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Ecological Security Patterns at Different Spatial Scales on the Loess Plateau

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Abstract: The study of ecological security patterns (ESPs) is of great significance for improving the value of ecosystem services and promoting both ecological protection and high-quality socio-economic development. As an important part of the "Loss Plateau-Sichuan-Yunnan Ecological Barrier" and "Northern Sand Control Belt" in the national security strategic pattern, there is an urgent need to study the ESPs on the Loess Plateau. Based on a remote sensing dataset, this study identified the ESPs at different spatial scales, and analyzed the similarities and differences of ecological sources, corridors, and key strategic points, so as to better inform the development and implantation of macro and micro ecological protection strategies. When taken as a whole unit, we identified 58 ecological sources (areas with higher levels of ecosystem services) on the Loess Plateau (total area of 57,948.48 km^2), along with 134 corridors (total length of 14,094.32 km), 1325 pinch points (total area of 315.01 km^2), and 2406 barrier points (total area of 382.50 km^2). When splits into ecoregions, we identified 108 sources (total area of 67,892.51 km^2), 226 corridors (total length of 13,403.49 km), 2801 pinch points (total area of 851.07 km^2, and 3657 barrier points (total area of 800.70 km^2). Human activities and land use types are the main factors influencing the number and spatial distribution of corridors, ecological pinch points, and barrier points. ESPs constructed at different spatial scales are broadly similar, but significant differences among details were identified. As such, when formulating ecological protection and restoration strategies, the spatial scale should be considered. Moreover, specific programs should be determined based on ESP characteristics to maximize the protection of biodiversity and ecosystem integrity from multiple perspectives and directions.

Keywords: spatial scale; ecological sources; ecological security patterns; the Loess Plateau

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Citation: Lin, L.; Wei, X.; Luo, P.; Wang, S.; Kong, D.; Yang, J. Ecological Security Patterns at Different Spatial Scales on the Loess Plateau. *Remote Sens.* **2023**, *15*, 1011. https://doi.org/10.3390/rs15041011

Academic Editor: Jeroen Meersmans

Received: 21 November 2022
Revised: 28 January 2023
Accepted: 8 February 2023
Published: 12 February 2023

1. Introduction

In the process of rapid global industrialization and urbanization, increasing human activities have posed a great threat to natural resources and the sustainable development of ecosystems [1]. Ecological problems such as depletion of natural resources, vegetation degradation, loss of biodiversity, agricultural pollution, shrinking rivers and lakes, soil erosion, and desertification have seriously affected ecological security and socio-economic development around the word [2–5]. How to ensure the structural integrity and functional stability of natural ecosystems is a global issue that must be addressed in order to achieve sustainable development [6–8]. Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed [9,10]; it is recognized as a global priority for improvement of the ecological environment, biodiversity conservation, and coordination between ecological protection and urbanization [11,12]. Balancing ecological restoration with economic growth is an important goal around the world, including in China [13–15].

First developed within the field of landscape planning, the ecological security patterns (ESPs) concept aims to ensure the security of natural resources, sustainable provision of ecosystem services, and well-being of mankind. ESPs is based on landscape elements that include ecological sources, resistance surfaces, corridors, and key strategic points (e.g., ecological pinch points and ecological barrier points) [16–18]. Under a background of rapid global industrialization and urbanization, many successes have been achieved under an ESPs framework, and the research paradigm has gradually formed with "determination of ecological sources-construction of ecological resistance surface-extraction of ecological corridors-identification of key strategic points" [19,20]. This research paradigm has shifted ecological security from isolated ecosystem control to integrated ecological management [21,22]. First, ecological sources as the main habitat of plants and animals are stable natural areas with abundant ecosystem services [23,24]. However, simply using stable ecological land such as nature reserves, scenic spots, forests, and grasslands as ecological sources is insufficient to fully meet the needs of ecological security. As such, scholars are increasingly focusing on ecological sources in terms of ecosystem service assessment and ecological landscape connectivity. In arid regions, ecosystem services such as soil conservation, carbon fixation, water yield, and habitat quality should also be considered, even beyond nature reserves. The circulation and exchange of materials, energy, and information between ecological sources is largely constrained by land use types and anthropogenic disturbances [25]. Therefore, ecological resistance surfaces should be well represented by natural conditions and human activity. Generally, a resistance surface is determined by assigning empirical resistance value to specific land cover [26]. In order to construct comprehensive and objective resistance surfaces that influence the flows of ecological process, factors such water sources, road distances, and terrain should also be considered [27,28]. Ecological corridors are channels that ensure the flow and exchange of materials, energy, and information between ecological sources, and are an important component in achieving the functional integrity of regional ecosystems. When species leave a specific core habitat, they are affected by resistance factors such as energy consumption, difficulty of movement, or mortality risk [29]. The minimum cumulative resistance model (MCR) has been used to extract ecological corridors [30]. This method can identify optimal corridors with the least resistance or cost, but it cannot explain the levels and relative importance of the corridors [16]. Since both ecological flow and electric current have the characteristic of random walk, circuit theory can be applied to simulate the migration process of species on the ecological resistance surface, which overcomes the limitations of previous methods [31–33]. Finally, key strategic points (e.g., ecological pinch points and ecological barrier points) are the important areas for ecological protection and restoration. Ecological pinch points, a concept proposed by McRae, are areas in corridors with high current density and high landscape connectivity [34]. When ecological pinch points are destroyed or degraded, the connectivity between habitats is highly likely to be severed. Ecological barrier points refer to the areas where species are impeded in their movement between ecological sources. The restoration of ecological barrier points can reduce ecological resistance and improve landscape connectivity [16].

The Loess Plateau is an important part of China's national ecological security strategic, and plays an extremely important role in social development and stability [35,36]. The extreme natural environmental conditions have become one of the important factors restricting the ecological restoration of the Loess Plateau [37]. At the same time, affected by irrational human exploitation, the soil erosion has been aggravated and the ecosystem has been degraded in certain regions. The exploitation of high-intensity coal resources also poses a huge challenge to ecological environmental protection [38,39]. As an important part of the "Loss Plateau–Sichuan–Yunnan Ecological Barrier" and "Northern Sand Control Belt" in the national ecological security strategy of "Two Screens and Three Belts", it is of great significance to determine the ESPs to inform spatial planning, ecological restoration, and coordination of ecological protection and high-quality development on the Loess Plateau [40,41]. Previous studies have followed the general procedure to determine the

ESPs for the part of the Loess Plateau, but they did not conduct research on the Loess Plateau as a whole [42,43]. Moreover, there is a lack of ESP assessment at different spatial scales, which hampers effective policy-making.

Owing to the heterogeneity of the ecological environment, economic conditions, population distribution, and production activities at different spatial scales, the number and arrangement of ecological elements constituting the ESPs also differs with the scale [44,45]. In addition, rapid industrialization and urbanization requires the construction of dynamic ESPs in both time and space so as to achieve diversification of ecosystem management at multiple spatial scales [46,47]. Therefore, the aims of this study are to: (1) Determine the ecological sources by considering ecosystem services, landscape connectivity, and nature reserves distribution; (2) construct a comprehensive resistance surface based on the resistance coefficient of land landscape, traffic distance, water source distance, slope and relief; (3) extract important ecological corridors based on circuit theory; (4) identify key strategic points including ecological pinch points and ecological barrier points; (5) analyze the similarities and differences of ESPs at different spatial scales and propose ecological restoration strategies. The results of this study offer a basis for the development and implementation of both macro and micro ecological protection and restoration strategies.

2. Study Area Data

2.1. Study Area

The Loess Plateau (100°54′E–114°33′E, 33°43′N–41°16′N) is located in north-central China and includes the northeastern Qinghai Province, central-eastern Gansu Province, most of Ningxia Hui Autonomous Region and Shanxi Province, north-central Shaanxi Province, western Henan Province, and south-central Inner Mongolia Autonomous Region. The topography is high in the northwest and low in the southeast, with an altitude of range of 800 to 3000 m. Landform types are diverse, and mainly include the Shanxi Plateau, Shaanxi–Gansu Plateau, Longzhong Plateau, Ordos Plateau, and Hetao Plain. The Loess Plateau has a typical warm temperate semi-arid continental monsoon climate with an annual average temperature of 7.3 °C and an average annual precipitation of 447 mm. The rainy season lasts from June to September (Figure 1a).

