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# Establishing and Optimizing the Ecological Security Pattern in Shaanxi Province (China) for Ecological Restoration of Land Space

**Han Li [1,2], Tian Zhang [1,2,*], Xiao-Shu Cao [1,2] and Qian-Qian Zhang [1,2]**

[1] Northwest Land and Resource Research Center, Shaanxi Normal University, Xi'an 710119, China; lihan@snnu.edu.cn (H.L.); caoxsh@snnu.edu.cn (X.-S.C.); zhangqq27@snnu.edu.cn (Q.-Q.Z.)
[2] Natural Resources and National Land Use Research Institute, Shaanxi Normal University, Xi'an 710119, China
* Correspondence: zhangtiangis@163.com

**Abstract:** Land space underpins an ecological civilization. A thorough grasp of regional natural resources and subsequent optimization of the ecological security pattern are both essential for the comprehensive development and overall planning of the management of natural resources. In this study, we established and optimized the ecological security pattern in Shaanxi Province, China. Landscape patches distinguished by high importance of ecosystem services (carbon fixation and oxygen release, water conservation, habitat maintenance, and soil conservation) and high sensitivity of ecological environment to human interference (ecological sensitivity index) were extracted as ecological sources. An ecological resistance surface was built based on the following resistance factors: land-use type, topographic position index, and soil erosion intensity. A minimum cumulative resistance model was used to identify ecological corridors. Our results showed that those ecological sources with high to extreme ecological importance and sensitivity together covered an area of 67,457 km$^2$ (32.8% of the total land area of Shaanxi Province). A total of 32 ecological nodes were identified at the center of important ecological sources to serve as main areas for implementing ecological protection projects. In addition, 72 ecological corridors were identified, towards which efforts should be targeted to maintain their functions for the inter-connection and serial connection of ecological nodes and source patches. The ecological corridors create favorable habitats for wildlife and superior spaces for ecological migration based on the blue and green linear corridor system. According to these findings, we propose establishing an ecological security pattern featuring "two barriers, three belts, and multiple corridors" in Shaanxi Province and that the green ecological security barriers should be strengthened based on their natural background and resource endowments.

**Keywords:** ecosystem services; ecological sources; ecological corridors; ecological security pattern; Shaanxi Province

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## 1. Introduction

Rapid economic growth is usually associated with frequent ecological disasters and declining ecosystem functions as well as resource and environmental problems [1,2]. These ecological problems can profoundly influence the sustainable development of regional economies [3]. In the face of worsening global ecological problems, researchers have achieved a consensus: it is important to recover ecosystem functionality through ecological restoration and thereby enhance the coordination of the human–land relationship [4,5]. In particular, regional ecological security is severely challenged in rapidly developing areas of China. Establishing ecological security patterns is now imperative for conserving regional biodiversity, maintaining complete ecosystem functions, and realizing the smart development of urban areas [6]. Therefore, the establishment of regional ecological security patterns has become one of China's major national strategies for sustainably coordinating ecosystem protection and economic development [7].

Land space is the material carrier of the common practice of nature and humans, and the extent to which humans are shaped by nature is no less than that of the opposite

transformation; therefore, a geosystem theory with the core of Coupled Human and Natural Systems has become the theoretical basis of land spatial planning and renovation [8]. Optimizing the patterns of land space development is the paramount task in constructing an ecological civilization. Implementing the ecological restoration of land space provides a vital pathway for the optimization of land space development patterns and major support for the construction of ecological civilization. At the core of this work is the devising of a plan for the ecological restoration of land space, which should follow ecological principles to explore promising strategies for improving system structure and function while considering planning methodologies that promote the harmonious and sustainable development of human and natural systems [9]. Research on ecosystem services forms a solid foundation for establishing ecological security patterns. The supply–demand relationship of ecosystem services is comprehensively influenced by natural and human factors, such as the natural environment, urbanization, and human population structures [10]. Therefore, we must strive to fully grasp the current utilization and endowment of regional natural resources, and then optimize the ecological security patterns accordingly.

Ecological security patterns are the formed by the spatial patterning of points, lines, and surfaces that comprise key parts of the natural landscape [11]. Many researchers have evaluated regional ecological conditions, mainly by applying the ecological network perspective. Historically, the development of ecological networks has gone through an iterative process, shifting from single ecological environments to multi-level and multi-objective networks encompassing ecology, economy, society, and humanity. Early on, European landscape boulevards focused on urban aesthetics. Then, European green belts and American park roads were built to suppress urban expansion and conserve biodiversity. Later on, American greenways were developed to improve ecological environments and protect cultural resources. Nowadays, there are multi-objective, multi-level green spaces. Altogether, these ecological network practices constitute a planning operation mode that is relatively mature. Following the objectives of regional habitat and biodiversity conservation, ecological nodes and corridors are selected by evaluating their accessibility, connectivity, and suitability. In this way, the ecological network pattern is established and then optimized [12–14].

For China, its ecological security pattern is typically proposed on the basis of ecological network research combined with knowledge of national conditions, being still in an initial stage that focuses on ecological corridor connections. More specifically, based on "patch–corridor–matrix" theory, "ecological source identification–resistance surface construction–potential corridor simulation" has become the core idea guiding ecological spatial planning in China [15]. According to the natural functional attributes of landscape patches, ecological sources are identified based on their patch size and biodiversity richness. When building the ecological resistance surface, its resistance factors are directly assigned values according to experts' experience and land-use type, and the spatial data are introduced to correct the resistance factors [16]. To simulate potential ecological corridors, the minimum cumulative resistance (MCR) model has been widely used. This model can reliably simulate the interaction relationships between landscape patterns and spatial movements of biological species, thereby accurately designating the potential ecological corridors [17,18]. For the accurate and efficient establishment of regional ecological networks, it is critical to identify extant ecological sources objectively, correct the ecological resistance surface using spatial data, and determine the threshold for ecological corridor extraction by considering both network connectivity and construction costs [12].

The aim of this study was to establish the ecological security pattern in Shaanxi Province. Explicitly taking into account the problems threatening ecological security in this region, we divided the landscape types and identified their ecological sources by evaluating the ecosystem service importance and ecological environment sensitivity of each. Then, ecological corridors were identified using the MCR model and the conflicts and deficiencies faced by them were discussed. Landscape components including ecological sources, corridors, and nodes were spatially overlaid to establish the ecological security

pattern. After optimizing this ecological security pattern, corresponding ecological planning suggestions were proposed. The results of this timely study could effectively guide the ecological restoration pattern incorporated into land space planning in the Shaanxi Province and might inspire ecological improvements in other regions with similar development backgrounds.

## 2. Materials and Methods

### *2.1. Study Area*

The Shaanxi Province is located in the hinterland of China (Figure 1), between the coordinates 105°29′–111°15′ E and 31°42′–39°35′ N. This region crosses the Yangtze River and Yellow River, while spanning the north subtropical zone and warm temperate zone. Due to its unique geographical location and complex geomorphologic and climatic features, the Shaanxi Province has distinctive physical geographical patterns, with prominent differences characterizing its regional ecological environment. Shaanxi is a major component of China's ecological security pattern characterized by "two barriers and three belts" (i.e., Qinghai–Tibet Plateau Ecological Barrier, Loess Plateau–Sichuan–Yunnan Ecological Barrier, Northeast Forest Belt, North Sand Control Belt, and South Hilly Mountain Belt). Overall, the regional ecological environment in the Shaanxi Province is fragile, yet one finds remarkable differences between its north and south. Three natural regions separated by the Beishan and Qinling Mountains are discernible: the Loess Plateau in northern Shaanxi, the Weihe Plain in central Shaanxi, and the Qinba Mountains in southern Shaanxi. The Loess Plateau is an essential soil conservation functional area that plays a key strategic role in the Yellow River Basin's ecological protection and ensuring its high-quality development and ecological security. The Qinling Mountains, also known as the "central water tower", are the geographic boundary between North and South China. As a major ecological barrier in China, the Qinling Mountains have vital functions including biodiversity maintenance and water conservation. The Shaanxi Province has 10 administrative districts and cities totaling 205,600 km$^2$ in land area, with a permanent population of 38.76 million (at the end of 2019).

