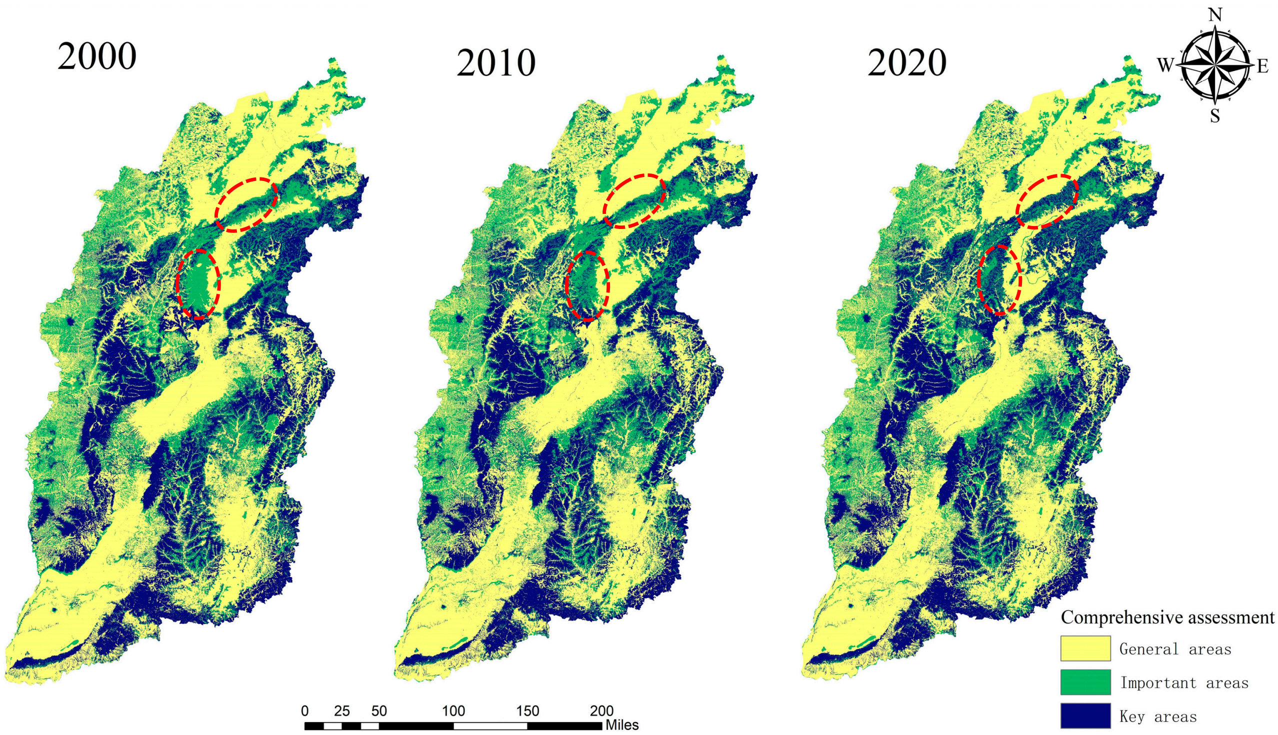

Figure 8. Comprehensive evaluation of ecosystem service value in the years 2000, 2010, and 2020. The red circles indicate typical changes from 2000–2020.

As can be seen from Figure 8, most of the key areas are located at mountain regions surrounded by important areas, and the general areas are occupied by human activity. As shown in in Table 3, the key and general areas of ecosystem function in Shanxi Province show an increasing trend from 2000 to 2020. In contrast, the important areas have decreased over the past 20 years, which means the buffer region between key and general areas shows a shrinking trend.

Table 3. Statistical analysis of the importance level area of comprehensive ecosystem services.