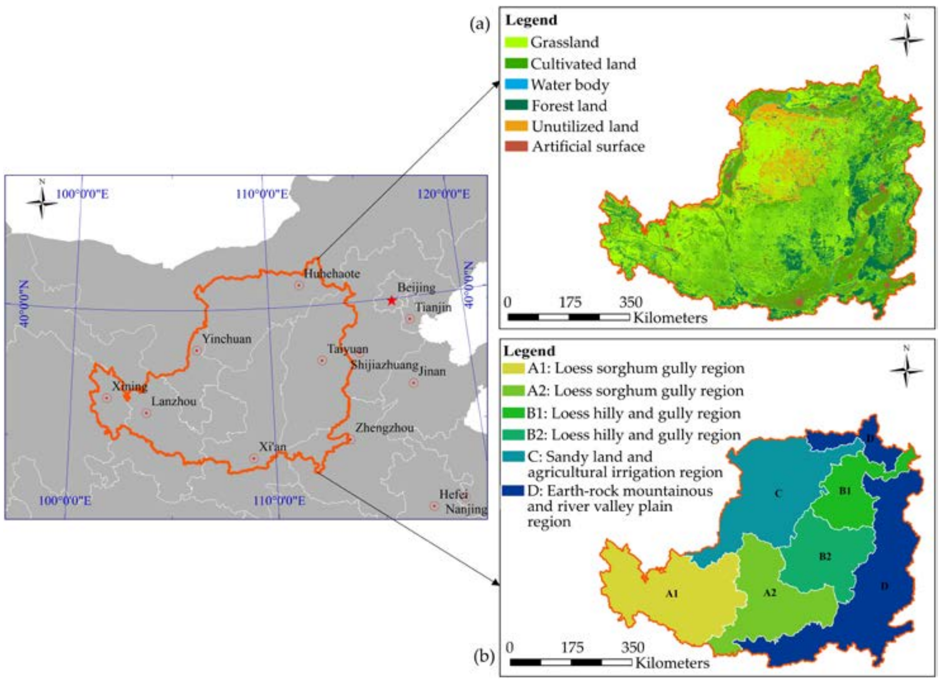


Figure 1. Geographical location, land cover, and ecoregions of the Loess Plateau. (**a**) shows the spatial distribution of land cover on the Loess Plateau. (**b**) shows the spatial location of six ecoregions (including two sub-regions) of the Loess Plateau.

Based on the terrain, climate, soil erosion control technologies and modes, distribution of ecological restoration projects, and relative integrity of administrative boundaries, the National Development and Reform Commission of China has divided the Loess Plateau into four regions: (A) the loess sorghum gully region, (B) the loess hilly and gully region, (C) the sandy land and agricultural irrigation region, and (D) the earth-rock mountainous and river valley plain region [48]. Among them the loess sorghum gully region and the loess hilly and gully region are subdivided into two sub-regions (Figure 1b and Table 1).

Table 1. Ecoregions of the Loess Plateau.

Ecoregion	Areas/km^2	Characteristic
A1 and A2: Loess sorghum gully region	217,851.98 km^2	The surface of the loess tableland is flat and broad, but is surrounded by deep gully loess highlands. The region has high annual precipitation and abundant heat and light resources, but soil erosion is relatively serious.
B1 and B2: Loess hilly and gully region	125,499.25 km^2	The landscape is dominated by mount and beam-like hills, with long gullies and broken terrain. The climate is arid and soil erosion is serious.
C: Sandy land and agricultural irrigation region	130,060.30 km^2	The sandy land is dominated by the Mao Wu Su sandy land, with an arid climate and small water erosion modulus. The agricultural irrigation area has flat terrain and is dominated by irrigation water sources. Soil erosion is relatively low.
D: Earth-rock mountainous and river valley plain region	175,883.58 km^2	Mountainous area is mostly covered by thin layers of loess with good vegetation conditions, forming an important water conservation area. The river valley plains are low and flat with sufficient water, low soil erosion, and abundant light and heat resources.

2.2. Data Sources

Several datasets were used in this study. The land use data with the resolution of 30 m × 30 m, the annual data of Normalized Difference Vegetation Index (NDVI) with 1000 m × 1000 m resolution, and the vector data of river network came from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 15 March 2022). The Digital Elevation Model (DEM) with the resolution of 30 m was obtained from the Geospatial Data Cloud (https://www.gscloud.cn/, accessed on 15 March 2022). The 8-day data of Leaf Area Index (LAI) with 500 m × 500 m resolution and the annual data of Net Primary Productivity of Vegetation (NPP) with 500 m × 500 m resolution were respectively obtained from the MOD15A2H product and MOD17A3HGF product of EOS/MODIS imagery (https://earthdata.nasa.gov/, accessed on 17 March 2022). We used 8-day Leaf Area Index (LAI) data to get annual data based on the maximum composite method. Soil-related data including soil organic matter content, soil texture, soil depth and root depth were obtained from the Harmonized World Soil Database (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/, accessed on 18 March 2022) at the scale of 1: 4,000,000. The soil erodibility factor dataset the resolution of 1000 m × 1000 m and the vector data of ecoregions were both obtained from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn, accessed on 18 March 2022). Temperature and rainfall data were derived from the China Meteorological Data Service Centre (http://data.cma.cn/, accessed on 20 March 2022), which was interpolated into grid format using the ArcGIS platform based on the Kriging method. The Road network vector data was extracted from Open Street map (https://www.openhistoricalmap.org/, accessed on 20 March 2022). Nature reserve vector data were from China Nature Reserve Specimen Resource Sharing Platform (http://www.papc.cn/, accessed on 15 March 2022). The coordinate system of all spatial data was unified as Albers Conic Equal Area and resampled into a resolution of 100 m × 100 m using the ArcGIS platform based on the nearest neighbor method. (Table 2).

Table 2. Basic introduction of research data.

Data	Format	Data Description
Land use	Raster	Used to assess habitat quality, a parameter of water yield and soil conservation
NDVI	Raster	Used to calculate Fraction Vegetation Coverage (FVC), a parameter of the crop management factor
NPP	Raster	Used to calculate carbon fixation
DEM	Raster	Used to calculate sub-basins, slope lengths, slopes, and topographic relief
LAI	Raster	Used to calculate annual average evapotranspiration
Temperature and rainfall	Raster	Obtained by interpolation and used to calculate annual average evapotranspiration, to calculate rainfall erosivity factors, and to estimate soil microbial respiration
Soil organic matter content, soil texture, soil depth, and root depth	Raster	Used to calculate the root restricting layer depth and the plant available water content (PAWC).
Soil erodibility	Raster	One of the parameters of soil conservation calculation
River network and road network	Vector	Used to construct the comprehensive resistance surface
Nature reserve	Vector	One of the ecological sources

3. Methods

The framework of our study is shown in Figure 2. We applied the research paradigm formed by "determination of ecological sources-construction of ecological resistance surface-extraction of ecological corridors-identification of key strategic points" to build the ESPs (step 1–4), and analyzed the similarities and differences of ESPs at different spatial scales (step 5). First, we determined ecological sources based on ecosystem services, landscape connectivity, and nature reserves. Second, traditional landscape resistance, slope resistance, topographic relief resistance, road distance resistance, and water source distance resistance were well considered to construct the comprehensive ecological resistance surface. Third, the Linkage Mapper module in ArcGIS was used to extract ecological corridors. Fourth, the Circuit-scape plug-in was used to identify ecological pinch points and ecological barrier points. Finally, by comparing the similarities and differences of ESPs at different spatial scales, we proposed some ecological restoration strategies.

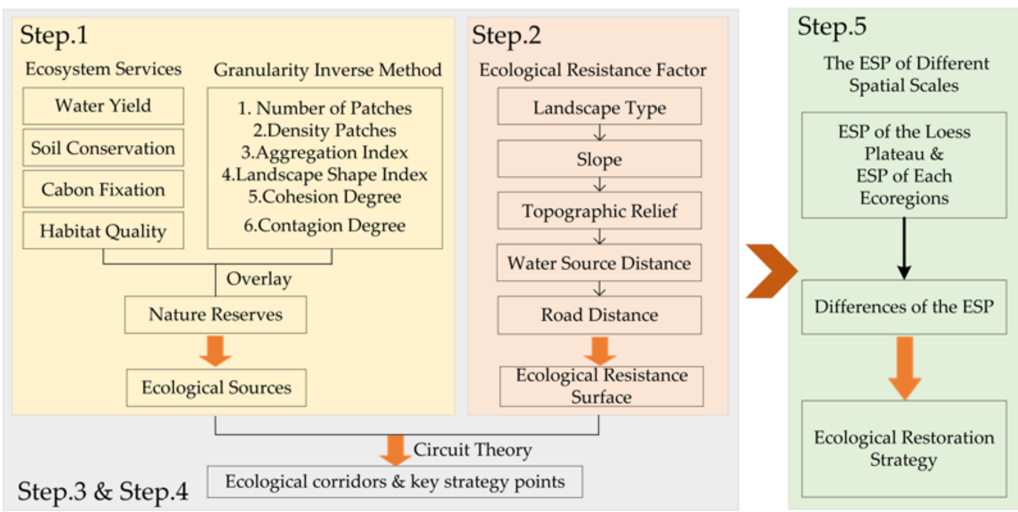


Figure 2. Framework for identifying key areas of ecological conservation and restoration.