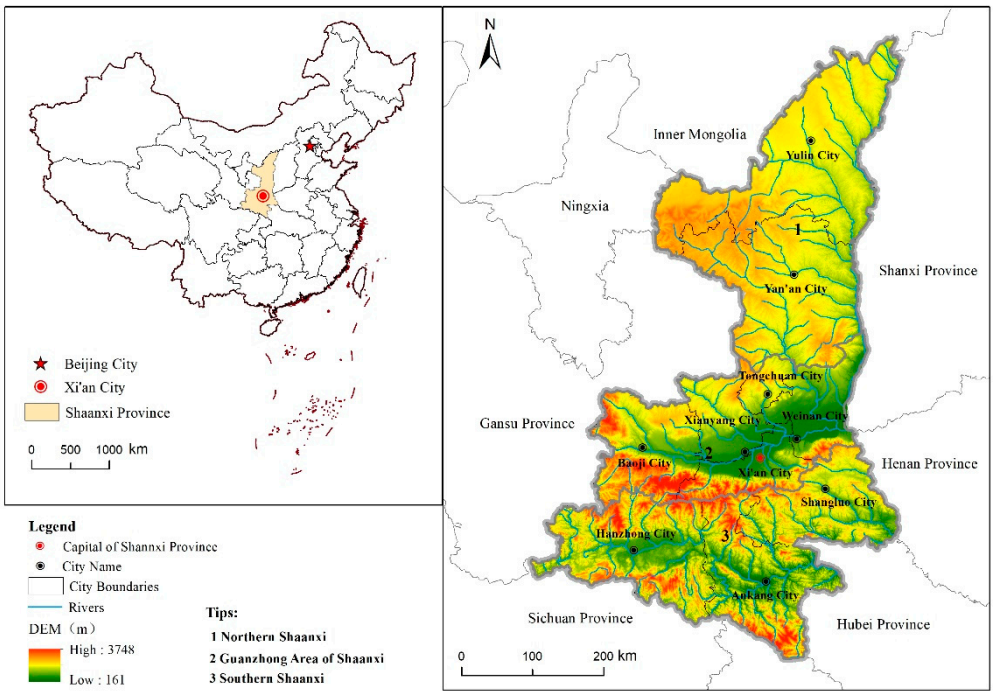



**Figure 1.** Geographical location of the study area (Shaanxi Province, China).

### 2.2. Data Sources

The data used in this study mainly included environmental data and spatial data of the Shaanxi Province. Specifically, precipitation data were derived from the observational data sets of meteorological stations provided by the Data Center for National Meteorological Science (http://data.cma.cn/; accessed on 25 March 2021); stations in and around Shaanxi were selected for data interpolation to generate a spatial distribution of precipitation. Evapotranspiration data were derived from the MODIS MOD16A3GF product at a spatial resolution of 500 m (https://lpdaac.usgs.gov/products/mod16a3gfv006/; accessed on 10 March 2021) [19]. Normalized vegetation index data came from the MODIS MOD13A3 product, having a spatial resolution of 1 km (https://lpdaac.usgs.gov/products/mod13a3v006/; accessed on 2 March 2021) [20]. Land-use and land-cover change data were derived from the MODIS MCD12Q1 product with a 500 m spatial resolution (https://lpdaac.usgs.gov/products/mcd12q1v006/; accessed on 10 March 2021) [21]. Net primary productivity data were obtained from the MODIS MOD17A3HGF product at spatial resolution of 500 m (https://lpdaac.usgs.gov/products/mod17a3hgfv006/; accessed on 2 March 2021) [22]. Elevation data were downloaded from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/Default.aspx; accessed on 10 March 2021), while soil erosion data were downloaded from the Ecosystem Evaluation and Ecological Security Database of China (http://www.ecosystem.csdb.cn/; accessed on 11 March 2021). River and traffic data respectively came from the Resource and Environment Science and Data Center (https://www.resdc.cn/data.aspx?DATAID=221; accessed on 3 April 2021) and OpenStreetMap platform (https://www.openstreetmap.org/; accessed on 3 April 2021). Historical and cultural linear heritage data were obtained through literature research and subsequent data vectorization.

### 2.3. Identification of Ecological Sources

The phrase 'ecological sources' refers to extant native ecosystems, such as native species' habitats, which are the sources of ecological flows. The objective of protecting ecological security is to use the least amount of ecological land to guarantee regional ecological security, further achieving effective control and continuous improvement of the regional ecological environment. Accordingly, the selected ecological sources should ensure the integrity of ecosystem structure, functioning, and processes, while facilitating ecosystem service supply and linking landscape processes [6]. Patches, as the most basic unit of the landscape, provide habitats for many organisms. Based on their different compositions, landscape patches can be divided into green, blue, and gray patches [23]. In Shaanxi Province, the green patches are mainly green spaces composed of farmland, forest land, and grassland; the blue patches are strip-like patches composed of rivers or lakes; and the gray patches are mainly composed of artificially constructed hardened surfaces, such as urban construction land and rural residential areas. The aim of ecological source identification is to extract key patches that are essential for sustaining regional ecological security. Taking into account ecosystem functioning and connectivity, we sought and selected only those patches having both high ecosystem service importance and high ecological environment sensitivity as ecological sources.

#### 2.3.1. Evaluation of Ecosystem Service Importance

In the Shaanxi Province, dense river networks safeguard the development of the ecological landscape. Therefore, water conservation is an essential ecosystem service in this region which plays a crucial role in maintaining regional ecological security. Further, uneven rainfall distribution and complex topography cause serious soil erosion; hence, soil conservation is also a key ecosystem service in this region. Given that the ecological landscape plays a vital role in regulating the local microclimate and providing biological products, both carbon fixation and oxygen release likewise merit attention. Habitat maintenance refers to the provisioning of places for crucial ecological processes, such as biological

growth, foraging, and reproduction. This service indirectly protects organisms via habitat conservation and maintains species co-occurrence and biodiversity. Since forest land and grassland patches occur widely and harbor abundant wildlife resources, habitat maintenance should be taken into account when identifying ecological sources in the Shaanxi Province. Therefore, we selected carbon fixation and oxygen release, water conservation, habitat maintenance, and soil conservation as metrics for use in evaluating the importance of ecosystem services in the study area.

The net primary productivity of vegetation is the difference between autotrophic photosynthesis and respiration, and is widely used to evaluate the carbon sequestration and oxygen release capacity of vegetation. In this study, water conservation capacity was calculated according to the water balance equation: average water conservation amount (mm) = average precipitation − average evapotranspiration.

The importance of habitat maintenance was evaluated using the Habitat Quality module of the InVEST project (https://naturalcapitalproject.stanford.edu/software/invest; accessed on 15 May 2021) This module analyzes the range and degradation levels of different habitat or vegetation types in a certain area, with habitat quality being dependent upon habitat accessibility for human land uses and their intensity. The Habitat Quality module determines different land-use types as habitats and threat sources and then combines the density data of habitat threats and their impacts on habitat quality. Further, the model extracts the threat sources and calculates several informative indicators, such as the relative degree of influence of each threat source type, the distance between habitat grids and threat source grids, and the relative sensitivity of each threat source type corresponding to each habitat type. The habitat quality score was calculated as follows [24]:

$$Qxj = Hj \times \left[1 - \left(\frac{D_{xj}^{z}}{D_{xj}^{z} - k^{2}}\right)\right] \quad (1)$$

where $Q_{xj}$ is the habitat quality of patch group $x$ under land-use type $j$; the $Hj$ is the habitat suitability of land-use type $j$ (including construction land, farmland, railways, and highways as threat sources); $D_{xj}$ is the threat level of grid $x$ in land-use type $j$; the $z$ value is set to 2.5 by default; and $k$ is the half-saturation constant. Resulting habitat quality scores of the landscape range between 0 and 1, with non-habitat areas scored as 0. A higher score indicates a better habitat quality, which is more conducive to maintaining species co-occurrence and biodiversity.