Importance Level	2000 (km^2)	2010 (km^2)	2020 (km^2)
General areas	74,884.69	74,073.19	75,274.62
Important areas	39,419.34	40,063.71	37,698.03
Key areas	42,572.01	42,738.69	43,903.08

Based on the evaluation results of ecosystem services, MSPA analysis was conducted to analyze the core area at the landscape level. As shown in Figure 9, the distribution of core areas is relatively stable. Meanwhile, it can be observed that the core areas of the central region are gradually increasing, especially in the middle regions. The core areas of the eastern and western regions show a relatively stable state. Therefore, our approach identified ecological source areas from a dynamic and morphological perspective. As a result, the identified ecological sources can be more stable compared with existing methods.

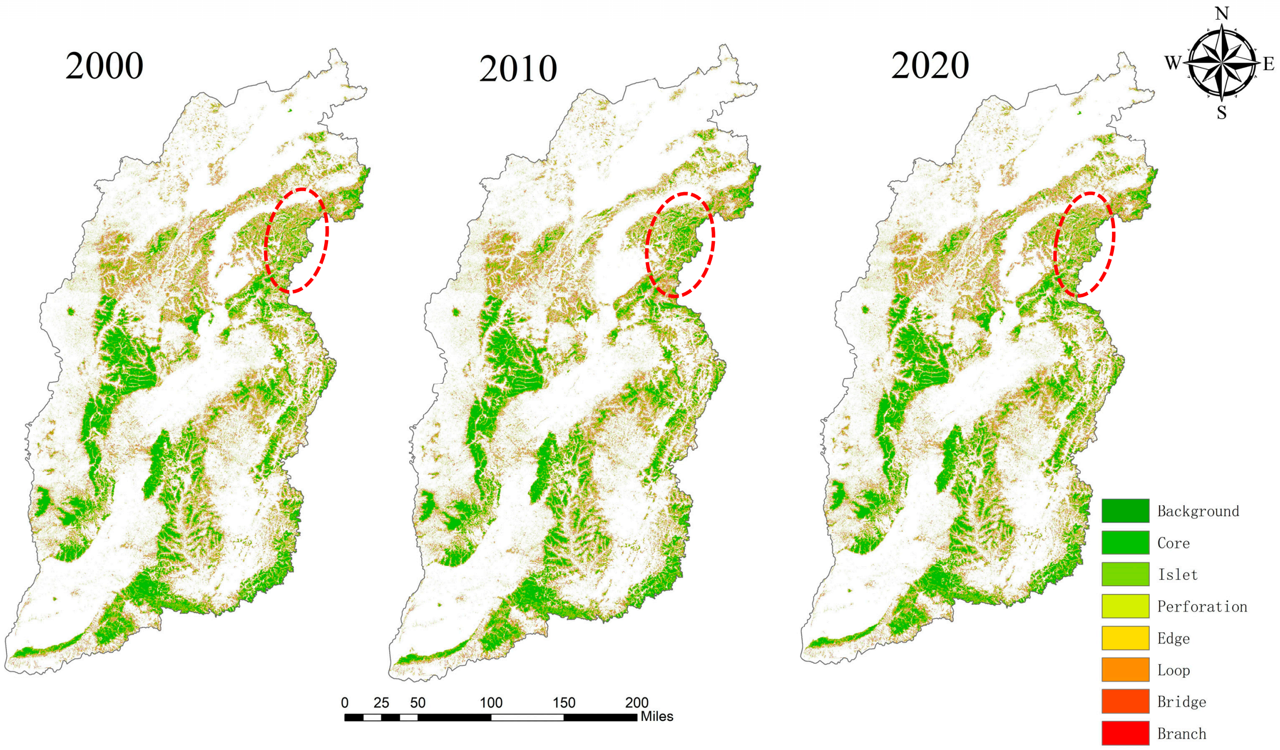

Figure 9. Results of morphological spatial pattern analysis in years 2000, 2010, and 2020. The red circles indicate typical changes from 2000–2020.

5.2. Optimization of Regional Spatial Structure and Layout

An ecological framework is optimized and proposed based on the extracted ecological components and existing river corridors, which comprised of "two axes, three belts, and three zones". This framework is an optimization and reorganization of ecological sources within the ESP, as depicted in Figure 10. Notably, the framework's most distinguishing feature is the establishment of a functional and structured spatial structure layout system.