3.1. Determination of Ecological Sources

3.1.1. Ecosystem Services

Water yield, carbon fixation, soil conservation, and habitat quality have ecological significance and provide ecological products for human survival and social development [49]; therefore, these four ecosystem services were selected for analysis. The specific evaluation methods and calculation process are shown in Table 3. To make the ecosystem services comparable, all the data were normalized by extreme difference standardization. The characteristics of the study area's ecosystems determined that water yield, carbon fixation, soil conservation, and habitat quality had the same importance in performing ecological functions [50], so we assigned the same weigh values respectively. Through the comprehensive index method, the importance of ecosystem services on each ecoregion of the Loess Plateau and the Loess Plateau as a whole were evaluated separately, and the natural breakpoint classification method was used to divide the results into five levels: extremely unimportant, unimportant, generally important, very important, and extremely important. We extracted regions of "extremely important" as ecological lands. The calculation process of the extreme difference standardization and comprehensive index method was as follows.

$$X_i{}' = (x_i - x_{imin})/(x_{imax} - x_{imin}) \tag{1}$$

where $X_i{}'$ is the standardized dimensionless value of ecosystem service type i; x_i is the actual value; x_{imax} is the maximum value; and x_{imin} is the minimum value.

$$U = \sum_{i=1}^{\mu} \left(X_i{}' \times 0.25\right) \tag{2}$$

where U is the index of importance of ecosystem services; $X_i{}'$ is the standardized dimensionless value of ecosystem service type i; μ is the number of ecosystem service types; and 0.25 is the weigh value.

Table 3. Method and calculation process of ecosystem services.

Ecosystem Services	Calculation Method	Parameters
Water yield	$Yield_{ni} = \left(1 - \frac{AET_{ni}}{P_n}\right) \times P_n$	Water yield is estimated by the water yield module of the InVEST model (https://www.naturalcapitalproject.org/invest/, accessed on 15 March 2022) [51,52]. In this formula, Y_{ni} is the amount of water yield (mm) of pixel n of land cover type j; P_n is the annual precipitation of pixel n; AET_{ni} is the annual average evapotranspiration (mm) of pixel n of land cover type j.
Carbon fixation	$NEP_n = NPP_n - R_{Hn}$	Carbon fixation is mainly measured using the vegetation net ecosystem productivity (NEP) estimation model [53]. In this formula, where NEP_{nt} is the vegetation net ecosystem productivity of pixel n in t year (gC/m^2); NPP_{nt} is the vegetation net primary productivity of pixel n in t year (gC/m^2); $R_{H_{nt}}$ is the soil microbial respiration of pixel n in t year (gC/m^2). When $NEP > 0$, it indicates that the carbon fixed by vegetation is greater than that emitted by soil respiration, and vegetation shows the role of carbon sink; when $NEP < 0$, it indicates that vegetation shows the role of carbon source.
Soil conservation	$A = R \times K \times LS \times (1 - C \times P)$	The amount of soil conservation is calculated using the Revised Universal Soil Loss Equation (RUSLE) [54]. In this formula, A is the amount of soil conservation (t/(hm^2·a)); R is the rainfall erosivity factor ((MJ·mm)/(hm^2·h·a)); K is the soil erodibility factor ((t·hm^2·h)/(hm^2·MJ·mm)); LS is the terrain factor; C is the crop management factor; and P is the erosion control practice factor. L, S, C, and P factors are dimensionless.

Table 3. *Cont.*

Ecosystem Services	Calculation Method	Parameters
Habitat quality	$Q_{nj} = H_j\left[1 - \left(\frac{D_{nj}^z}{D_{nj}^z + k^z}\right)\right]$	Habitat quality is assessed using the habitat quality module of the InVEST model (https://www.naturalcapitalproject.org/invest/, accessed on 15 March 2022) [55]. In this formula, Q_{nj} is the habitat quality index of pixel n of habitat type j; H_j is the habitat suitability of habitat type j; k is the half-saturation constant, which is taken as 0.5 according to the references because it is helpful to intuitively represent the heterogeneity of the whole landscape quality; D_{nj} is the habitat degradation degree of pixel n of habitat type j; z is the normalization constant, which is usually set to 2.5.

3.1.2. Granularity Inverse Method

Small, fragmented patches of extremely important ecological land were extracted using the natural breakpoint classification method; these patches belonged to the inferior landscape type. The patches with different area and fragmentation reflect different amount of information. With changing area and scale, information on inferior landscape type was gradually substituted with that of superior landscape type [56,57]. In order to remove inferior landscape type in ecological land, preserve the superior landscape type that was capable of maintaining landscape diversity and biodiversity, we used the granularity inverse method to determine optimal landscape size [58]. First, the resampling tool in ArcGIS was used to resample the ecological land into different landscape sizes of 100, 200, 400, 600, 800, 1000, and 1200 m. Second, the Fragstats software (http://www.umass.edu/landeco/research/fragstats/fragstats.html, accessed on 21 May 2022) was used to calculate landscape indices of different sizes of ecological land (Table 4). Finally, the optimal landscape size was determined by analyzing the change characteristics of each index in different sizes, and the landscape components under this optimal size were used as a reference to merge and delete ecological lands with scattered distribution, small area, and large fragmentation by way of manual interpretation.

Table 4. Landscape indexes.

Index	Unit	Description
Number of Patches (NP)	-	Number of landscape patches
Density Patches (PD)	-	Density patches in the landscape can reflect the fragmentation degree of a certain landscape type
Aggregation Index (AI)	%	Connectivity between patches of each landscape type
Landscape Shape Index (LSI)	-	Non-integer dimension of irregular geometry landscape, reflecting the complexity of landscape shape
Cohesion Degree (COHESION)	%	Aggregation and dispersion of patches in the landscape
Contagion Degree (CONTAG)	%	Agglomeration degree or tendency of patches to spread in a certain landscape

3.2. Construction of Ecological Resistance Surface

The resistance surface represents the impact of landscape heterogeneity on the flow of ecological processes [59]. The flow of ecological processes is not only limited by natural conditions, but also related to human activities. Based on the consideration of natural and socio-economic conditions, we took land use, slope, topographic relief, and distance of water source as natural resistance, and viewed rural residential areas, urban land, other construction land, and road distance together as disturbances of human activities. We assigned ecological resistance values to ecological resistance factors, and then used the weighted summation method to calculate the ecological resistance surface of the Loess

Plateau. Through the yaahp tool (https://www.metadecsn.com/, accessed on 27 May 2022), the weight of each ecological resistance factor was determined by the Analytic Hierarchy Processes (AHP); resistance coefficients mainly referred to previous studies [60,61] (Table 5). The formula of the weighted summation method is as follows:

$$R = \sum_{i=1}^{k} (F_i \times W_i) \tag{3}$$

where R is the ecological resistance surface; F_i is the resistance coefficient of resistance factor i; W_i is the weight of resistance factor i; and k is the number of resistance factor.

Table 5. Comprehensive ecological resistance surface weights and resistance coefficients.

Ecological Resistance Factor	Weight	Index	Resistance Coefficient
Landscape type	0.40	Woodland	1
		Shrubland	10
		Open woodland and other woodlands	30
		High coverage grassland	30
		Medium coverage grassland	50
		Low coverage grassland	80
		Water body	100
		Water field	100
		Dry land	200
		Unutilized land	700
		Rural residential area	900
		Urban land and other construction land	1000
Slope	0.10	<8°	1
		8~15°	10
		15~25°	50
		25~35°	70
		>35°	100
Topographic relief	0.10	<25 m	1
		25~50 m	10
		50~70 m	50
		70~100 m	75
		>100 m	100
Water source distance	0.20	<1000 m	150
		1000~3000 m	200
		3000~5000 m	400
		5000~10,000 m	600
		>10,000 m	800
Road distance	0.20	>8000 m	30
		5000~8000 m	100
		3000~5000 m	300
		1000~3000 m	500
		<1000 m	800

3.3. Extraction of Ecological Corridor

Based on the ecological sources and resistance surfaces, the ecological corridors were extracted with the minimum cumulative resistance model implemented using the Linkage Mapper 2.0 toolbox in ArcGIS (https://www.circuitscape.org/linkagemapper, accessed on 27 May 2022). The principle of the minimum cumulative resistance model is as follows:

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

where MCR is the cumulative resistance value of the landscape units in the study area to the ecological sources; f reflects the positive correlation between the cumulative resistance value and the ecological process of the landscape; *min* is the minimum cumulative resistance value; D_{ij} is the spatial distance from the landscape units i to the ecological sources j; and R_i is the resistance coefficient of landscape units i to the movement diffusion of a target unit.