The soil conservation service was evaluated by applying the Revised Universal Soil Loss Equation (RUSLE). To obtain the soil conservation amount, the amount of actual soil erosion was subtracted from the amount of potential soil erosion [25]. In this model, the soil conservation amount of each pixel is related to topographic relief, soil erosion resistance, rainfall erosivity, and vegetation coverage, as well as the water and soil conservation practices in that given pixel. The equation used to calculate soil conservation amount is given below:

$$A = R \times K \times LS \times (1 - C \times P) \quad (2)$$

where $A$ is the soil conservation amount (t/ha year); $R$ is the rainfall erosivity factor (MJ·mm·ha·h$^{-1}$·a$^{-1}$); $K$ is the soil erodibility factor (t·ha·h·MJ$^{-1}$·mm$^{-1}$·ha); $LS$ is the slope and length factor (dimensionless); $C$ is the vegetation cover and management factor (dimensionless); and $P$ is the soil erosion control practice factor (dimensionless).

In assessing the importance of ecological services, we first normalized the indicator values of different services to eliminate the influence of dimensionality. According to the ecological environment's current status in Shaanxi, the four ecosystem services were assigned weights of 0.2 (carbon fixation and oxygen release), 0.3 (water conservation), 0.2 (habitat maintenance), and 0.3 (soil conservation). Then, a weighted overlay was generated in ArcGIS v10.2 (ESRI Inc., Redlands, CA, USA) to obtain the importance layer of ecosystem services in the study area. Further, these calculation results for ecosystem service importance were divided into five levels using the natural breakpoint method,

where a higher level indicates a greater importance of ecosystem services. The results were then named as: generally important, relatively important, moderately important, highly important, or extremely important—in ascending order of ecosystem service importance.

#### 2.3.2. Evaluation of Ecological Environment Sensitivity

In the landscape environment, the tolerance threshold to external factors that ecological elements can withstand while persisting in a non-damaged state is termed ecological environment sensitivity. According to their sensitivity, ecological factors within a region can be divided into blocks, and subsequent analysis of their distribution structure can reveal regional ecological and environmental problems. The ecological sensitivity index is often used to quantify human interference with the environment in the evaluation of ecosystem stability [26]. Here, we selected vegetation coverage, elevation, slope, land-use type, and soil erosion intensity as evaluation factors. Among them, soil erosion intensity was used to indicate the sensitivity of the ecological environment to soil and water erosion—the most prominent ecological problem in the Shaanxi Province. This factor was calculated using RUSLE and then classified as previously described [27]. The weights of the five evaluation factors were assigned by the analytic hierarchy process (Table 1). The ecological environment sensitivity was obtained through a weighted summation of the factor values. Then, the natural breakpoint method was used to classify the ecological environment sensitivity into five levels (insensitive, slightly sensitive, moderately sensitive, highly sensitive, and extremely sensitive).

**Table 1.** Classification and weights of the evaluation factors for ecological environment sensitivity.

| Evaluation Factor | Ecological Sensitivity Value | | | | | Weight |
|---|---|---|---|---|---|---|
| | 9 | 7 | 5 | 3 | 1 | |
| Vegetation coverage | >0.75 | [0.65, 0.75] | [0.50, 0.65] | [0.35, 0.50] | [0.35, 0] | 0.15 |
| Elevation (m) | [0, 500] | [500, 1000] | [1000, 1500] | [1500, 2000] | >2000 | 0.20 |
| Slope (°) | [0, 5] | [5, 10] | [10, 15] | [15, 25] | >25 | 0.25 |
| Land-use type | Forest land and waters | Grassland | Garden land | Farmland | Others | 0.10 |
| Soil erosion intensity | Extremely intense | Intense | Moderate | Mild | Slight | 0.30 |

Finally, we extracted those patches deemed highly to extremely important in terms of ecological services, and likewise those highly to extremely sensitive in terms of ecological environment, to serve as the ecological sources [28]. The selection of ecological sources was carried out using the spatial recognition function of ArcGIS v10.2.

### *2.4. Construction of Ecological Resistance Surface*

The choice of methods and indicators for constructing an ecological resistance surface will directly determine the quality and transmission efficiency of the ecological network [29]. Landscape cover type and topographic slope were the main sources of resistance to the outward expansion of ecological sources, the process of which is closely associated to the sensitivity level of the ecological environment. Taking into account the major ecological and environmental characteristics of the study area, we selected the following resistance factors: topographic position index [30], land-use type, and soil erosion intensity. The relative resistance values of these selected factors were set and their weights were determined using the analytic hierarchy process (Table 2) [28]. A weighted summation was used to quantify the cumulative resistance to the outward expansion of ecological sources. The higher the resistance value, the lower the ecological security—and vice versa. Based on the MCR model [31], we used the Cost–Distance module in ArcGIS v10.2 to calculate the cumulative cost-distances from the ecological sources to other landscape units.

**Table 2.** Weights and values and weights of the three resistance factors for resistance surface construction.

| Resistance Factor | Relative Resistance Value | | | | | | | Weight |
|---|---|---|---|---|---|---|---|---|
| | **0** | **10** | **30** | **50** | **70** | **90** | **100** | |
| Land-use type | Forest land | Waters and wetland | Grassland | Farmland | Others | – | Construction land | 0.3 |
| Topographic position index | – | 0.891–1.406 | 0.699–0.891 | 0.508–0.699 | 0.290–0.502 | 0.119–0.290 | – | 0.3 |
| Soil erosion intensity | – | Slight | Mild | Moderate | Intense | Extremely intense | | 0.4 |

### *2.5. Establishment of Ecological Network*

Via the communication between biological species in combination with the embedded landscape matrix, many ecosystems are linked to form a spatially coherent network system [32]. An ecological network is composed of ecological nodes and crisscrossing ecological corridors. Ecological nodes are the center point of major ecological source patches and ecological corridors are banded areas that function prominently in linking the material, energy, and information flows of the ecological network, which provide essential conduits for animal migration [16]. Consequently, establishing an ecological network reduces the harm of landscape fragmentation, contributes to biodiversity conservation and ecological quality improvement, and maintains the integrity of ecological processes in the face of human activities [33].

The MCR model was initially proposed by Knappen et al. (1992) and used to study species dispersal. This model takes into account three factors: source, distance, and landscape interface characteristics. It estimates the cost of "sources" to pass through landscapes differing in resistance, or the work done to overcome this resistance. Here, we used a modified MCR model [34] to construct the ecological source expansion resistance surface [24,35]. The MCR is calculated this way:

$$MCR = f_{min} \sum_{j=n}^{i=m} D_{ij} \times R_i \quad (3)$$

where *MCR* is the minimum cumulative resistance; *Dij* is the spatial distance of a certain species from the ecological source *j* to landscape unit *i*; *Ri* is the resistance factor of landscape unit *i* to the movement of a given species; and *f* is the positive correlation between *MCR* and the ecological process.

Ecological sources should not only have a high importance for ecosystem services, but they should also be large concentrated and contiguous areas. Accordingly, we selected the source patches with an area >4 $km^2$ and identified the corresponding ecological nodes. By taking each node as the center, the remainder $n - 1$ ($n$ = the total number of ecological nodes) formed the target node cluster. Based on the MCR model, $n$ layer-based minimum cost paths were obtained as ecological corridors between ecological sources. Through ecological corridors, different green spaces—including natural environments, urban spaces, and rural areas—in each region were organized to form a networked spatial system.

### *2.6. The Technology Flowchart*

To sum up, the technology flowchart of the process used to establish the ecological security pattern in the Shaanxi Province can be found in Figure 2. Based on multi-source datasets, and after making weighted summation, four ecosystem services were used to evaluate the ecosystem service importance, five evaluation factors were used to calculate the ecological environment sensitivity, and three resistance factors were used for resistance surface construction. Furthermore, based on the MCR model, an ecological network and ecological security pattern could be established.