Specifically, the "two axes" are mainly constructed along the distribution of obstacle points between different large-scale ecological resources, represents the ecological axes of the Fenhe River and Taihang Mountain. Currently, due to the active human activities, the biodiversity and habitat quality in such axes is relatively weak, resulting an obvious decrease in migration efficiency between ecological sources in the east and west. To alleviate the impact of human activities, the governors should try to prioritize the construction of ecological corridors and adopt effective measures to reduce the influence of construction and farmland [61,62].

The "three belts " refers to three ecologically fragile and sensitive areas between some small and scattered ecological resources, which are the northern and central ecological control areas and the conservation area. The ecological control areas are frequently affected by sand and dust storm, resulting in a relatively large number of ecological obstacles that decrease the efficiency of migration. Therefore, greater efforts, such as protection of native vegetation [63,64] or installing sand barriers [65], are needed to restore these areas. The ecological conservation zone is located between Taihang Mountain and Taiyue Mountain, with a higher density of ecological pinch points and fewer ecological obstacles, making it a key and sensitive area for migration.

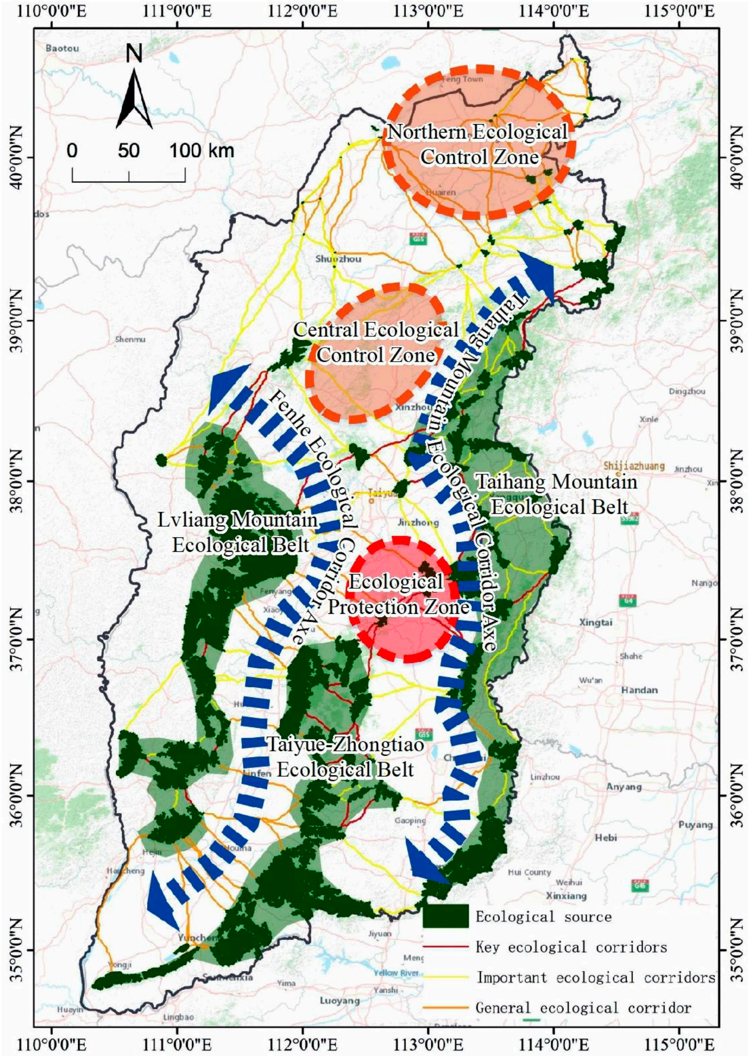

Figure 10. Ecological framework constructed in Shanxi Province.