3.4. Identification Ecological Pinch Points and Ecological Barrier Points

Circuitscape (https://circuitscape.org/, accessed on 1 June 2022) uses circuit theory to model connections between different landscapes [62]. The key strategy points, including ecological pinch points and barrier points, were obtained using the Pinch point mapper and barrier mapper of the Circuitscape plug-in through the ArcGIS platform.

The pinch point mapper can combine least-cost corridors with circuit theory to identify areas with high current density. There are few or no alternative paths in these areas, suggesting that degradation or disruption of these areas will highly likely cut off the connectivity of the ecological sources [63]. The identification of pinch points included the following steps. First, the pinch point mapper module was used for calculating current density. Second, the natural breakpoint method was used to classify the current density into four levels. Finally, the highest current density level was selected as ecological pinch points.

The barrier mapper is mainly used to detect the percentage of improvement scores after removing the barrier points within different radius search windows [64]. The higher the ratio of the two, the better the connectivity will be after implementation of ecological restoration [65]. The identification of barrier points included the following steps. First, the barrier mapper module was used for calculating potential ecological barrier points. Second, the natural breakpoint method was used to classify the results into four levels. Finally, the highest ratio level was selected as the identification of ecological barriers.

4. Results

4.1. Ecological Land Identification

The ecosystem services of the Loess Plateau were divided into five levels using the natural breakpoint method (Figure 3). The carbon fixation capacity was mainly at low and lower levels; carbon fixation capacity at the higher level was mainly distributed in central and southwestern parts of ecoregion A2, and the weakest carbon fixation capacity was in ecoregion C. Differences in habitat quality among ecozones on the Loess Plateau were relatively small. In general, areas with a higher level of ecological quality were mainly distributed in eastern parts of ecoregions B2 and A2; habitat quality in ecoregion C was at lower and low levels. The soil conservation capacity of the Loess Plateau was also dominated by low and lower levels. The soil conservation capacity of ecoregions A2 and A2 were dominated by low level, median level, and high level; ecoregion C was dominated by lower level. Areas with higher and high levels of water yield were mainly located in ecoregions A1 and A2, while ecoregion C had a lower level of water yield. To sum up, the spatial distribution characteristics of ecosystem services were obviously affected by natural conditions. Ecoregions A1, A2, B1, and B2 have high annual precipitation and abundant heat and light resources. Although the landscape of these regions is characterized by long gullies and broken terrain, vegetation was in good conditions. Ecoregion C mainly includes the Mu Us Sandy Land, which hosts irrigation water sources and poor vegetation conditions. Ecoregion D, dominated by mountains and river valley plains, had a higher level of ecosystem services, but spatial heterogeneity was obvious because of the topography.

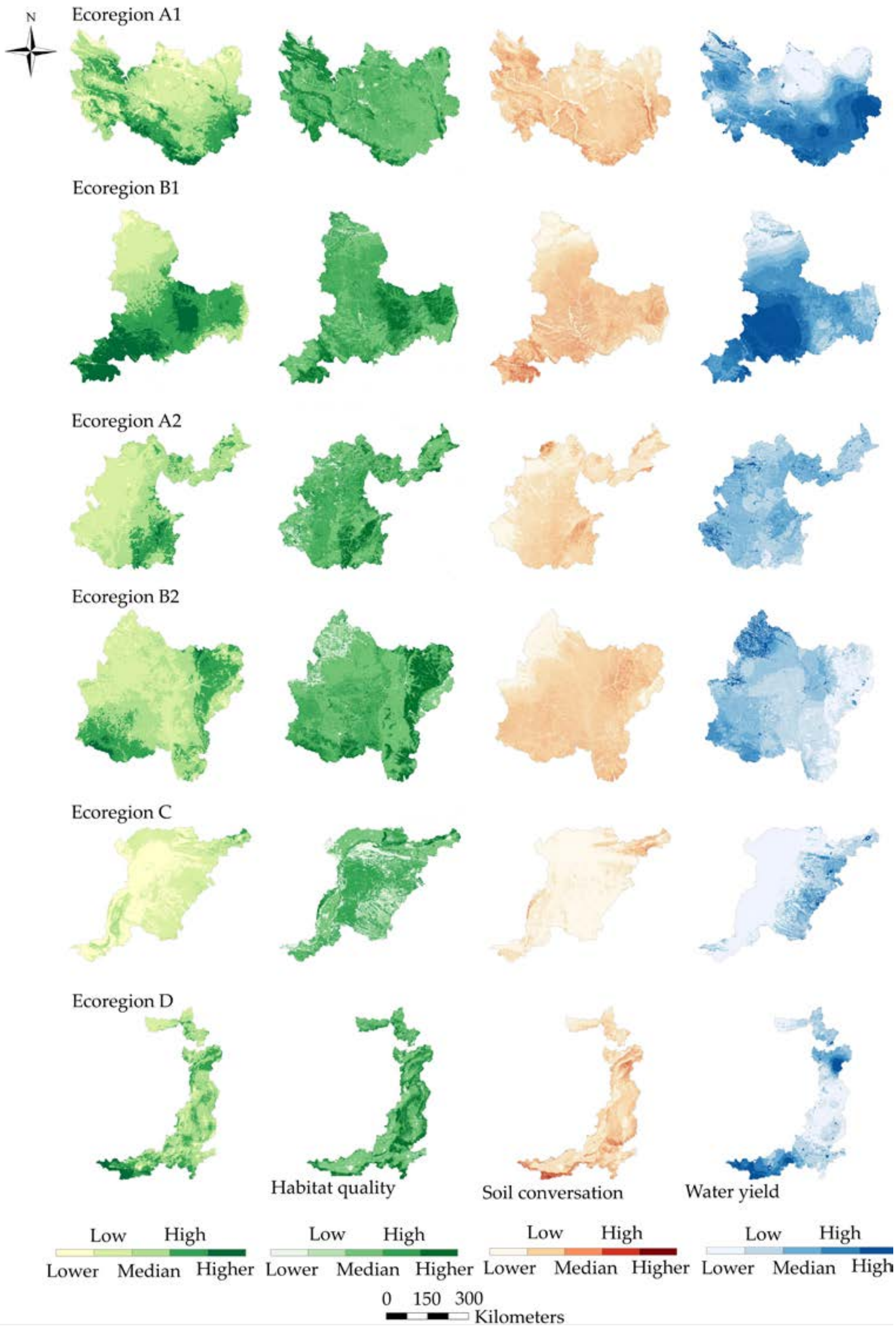


Figure 3. Spatial distribution pattern of ecosystem services on the Loess Plateau.

Landscape indices for different sizes of ecological land are shown in Figure 4. Based on the change characteristics, when the landscape size of ecoregions A1, A2, B1, B2, D, and the Loess Plateau as a whole were >400 m, and the landscape size of ecoregion C was >600 m, all the landscape indices tended to be stable and optimal. After merging and deleting small and fragmented patches of ecological land, the landscape connectivity of ecological lands was optimized.