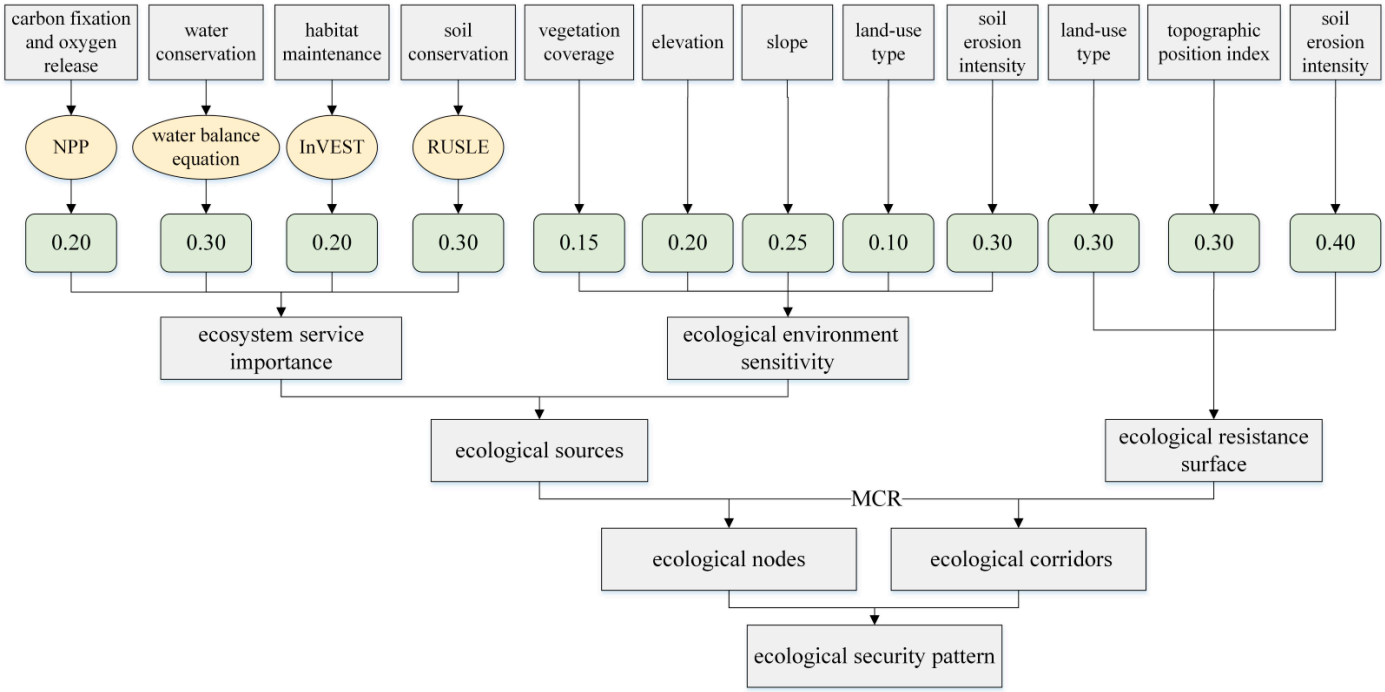



**Figure 2.** The technology flowchart of the process used to establish the ecological security pattern in the Shaanxi Province.

## 3. Results

### *3.1. Spatial Patterns of Typical Ecosystem Services*

The carbon fixation and oxygen release capacity of Shaanxi ranged from 0 to 1192.8 gC/m$^2$/year, reaching high levels in the Qinba Mountains (southern Shaanxi), where it sporadically exceeded 1000 gC/m$^2$/year in some areas. By contrast, the carbon fixation and oxygen release capacity was relatively low in the Guanzhong Plain (central Shaanxi), especially in the Guanzhong urban agglomeration. Further, there was a marked reduction in the carbon fixation and oxygen release capacity in the Loess Plateau (northern Shaanxi; Figure 3a). Water conservation capacity also exhibited pronounced spatial differentiation, with a decreasing trend from south to north. Under the joint action of regional precipitation and surface evapotranspiration, the average amount of water conservation in the Shaanxi Province varied between −517.62 and 1221.73 mm/year, with the ecological landscape in northern Shaanxi characterized by a relatively low water conservation capacity (Figure 3b).

In terms of habitat quality, southern Shaanxi earned the highest average score of 0.915, making it the most favorable area for maintaining biodiversity. The average habitat quality score of northern Shaanxi was lower, at 0.799, which indicated a slightly worse habitat quality than in southern Shaanxi; the lowest average habitat quality score, at 0.710, was in central Shaanxi which contained many non-habitat areas. Among different cities, the average habitat quality score was greatest for Shangluo at 0.926 and least for Weinan at 0.581 (Figure 3c). With respect to soil conservation, the average score of southern Shaanxi was the highest (68.264 t/hm$^2$·year), followed by that of central Shaanxi (60.146 t/hm$^2$·year), and being lowest for northern Shaanxi at 34.062 t/hm$^2$·year (Figure 3d). Overall, the ecosystem services were relatively rich in the southern part, modest in the central part, and poor in the northern part of the study area.

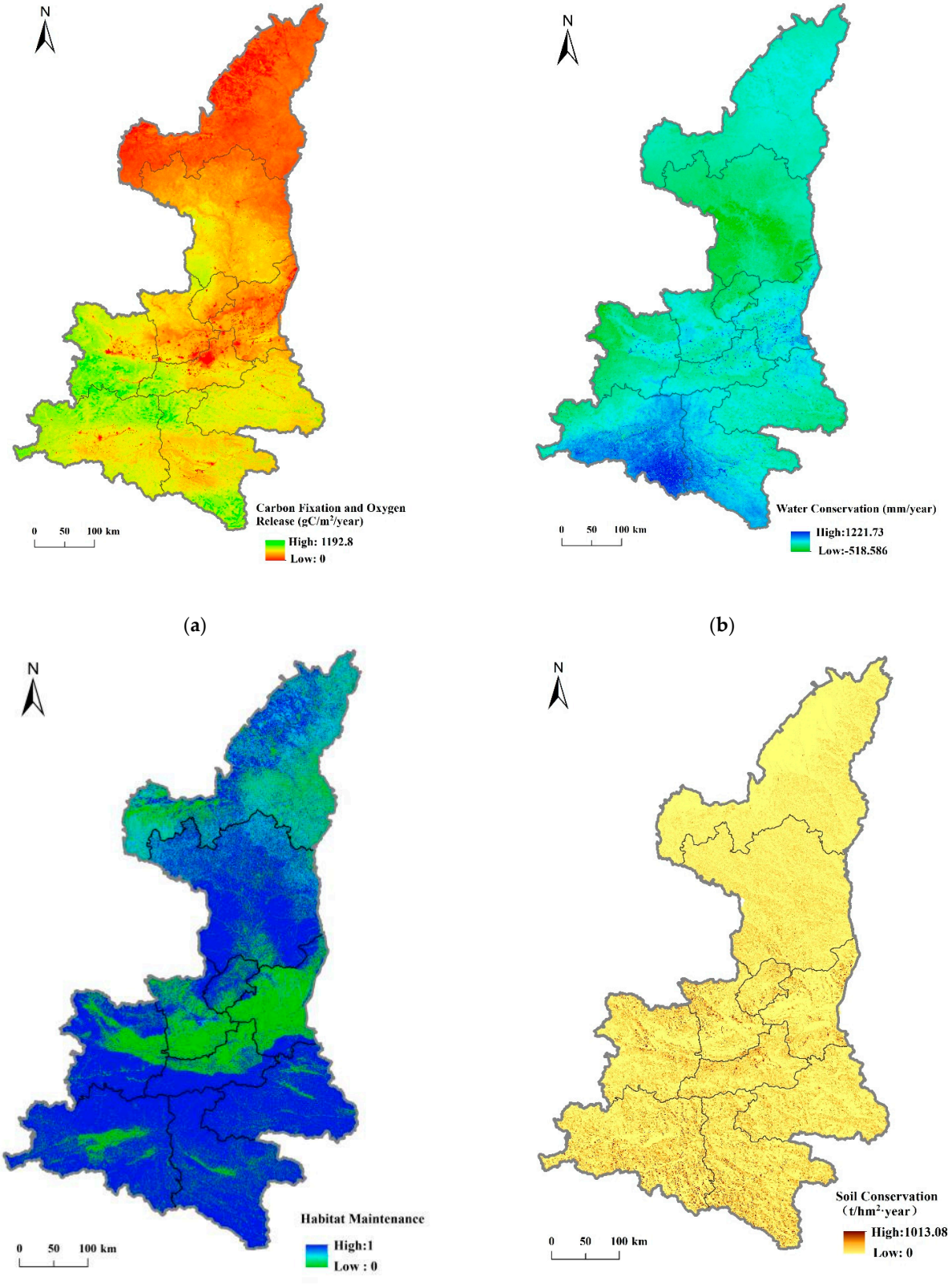
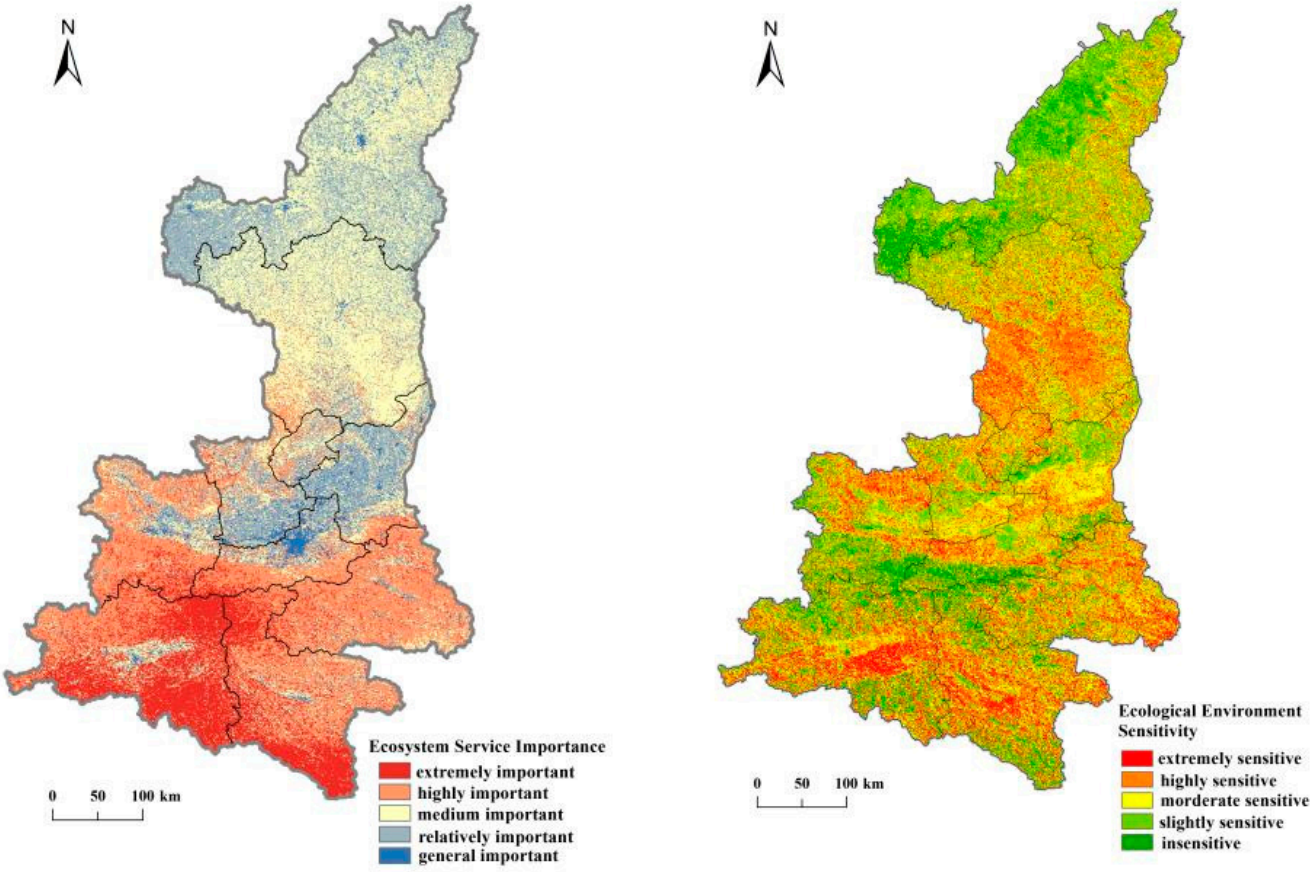