The "three zones" are composed of ecological sources in Lvliang Mountain, Taihang Mountain, and Taiyue-Zhongtiao Mountain, with the most suitable ecological environments for species. These regions are generally covered with vegetation, especially forests in the central areas, providing ideal habitats for wildlife. Meanwhile, these areas have plenty of water resources, where rivers and lakes play a crucial role in regulating the ecological environment in plateau areas. Furthermore, land use patterns in such areas are relatively simple due to the limited human activities; thus, it is still important to protect or increase the areas of forests or grassland, which is important to improve the quality and areas of ecological sources [66,67]. Consequently, these areas have a better ecological environment and biodiversity, serving as important ecological sources for Shanxi Province. It is necessary to protect these areas and leverage their ecological functions.

5.3. Comparison of Results with Related Studies

In this study, we constructed and optimized the ESP in loess plateau areas in a pattern of "source-resistance-corridor". For the identified ecological sources, results show that most of the ecological resources are stable and continuous areas with important ecosystem services, which is consistent with previous studies [26,68]. Furthermore, we also find that the ecological sources tend to keep away from human activities, especially the land use intensity such as construction and cultivated land. Different from human activities, negative nature factors tend to produce dispersive distribution of ecological sources. As for the constructed of comprehensive resistance surfaces, most of the studies show that higher values tend to appear in construction areas [69,70], which is similar to our study. However, there are generally obvious salt-and-pepper effects and few buffer zone between different levels of resistance values in these studies [26,42,71]. To solve such problems, we tried to use the nightlight data to correct the primary resistance surfaces in our study. As for the constructed ecological corridors, we find that the key corridors tend to be distributed in the regions with better ecosystem services, which means more species tend to migrate in such regions. Meanwhile, the corridors tend to connect ecological sources within a relatively short distance, which is consistent with previous studies [72,73].

5.4. Limitations and Future Research

Despite the contributions of method proposed in this study, there are also some limitations that need to be addressed. First, the ESP was established from the nature supply perspective, which is the ecosystem services evaluated in our study. However, the integration and balance of requirements from human beings, especially for the urban or cultivated regions, requires further consideration [74]. Second, only typical ecosystem services were evaluated from existing data for the identifying of ecological sources, which may make it difficult to reflect the benefits of established ESP. Future studies could incorporate additional ecological processes into the evaluation system, which may be used to simulate the advantages of different protection strategies [75].

6. Conclusions

Due to the coexistence of fragile ecosystems and intensive mining activities in Loess Plateau, ecological and environmental problems have largely increased. It is imperative and challenging to establish the ESP in such an unstable and scattered ecological environment. For example, it is difficult to quantitatively select stable ecological resources at a large scale. Furthermore, the construction of a representative resistance surface still remains difficult. And it is also hard to identify ecological corridors when considering the random choices of species and different potential of various sources. To solve these problems, this study tried to identify and constructed ESP in a pattern of "source-resistance-corridor". The ecological sources were identified by exploring stability, important ecosystem services, and landscape relations of regions, which was achieved by combining evaluation of ecosystem functions, MSPA, and long-term dynamic assessment. Then, we employed the comprehensive resistance surface with representative factors and circuit theory to extract ecological corridors and ecological nodes to determine the ESP. The conclusions are as follows:

(1) A total of 115 ecological source areas have been identified in the study area, with a total area of 13,592 km^2, accounting for approximately 9% of the total area. Most of the ecological sources are distributed in the western and eastern mountains, providing stable and continuous ecosystem services at the landscape scale.
(2) The distribution of high values in the comprehensive resistance surface is consistent with the human activities in space. As most of the human activities concentrate on the urban or cultivated regions, which has significantly changed the ecological environment (such as land use intensity, vegetation coverage, and so on), human activities have caused obvious resistance for the migration of species.
(3) The constructed ESP mainly includes 252 ecological corridors with a total length of 8519.64 km, 166 ecological checkpoints, and 111 ecological obstacle points.

Following the framework of "source-resistance-corridor", the constructed ESP would effectively identify the potential ecosystem problems and improve the regional ecological security, which provides scientific support for sustainable development in Loess Plateau regions. Future study may try to establish the ESP considering integration and balance of requirements from human beings, especially for the urban or cultivated regions [74]. In addition, more recently proposed deep-learning-based methods may also be used to simulate the ecological processes in the evaluation or the advantage of different protection strategies [75–78].

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