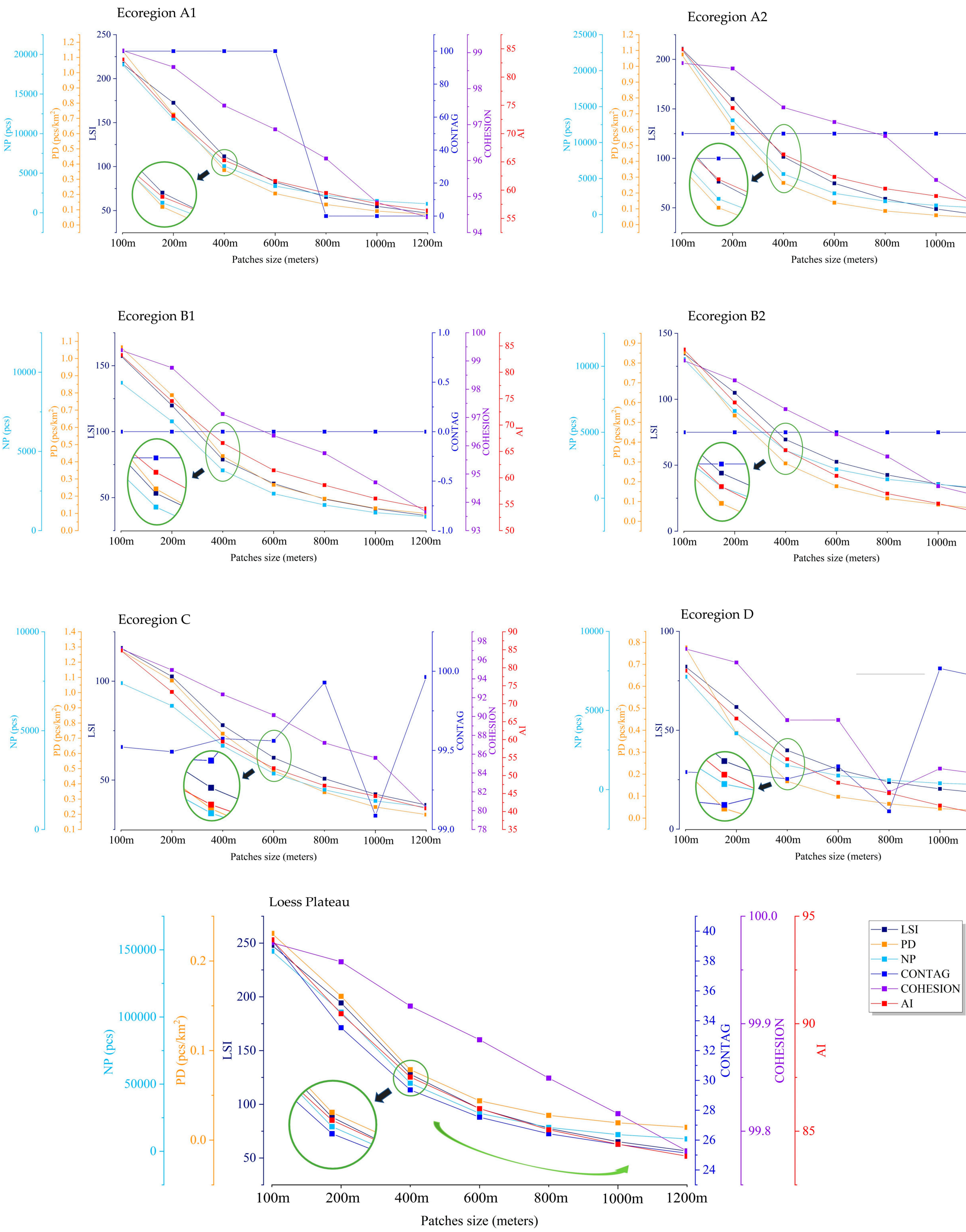


Figure 4. Landscape Pattern Index of the Loess Plateau and all ecoregions.

4.2. *Ecological Sources*

4.2.1. Ecological Sources on the Loess Plateau

Ecological sources of the Loess Plateau as a whole were obtained by superimposing nature reserves on ecological lands selected by the granularity inverse method (Figure 5). We identified 58 ecological sources with a total area of about 57,948.48 km^2, accounting for 8.89% of the total area of the Loess Plateau. The ecological sources were mainly located in ecoregion A2 and ecoregion D (areas of 93,98.59 and 16,884.47 km^2, accounting for 33.48% and 29.14%, respectively). Ecoregion B1 and ecoregion B2 had the smallest areas of ecological sources (22,11.88 and 1676.08 km^2, accounting for 3.82% and 2.89%, respectively). Ecological sources were mainly concentrated in southern Loess Plateau.

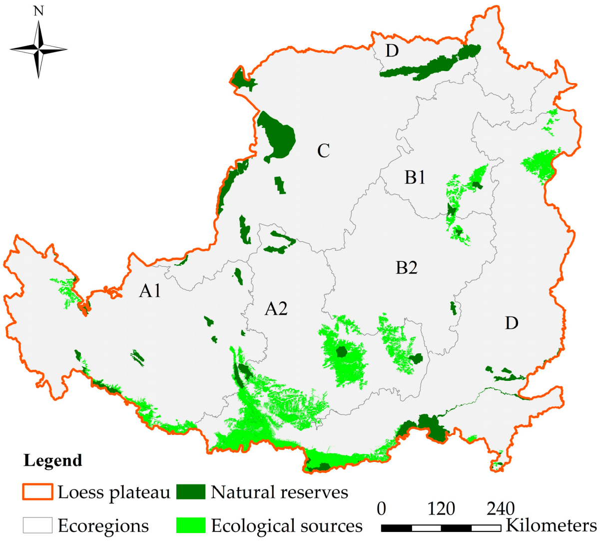


Figure 5. Spatial distribution of ecological sources on the Loess Plateau.

4.2.2. Ecological Sources of Ecoregion

The same method was used to determinate ecological sources in each ecoregion (Figure 6). In total, we obtained 108 ecological sources with a total area of 67,892.51 km^2, accounting for 10.42% of the area of the Loess Plateau. Ecoregion A2 had the largest ecological sources area (17,327.76 km^2, accounting for 25.52%). Ecoregion B1 had smallest ecological sources area (5392.78 km^2, accounting for 7.94%). The proportions of ecological sources in ecoregions A1, B2, C, and D were between 10% and 20%. Overall, ecological sources were more significant in the central Loess Plateau (compared with taken the whole Plateau as a single unit), and these sources were connected with the northern Qinling Mountains to the south and a nature reserve to the north, forming a belt-like structure.

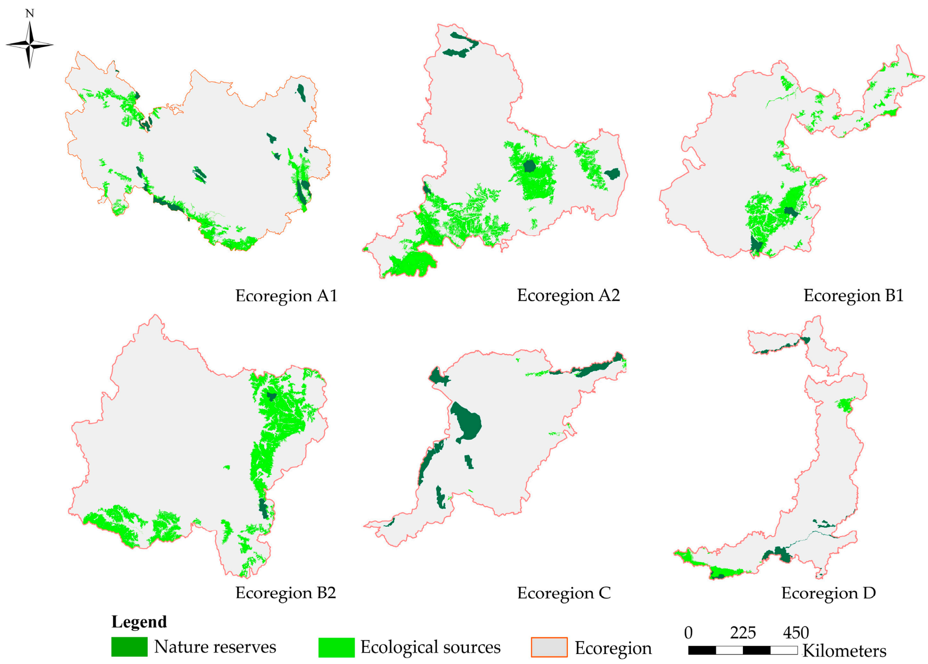


Figure 6. Spatial distribution of ecological sources in each ecoregion.

4.3. Ecological Resistance Surface

The comprehensive resistance surface of the Loess Plateau was calculated by the weighted summation method (Figure 7). Ecological resistance values ranged from 26.6 to 735. The high values were mainly distributed in areas where human activities were concentrated, such as the provincial capital and other cities and counties. A network of high resistance values formed by roads and cities cut off the flows of ecological processes. Ecoregion C had the relatively high resistance values; in this area, large areas of unutilized land, including sand, Gobi Desert, saline-alkali land, and bare land hinder species dispersal and migration.