**Figure 3.** Spatial patterns of typical ecosystem services in the Shaanxi Province. (**a**) Carbon fixation and oxygen release, (**b**) water conservation, (**c**) habitat maintenance, and (**d**) soil conservation.

### *3.2. Identification of Ecological Sources*

The areas with highly to extremely important ecological services were mainly distributed in southern Shaanxi, covering an area of 86,923 km$^2$ (42.95% of the province's total land area). Based on the ecosystem service scores, southern Shaanxi had an average score of 0.428, the most favorable for biodiversity maintenance. The average score of central Shaanxi was 0.344, which indicated a slightly lower ecological service capacity than that of southern Shaanxi. Northern Shaanxi contained many non-habitat areas and received the lowest average score, at 0.314. Overall, the importance of ecosystem services in the Shaanxi Province was generally high in the south and low in the north (Figure 4a).




(**a**) (**b**)

**Figure 4.** Spatial patterns of ecosystem service importance (**a**) and ecological environment sensitivity (**b**) in the Shaanxi Province.

Ecological environment sensitivity in Shaanxi also exhibited marked spatial differentiation. Those areas with a highly to extremely sensitive ecological environment were mainly concentrated in the Qinba Mountains and Weibei Plateau, amounting to an area of 70,395 km$^2$ (34.69% of the total land area of the province). The slightly sensitive and insensitive areas were mostly distributed in the Guanzhong Plain, but also in some windy and sandy areas of northern Shaanxi (Figure 4b).

Ecological source patches were identified in terms of ecological service importance and ecological environment sensitivity, which covered a total area of 67,457 km$^2$. These source patches were mainly distributed in the Qinba Mountains and the two "green lungs" in northern Shaanxi, together accounting for 32.8% of the province's total land area. Given these ecological source patches, the ecological bottom line of urbanization development, resource exploitation, and environmental construction should be strictly guarded. In addition, 32 ecological nodes were identified after combining the aggregation and distribution

patterns of ecological source patches. These ecological nodes mainly appeared in southern Shaanxi (Figure 5). They should be considered key targets for ecological protection and restoration projects as well as ecological environment and biodiversity conservation in the Shaanxi Province.

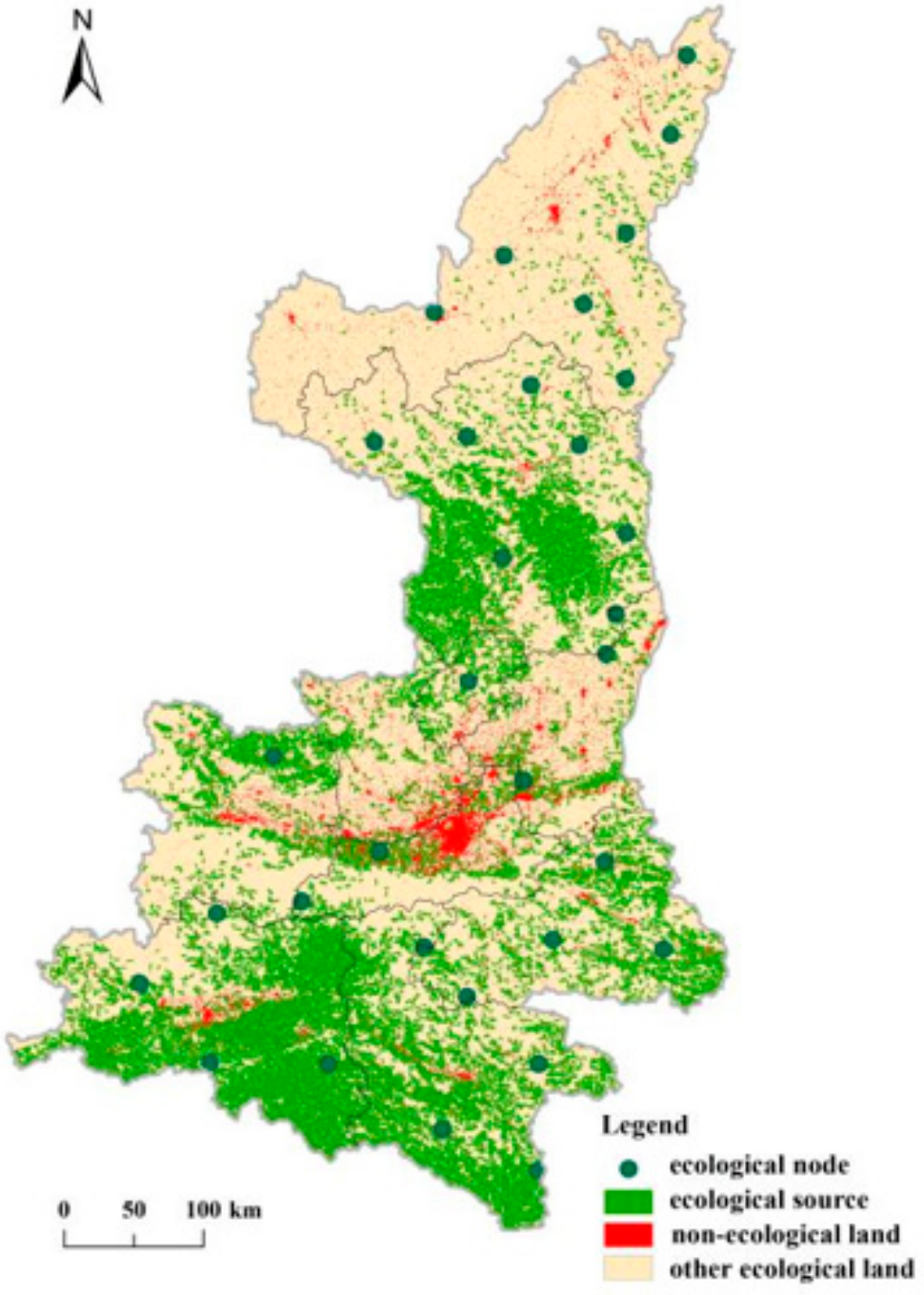



**Figure 5.** Distribution of ecological sources and nodes in the Shaanxi Province.

### *3.3. Expansion of Ecological Sources in the Shaanxi Province*

The MCR surface for ecological source expansion in Shaanxi Province is depicted in Figure 6. Overall, the ecological resistance values were low in southern Shaanxi, moderate in northern Shaanxi, and high in central Shaanxi. The highest resistance to ecological source expansion appeared in the Guanzhong urban agglomeration, an area associated with intensive human activities and dense road networks. In stark contrast, the lowest

resistance was found in the Qinba Mountains, a location with less human activity, the impact of which was relatively little.

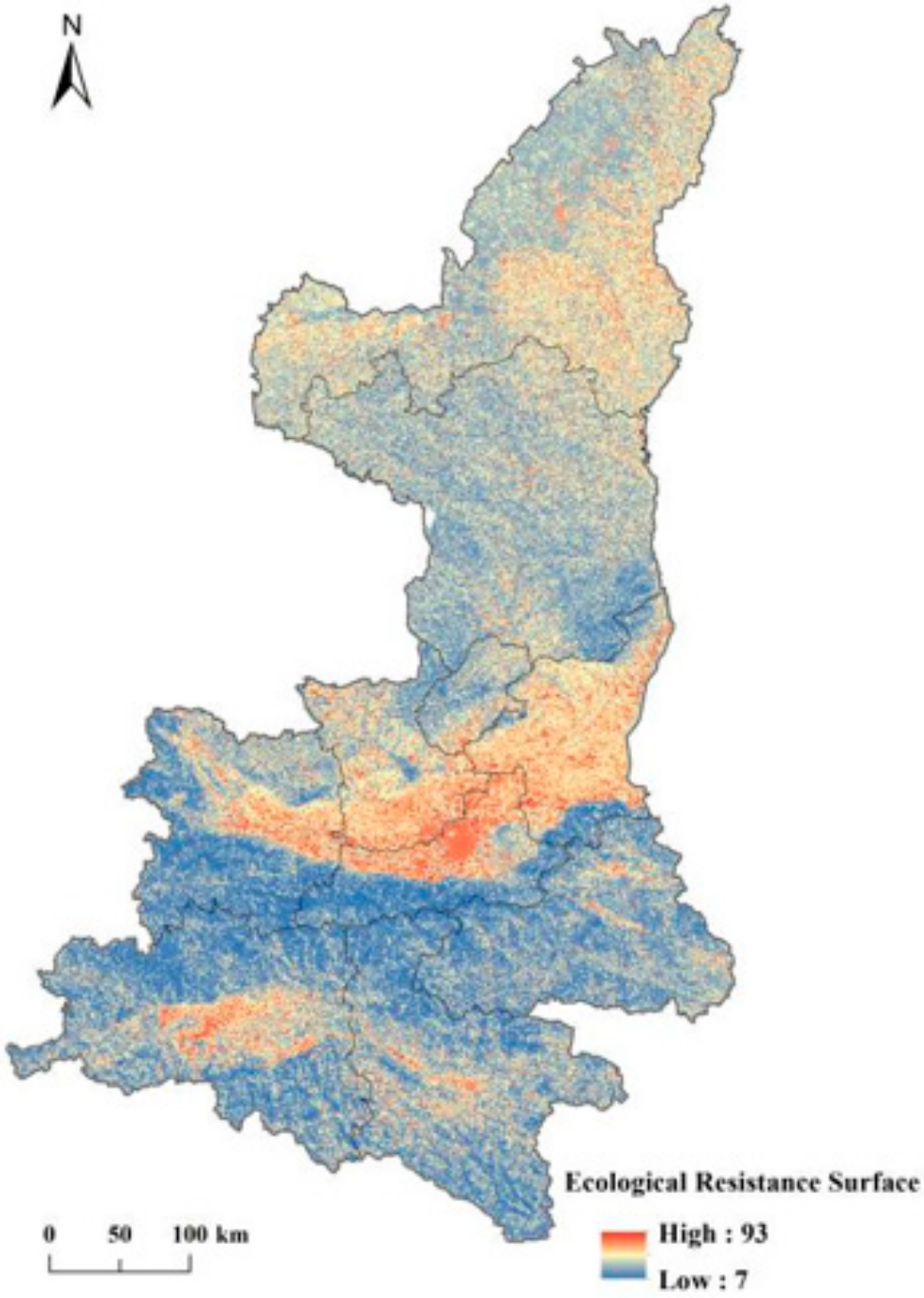



**Figure 6.** Distribution of ecological resistance in the Shaanxi Province based on the minimum cumulative resistance model.

### *3.4. Establishment of Ecological Security Pattern Based on the Ecological Network*

After identifying the ecological sources and constructing the ecological resistance surface, we distinguished 72 ecological corridors in Shaanxi Province via the MCR model. These ecological corridors were classified into three levels according to their spatial distribution and connectivity. Specifically, there were 31 first-level, 16 s-level, and 25 third-level ecological corridors (Figure 7).