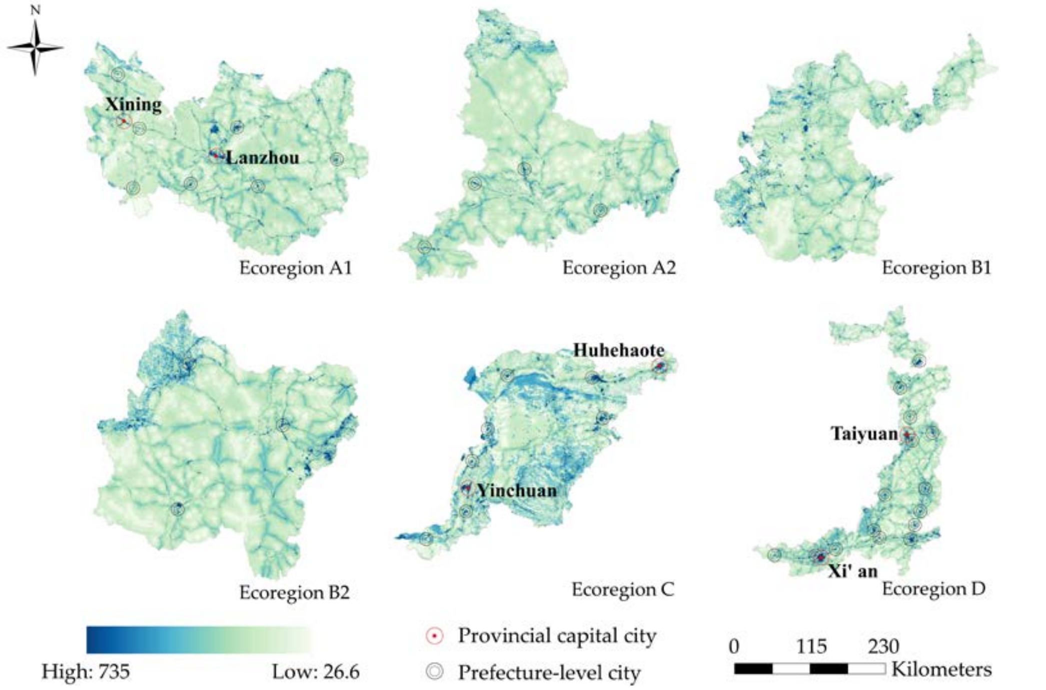


Figure 7. Spatial distribution of ecological resistance surface in each ecoregion.

4.4. Ecological Corridors and Key Strategy Points

4.4.1. Ecological Corridors and Key Strategy Points of the Loess Plateau

The ecological corridors of the Loess Plateau were extracted by the minimum cumulative resistance model (Figure 8). When taking the whole Loess Plateau as a single unit, we obtained 134 ecological corridors with a total length of 14,094.32 km. Owing to the large area and dense distribution of ecological sources in the southern Loess Plateau, ecological corridors in this area had shorter lengths and were more sparsely distributed. The number, length, and density of ecological corridors increased in the central Loess Plateau because of the smaller number and scattered distribution of ecological sources.

Ecological pinch points identified using the pinch point mapper are shown in Figure 9a. When taking the whole Loess Plateau as a single unit, we obtained 1325 ecological pinch points with a total area of 315.01 km^2, of which the areas of the largest and smallest pinch points were 6.35 and 0.01 km^2, respectively. Grassland accounted for the largest proportion (46.53%), followed by cultivated land (21.06%), forest land (12.90%), water bodies (9.82%), artificial surface land (1.66%), and unutilized land (8.03%).

Ecological barrier points identified using the barrier mapper are shown in Figure 9b. When taking the whole Loess Plateau as a single unit, we obtained 2406 ecological barrier points with a total area of 382.50 km^2; the areas of largest and smallest barrier points were 12.66 and 0.01 km^2, respectively. Some barrier points overlapped with pinch points. Cultivated land accounted for the largest proportion of barrier points (43.36%), followed by grassland (37.94%), forest land (12.90%), water bodies (9.82%), unutilized land (8.03%), and artificial surface land (1.66%).

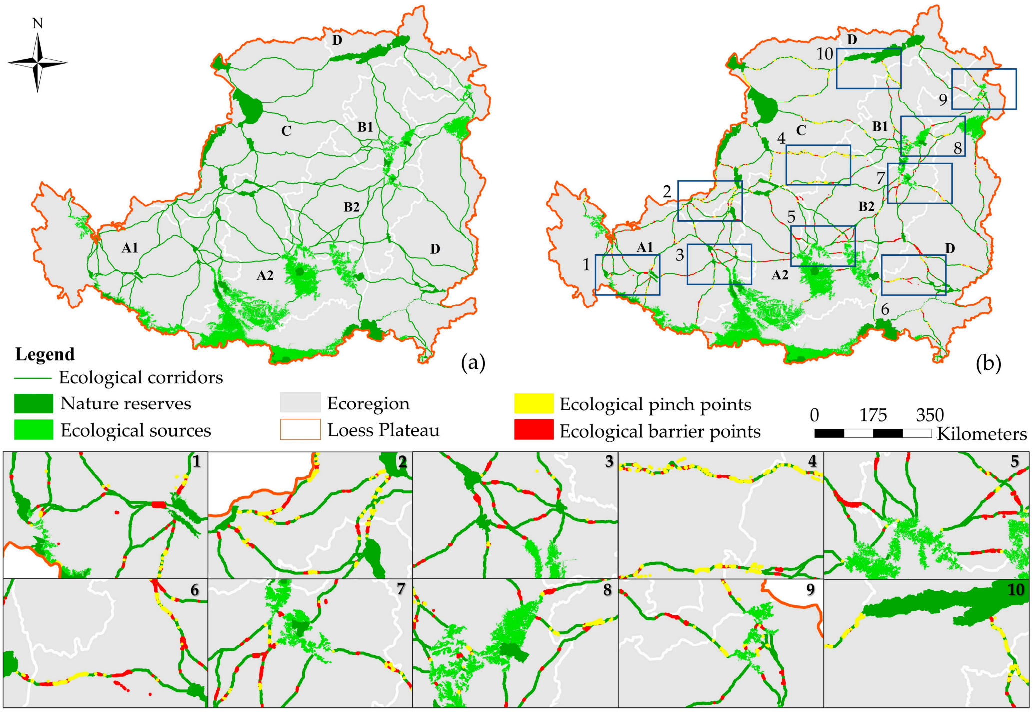


Figure 8. Spatial distribution of ecological security patterns (ESPs) on the Loess Plateau. (**a**) shows the whole ESPs of the Loess Plateau, and (**b**) shows the location diagram of local ESPs of the Loess Plateau.

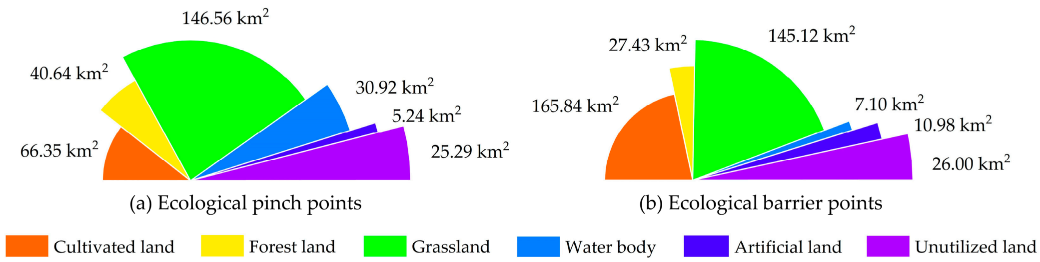


Figure 9. Land used areas of pinch points and barrier points in the Loess Plateau.

4.4.2. Ecological Corridors and Key Strategy Points of Ecoregions

The ecological corridors, pinch points, and barrier points for each ecological are shown in Figure 10. In total, we obtained 226 ecological corridors with a total length of 13,403.49 km. A1 had 64 corridors with a total length of 4261.05 km; A2 had 17 corridors with a total length of 1087.98 km; B1 had 49 corridors with a total length of 1078.26 km; B2 had 24 corridors with a total length of 733.08 km; C had 37 corridors with a total length of 3392.04 km; and D had 35 corridors with a total length of 2851.08 km. In terms of the number, ecoregion A1 had the largest number and longest length because ecological sources had homogeneous dispersion and needed more ecological corridors to connect them; ecoregion A2 had the smallest number but their length was not the shortest, mainly because the ecological sources had large areas but small number and long distances, resulting in longer corridors. In terms of the length, ecoregion A1 had the largest number and longest length; ecoregion B2 had the shortest corridor length, but the number was not the least, mainly because the fact that ecological sources in the eastern and southern parts showed the characteristics of concentrated distribution and large number, where not only more corridors were required to connect multiple ecological sources, but also the length was limited by distance between ecological sources.