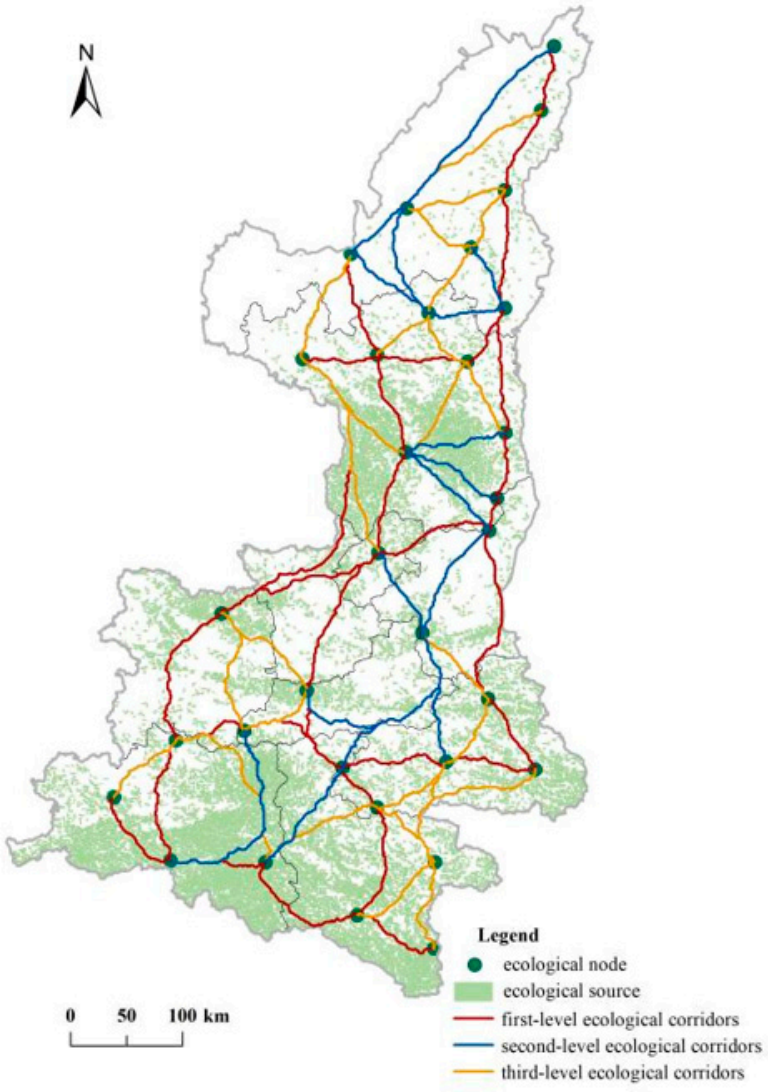



**Figure 7.** Networks of ecological corridors in Shaanxi province.

The first-level ecological corridors ("four horizontal and three vertical") perform their functions in serial connection of important ecological spaces and inter-connection of major river basins with main river systems on a macroscale. They need to be urgently restored, while serially connecting vital ecological spaces and inter-connecting major river basins to main river systems. The second-level ecological corridors play a role in the serial connection of important ecological nodes so as to realize the spatial connection of first-level corridors on a mesoscale. They are oriented to inter-connect important ecological nodes, improve the spatial structure of first-level corridors, and solve local conflicts. Lastly, the third-level ecological corridors fully inter-connect the ecological sources and nodes, thereby forming a comprehensive network of first- and second-level ecological corridors that impart effective serial connection and inter-connection to the multi-corridor network. They are aimed at connecting ecological nodes throughout a region and refining the ecological network pattern; hence, they require key protection.

An ecological security pattern is crucial for maintaining or controlling ecological processes in a specific region. The ecological sources identified in the Shaanxi Province were found mainly distributed along the Ziwuling, Huashan, Zhongnan, Taibai, and Bashan Mountains. These mountainous areas are characterized by high vegetation coverage, abundant wildlife, and high ecosystem service value, all of which contribute greatly to regional ecological security. Further, the ecological corridors inter-connect the Yellow River, Jinghe River, Luohe River, Hanjiang River, and Danjiang River in the province. These major

river systems are a fundamental safeguard of ecological information and biological flows that rely on water resources.

## 4. Discussion

### 4.1. Conflicts between Human Activities and Ecological Security Pattern

The ecological corridors in the Shaanxi Province are beset by two problems: conflicts and deficiencies. In particular, we paid attention to the intersections between different types of corridors and determined whether there were conflicts between them. In this study, we identified the spatial network relationship of existing gray corridors (roads and railways), blue corridors (rivers), ancient roads, and ecological corridors in Shaanxi Province. It was found that the ecological nodes were actually surrounded by multiple intersections (Figure 8), which would hinder the formation of ecological corridors. In addition, no ecological nodes were detected in the ecologically fragile zone of windy and sandy grass shoal areas in northern Shaanxi, implying a deficiency of ecological corridors there too. The protection and supplement of ecological sources and nodes should be the primary task in this region.

The intersections of ecological corridors and roads were concentrated in Yan'an, Weinan, Shangluo, and Xi'an city, which is consistent with the result of ecological fracture points in the research of Du et al. (2021) [36]. More attention should be paid to the reasonable avoidance of ecological corridors in the planning of urban road networks in those cities. The intersections of ecological corridors and rivers in the Shaanxi Province were mainly concentrated in two cities, Yan'an and Xi'an. In other cities, such as Hanzhong and Ankang, the trends of ecological corridors and rivers showed a relatively high spatial consistency; thus, both the ecological corridors and rivers could provide strong support for species migration and the sustained transmission of biological information.

As the wide distribution of ancient roads is a characteristic of the Shaanxi Province, appropriate connections with ecological corridors ought to be taken into account when developing and constructing cultural corridors. At present, although there is no systematic methodological framework for combining an ecological corridor with a cultural corridor [37], some researchers have made useful explorations into the construction of integrated ecological and cultural corridors or traditional settlements [18,37,38]. Yu et al. (2009) proposed a cultural heritage security pattern based on cultural heritage protection and recreation in Beijing [34]. It is pertinent to promote the coordinated arrangement of cultural–ecological corridors, as this would highlight the advantages of the Shaanxi Province, with its abundant reserves of diverse historical and cultural linear heritages (e.g., the Expressway of Qin Dynasty, the Qin–Chu Ancient Road, and ancient postal roads and plank roads). Therefore, we propose strengthening the overall ecological restoration of cultural–ecological corridors to thereby drive the organic integration of historical and cultural corridors into a final realized ecological network pattern. Moreover, "secure water-accessible river courses, healthy ecological corridors, and unique cultural post roads" could be built to improve the human settlement environment in the Shaanxi Province.

The intersections of ecological corridors with cultural corridors are mainly concentrated in Hanzhong, Ankang, and Yan'an. On the contrary, there are few conflicts in the cities of Shangluo and Weinan, which is largely due to the concentrated distribution of cultural corridors in the western half of the Shaanxi Province. To reduce these conflicts within the range of the Liuba County, Mian County, Hantai District, and Nanzheng District (Hanzhong City), the priority action is to integrate abundant ancient roads into the construction of ecological corridors in the Qinba Mountains, forming an integrated network of cultural tourism–ecological corridors at the southern foot of the Qinling Mountains. In the territory of the Yuyang District and Hengshan District (Yulin City), the priority is to incorporate linear heritage corridors of the Great Wall Ruins of Ming Dynasty within the ecological network to form an integrated network of heritage–ecological corridors. In the Chang'an District, Huyi District (Xi'an City), and Ningshan County (Ankang City), the

establishment of an integrated network of cultural–ecological corridors should be taken into full account.