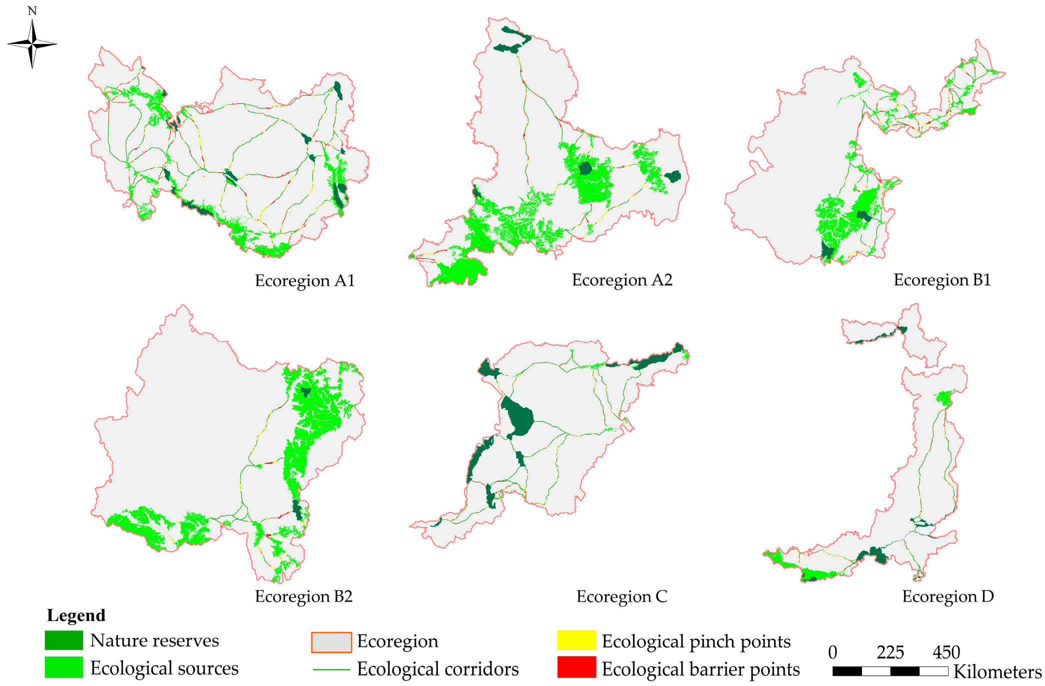
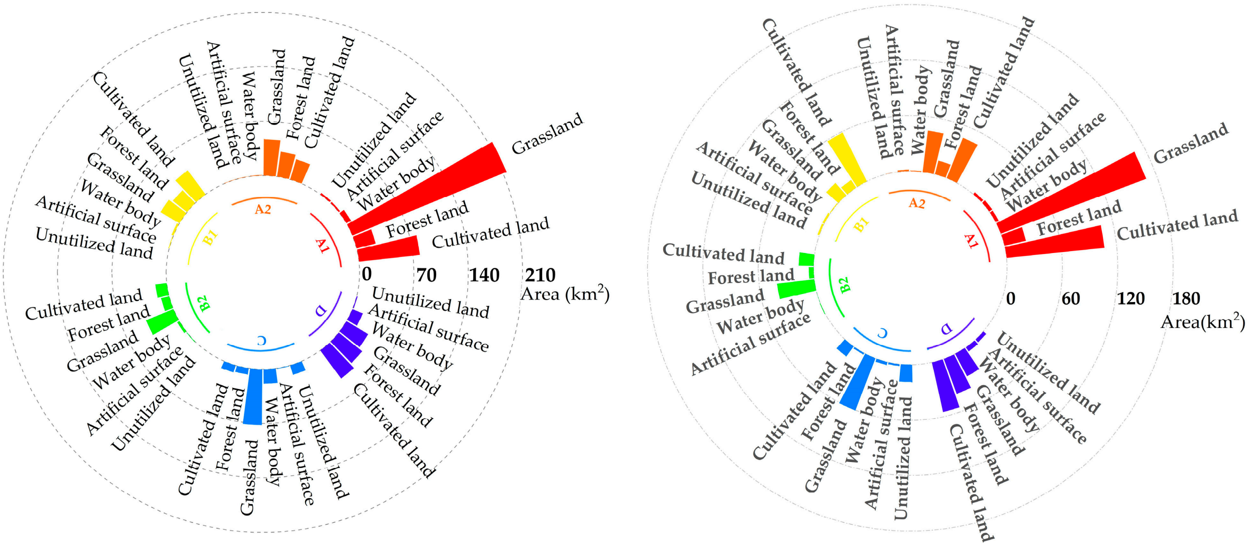


Figure 10. Spatial distribution of ecological security patterns (ESPs) in each ecoregion.

Among all the ecoregions, we identified 2801 ecological pinch points with a total area of 851.07 km^2, and 3657 ecological barrier points with a total area of 800.70 km^2. Ecoregion A1 had 961 pinch points with a total area of 330.84 km^2 and 1448 barrier points with a total area of 307.4 km^2; A2 had 274 pinch points with a total area of 106.79 km^2 and 685 barrier points with a total area of 108.9 km^2; B1 had 408 pinch points with a total area of 93.3 km^2 and 429 barrier points with a total area of 90.24 km^2; B2 had 198 pinch points with a total area of 67.56 km^2 and 131 barrier points with a total area of 62.75 km^2; C had 473 pinch points with a total area of 121.09 km^2 and 444 barrier points with a total area of 100.2 km^2; and D had 487 pinch points with a total area of 131.49 km^2 and 520 barrier points with a total area of 131.21 km^2. As discussed, ecoregion A1 had the largest number and longest length of corridors, reflective of complex ecological resistance and high ecological vulnerability. Therefore, A1 also has the largest numbers and areas of pinch points and barrier points. Ecoregion B2 had the small numbers and shortest lengths of corridors, and so also had the smallest numbers and areas of pinch points and barrier points.

In ecoregion A1, grassland accounted for the largest proportion (65.10%) of pinch points (Figure 11a); artificial surface land (2.02%) and unutilized land (2.37%) accounted for the smallest proportions. In A2, grassland accounted for the largest proportion (43.45%), while water bodies (0.48%), artificial surface land (0.47%), and unutilized land (0.40%) accounted for the smallest proportions. In B1, cultivated land accounted for the largest proportion (41.19%), and unutilized land accounted for the smallest proportion (0.01%). In B2, grassland land accounted for the largest proportion (56.70%) and unutilized land accounted for the smallest proportion (0.06%). In C, grassland accounted for the largest proportion (59.00%) and artificial surface land accounted for the smallest proportion (0.54%). In D, cultivated land accounted for the largest proportion (34.29%) and unutilized land accounted for the smallest proportion (0.02%).



(a) Ecological pinch points (b) Ecological barrier points

Figure 11. Land use areas of pinch points and barrier points in each ecoregion.

The land use compositions of barrier points were similar to those of pinch points (Figure 11b). In ecoregion A1, grassland accounted for the largest proportion (54.47%) and unutilized land accounted for the smallest proportion (0.91%). In A2, cultivated land accounted for the largest proportion (42.99%) and unutilized land accounted for the smallest proportion (0.18%). In B1, cultivated land accounted for the largest proportion (64.36%) and water bodies accounted for the smallest proportion (1.05%). In B2, grassland land accounted for the largest proportion (64.75%), while water bodies (0.48%) and artificial surface land (0.96%) accounted for the smallest proportion (note: there was no unutilized land). In C, grassland accounted for the largest proportion (60.53%) and forest land accounted for the smallest proportion (1.77%). Finally, in D, cultivated land accounted for the largest proportion (41.45%) and unutilized land accounted for the smallest proportion (0.02%).

4.5. ESPs Variation at Different Spatial Scales

The total area and number of ecological sources calculated by ecoregion were larger than that for the Loess Plateau as a whole. Among them, the ecological source areas of ecoregions A1, B2, B2, and C increased, while those of A2 and D decreased. Regardless of spatial scales, the spatial distribution characteristics of ecological sources were generally similar, and were centered on extremely important level areas of ecosystem services.

The number of corridors on the Loess Plateau as a single unit was less than the total number obtained from all of the ecoregions, but the total length was greater than that of all the ecoregions. The number and area of pinch points and barrier points for the Loess Plateau as a whole were both smaller than the total number and area taken from the different ecoregions. In summary, the number of ecological sources affects the number and length of corridors, which in turn affects the number and area of pinch points and barrier points. When the number of ecological sources is large, patches are fragmented and distribution is dispersed; in addition, the number and length of corridors increases. However, the greater the number and length of corridors, the more obvious the impact of ecological resistance. At this time, corridors are more likely to have pinch points and barrier points where ecological security is vulnerable.

5. Discussion

5.1. Optimal Landscape Structure

Based on the ecological sources and ecological resistance surface, we extracted ecological corridors and identified key strategic points for the Loess Plateau as a whole and for its constituent ecoregions. The spatial distribution characteristics of ecosystem services on the Loess Plateau were consistent with those identified in previous studies [66–68]. Soil conservation, habitat quality, water yield, and carbon fixation were generally high in the southeast and low in the northwest, and were strongly correlated with vegetation cover and ecological environment quality. The best connectivity and integrity of ecological landscape components within the ecological sources was found when the landscape size was 400 m. This is consistent with the results of Fang et al. [62]. However, Tang et al. suggested that a landscape size of 1800 m was optimal in Dongfang City, China [69], while Chen et al. showed that 1400 m was optimal in Haikou City, China [70]. The optimal landscape size may be related to factors such as the size of the study area and fragmentation degree of landscape patches. In the process of constructing the ecological resistance surface, Wang et al. [25] argued that increasing human activity had disturbed natural landscape conditions, and in particular, urban expansion had exacerbated changes in the natural landscape. These factors have a huge impact on species migration, ecological security, and regional stability. The spatial distribution characteristics of the ecological resistance surface are also influenced by these factors. Therefore, it is necessary to focus on protecting and restoring areas with high levels of human activity disturbance, as well as the areas with relatively poor natural conditions, in order to maintain the integrity of the ecosystem.

5.2. Distribution of ESPs and Restoration Strategies

Regardless of spatial scale, pinch points and barrier points were dominated by grassland and cultivated land. Grassland is one of the main land use types on the Loess Plateau and has ecological functions that include wind proofing and petrification of sand water conservation. As a buffer zone between urban and ecological land, cultivated land also has high ecological value [71,72]. Both grasslands and cultivated land provide space for the diffusion of organisms in natural ecosystems, but they are also significantly affected by human activities. Therefore, we should not only pay attention to the quality evaluation and management of cultivated land, but also implement the conversion of cultivated land with low quality to forest or grassland in future ecological restoration process [73]. At the same time, it is necessary to enhance the ecological function of grasslands to improve the ecological environment.

The Loess Plateau is a geologically hazard-prone area. Geological hazards, as well as the effects of mining and urbanization, tend to impede the flow of ecological processes between ecological sources [74]. Hence, there is also a need to reduce pollutant emissions, control population and development scale, and strengthen mining geo-environmental protection and restoration. Although the proportion of unutilized land and artificial surface land in pinch points and barrier points was small, these land use types have fragile ecosystems. The ecological environment in these areas will also become more fragile owing to extreme climatic conditions and frequent human activities disturbances [75]. As such, in the future, it will also be necessary to implement suitable ecological restoration measures in these areas, strengthen ecological protection and management of pinch points, and solve the ecological problems of barrier points.

Furthermore, we found overlapping pinch points and barrier points. These areas are mainly distributed near unutilized land and artificial surface land, which indicates that species have a great probability to pass through these areas in the migration process, but at the same time must overcome relatively high resistance [76]. In future restoration, we should focus on these areas and implement corresponding engineering and biological measures to promote energy flow and material circulation among species, as well as reduce regional ecological risks and ensure regional ecological security.

5.3. Comparison of ESPs at Different Spatial Scales

In recent years, the Chinese government has attached great importance to the ecological restoration of national land space and has issued a series of important policy documents that present clear requirements for the ecological restoration of national land [77–79]. However, in the protection of pinch points and restoration of barrier points, the spatial scale of ecological restoration needs to be well considered in addition to the impact of land use conversion on changes in ecosystem service values [80]. ESPs differ at different spatial scales, mainly because of variation in the identification of ecological sources and the limitations of regional boundaries. ESPs at larger spatial scales tend to ignore small areas with important ecological functions, while ESPs at smaller spatial scales can be cut by regional boundaries, artificially fragmenting the ecological sources.

Here, the ESPs for the whole Loess Plateau as a single unit focused on core sources and effective connection of corridors, which has important significance for delineating the spatial scope of ecological protection and restoration. This exercise provides theoretical support for macro regional economic development strategy. On the other hand, the construction of ESPs for the various ecoregions within the Loess Plateau revealed more refined ecological sources, which will facilitate smaller scale development planning, improvements to landscape structure, and enhanced security of the natural ecosystem. Ultimately, assessing the practicality and applicability of ecological restoration in critical areas requires analysis at multiple spatial scales [81]. However, a full ecological risk evaluation and diagnosis of ecological problems still needs to be studied in depth.

5.4. Significance of ESPs on the Loess Plateau

Affected by natural factors such as broken terrain, loose soil, concentrated rainfall and man-made factors such as overgrazing, steep slope reclamation and urbanization development, the Loess Plateau suffers from serious soil erosion, widespread desertification, grassland degradation, and other ecological problems. The human well-being is under severe challenges [82]. Protecting ecosystems and sustaining human well-being have become a key concern of international scientific research programs. In "Transforming Our World: The 2030 Agenda for Sustainable Development", the United Nations further included "protecting, restoring and promoting sustainable use of terrestrial ecosystems, sustainably managing forests, combating desertification, halting and reversing land degradation, and halting biodiversity loss" as one of the global sustainable development goals [83]. Therefore, based on the research paradigm of ESPs, we constructed ESPs for different spatial scales of the Loess Plateau, analyzed the similarities and differences among ecological sources, corridors, and key strategic points, and proposed corresponding control strategies so as to provide references for promoting integrated ecosystem management and exploring ecological restoration directions. The study emphasizes the ecological importance of the Loess Plateau, responds to the need for high-quality development in China, and provides theoretical support for achieving sustainable development goals.

6. Conclusions

Organically combining ESPs theory with ecological restoration strategies can reconcile the contradiction between ecological protection and economic development, and enhance the relevance and practicality of restoration policies. However, although ESPs has been applied for many decades, more research is needed in the selection of ecological sources, the construction of ecological resistance surfaces, the identification of key ecological restoration locations, and understanding differences at different spatial scales.

Based on the minimum cumulative resistance model and circuit theory, ecological corridors, ecological pinch points, and ecological barrier points were identified at different spatial scales on the Loess Plateau. The research results showed that the spatial distribution of ecological sources at different spatial scales are generally similar, but differ in detail. The spatial distribution characteristics of ESPs are closely related to human activities and land use types. The number of ecological sources affect the number and length of corridors, which in turn affect the number and area of pinch points and barrier points. Areas where pinch points and barrier points overlap are mainly distributed near unutilized land and artificial surface land; at these points, species have a great probability of passing through the areas, but at the same must overcome relatively high resistance. Our results clearly demonstrate that when formulating ecological protection and restoration strategies, spatial scale should be considered according to the development goals. Specific programs should be determined based on ESPs characteristics so as to ensure maximum benefit for biodiversity and ecosystems integrity from multiple perspectives. The results of this study provide theoretical support for achieving sustainable development goals in this region. However, ESPs construction is a combination of landscape ecology and geography, which is an extension of the core idea of "pattern-process" [84]. More research support is needed on how to specifically apply research about ESPs to meet the practical needs of achieving sustainable development goals.

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

Funding: This research was funded by National Science and Technology Major Project, China (grant number: 2019QZKK0405), Study on Classification of Garden and Grassland in Shaanxi Province (grant number: 2022610001007238), Annual cultivated land resources quality classification update and monitoring of in Shaanxi Province (grant number: 2022610001006904), National Key R&D Program of China (grant number: 2018YFE0103800), China Scholarship Council (Grant No.: Liujinmei [2022] No. 45; Liujinxuan [2022] No. 133), International Education Research Program of Chang'an University (grant number: 300108221102), General Project of Shaanxi Provincial Key R&D Program-Social Development Field (grant number: 2021SF-454), China National Social Science Fund Project (grant number: 20XKS006), Project of Ningxia Natural Science Foundation (grant number: 2022AAC03700) and 2022 Guangdong University Youth Innovation Talent Program (grant number: 2022KQNCX143).

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the support of Yinshanbeilu Grassland Eco-hydrology National Observation and Research Station, China Institute of Water Resources and Hydropower Research, Beijing 100038, China, Grant No. YSS2022004.

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

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