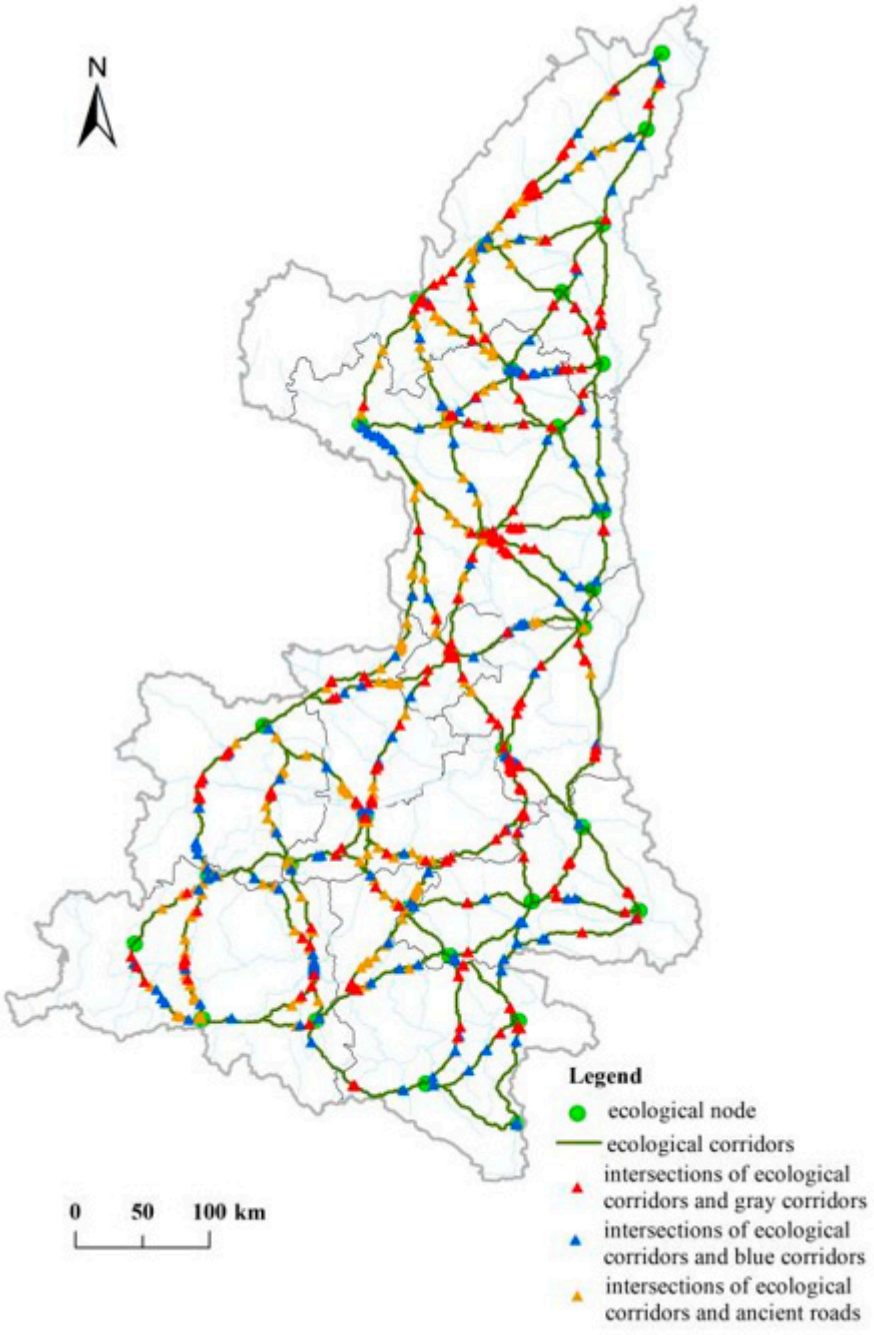



**Figure 8.** Intersections of ecological corridors and other linear elements in the Shaanxi Province.

*4.2. Optimization of Ecological Security Pattern in Shaanxi Province*

Integrating the distribution of ecological space, agricultural space, and urban space as well as the ecological network built in the Shaanxi Province, we established the ecological restoration pattern of land space with "two barriers, three belts, and multiple corridors" (Figure 9). In this ecological restoration pattern, "two barriers" refers to the ecological safety barriers, "three belts" refers to ecological restoration belts, and the "multiple corridors" are the 72 corridors that cover the entire landscape of the Shaanxi Province. As a comparison with a relevant article, Yang et al. (2017) proposed the layout of eco-spatial structure of "the mode of corridor group network with green cores" in thr Guanzhong urban agglomeration with "four belts, three regions, seven groups, ten corridors, and

multi-centers" as the core [28]. The Guanzhong urban agglomeration is located in the center of the Shaanxi Province, and the ecological restoration pattern we built could form a strong spatial connection with their results. Feng et al. (2021) put forward the ecological security pattern of "one bay, two belts, three barriers, four districts and multi-centers" in Inner Mongolia [35], in which the soil and water conservation, as well as the wind-breaking and sand-fixing area, in the Loess Plateau is spatially connected with the corresponding belt in the Shaanxi Province.

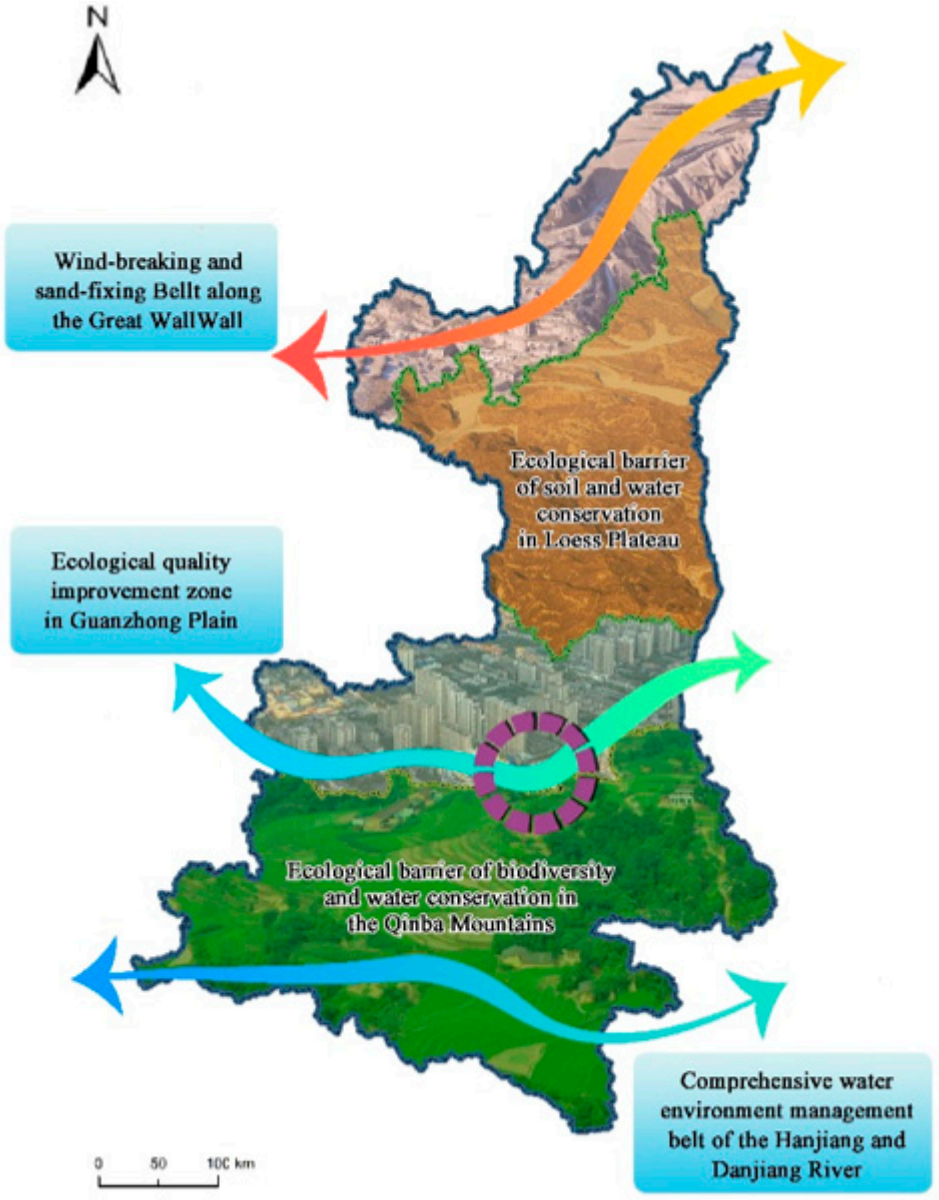



**Figure 9.** Ecological restoration pattern of land space in Shaanxi Province featuring "two barriers, three belts, and multiple corridors".

Furthermore, we propose the following suggestions for enhanced ecological restoration planning of land space in Shaanxi Province. Considering the ecological barrier for soil and water conservation in the Loess Plateau, such planning should strive to strengthen the protection and restoration of vegetation and enhance both water and soil conservation functions. Given the ecological barrier for biodiversity and water conservation in the Qinba Mountains, this planning should also aim to promote comprehensive environmental management, safeguard biodiversity, and enhance water conservation functions in the long-term. In the wind-breaking and sand-fixing belt along the Great Wall, shelter forest

construction and grassland protection should be reinforced to augment the wind prevention and sand fixation functions. In the ecological quality improvement belt of the Guanzhong Plain, urban ecological construction should be carried out to build green channels to better coordinate urban development with the ecological environment. In the comprehensive water environment management belt of the Hanjiang and Danjiang River, improving the water conservation capacity there as well as the comprehensive treatment of the water environment, to safeguard the water ecology and water security in Shaanxi Province and that of the 'South-to-North Water Diversion Project'.

To optimize the ecological security pattern of Shaanxi Province, the concentration areas of the conflicts between human activities and ecological network should be highly-regarded. Gong et al. (2020) declared that the integration distribution of mountains and rivers should be mainly considered in the implementation of regional ecological restoration planning strategies [9]. Therefore, the eight mountain systems (i.e., Baiyu, Ziwuling, Huashan, Zhongnan, Shouyang, Taibai, Daba, and Hualong), nine river systems (i.e., Kuye, Wuding, Yanhe, Luohe, Jinghe, Weihe, Jialingjiang, Hanjiang, and Dan-jiang) in the Shaanxi Province should also be an important reference when formulating optimization strategies. Therefore, we propose three ecological corridor construction and restoration projects that could be set up in the Shaanxi Province (Figure 10).

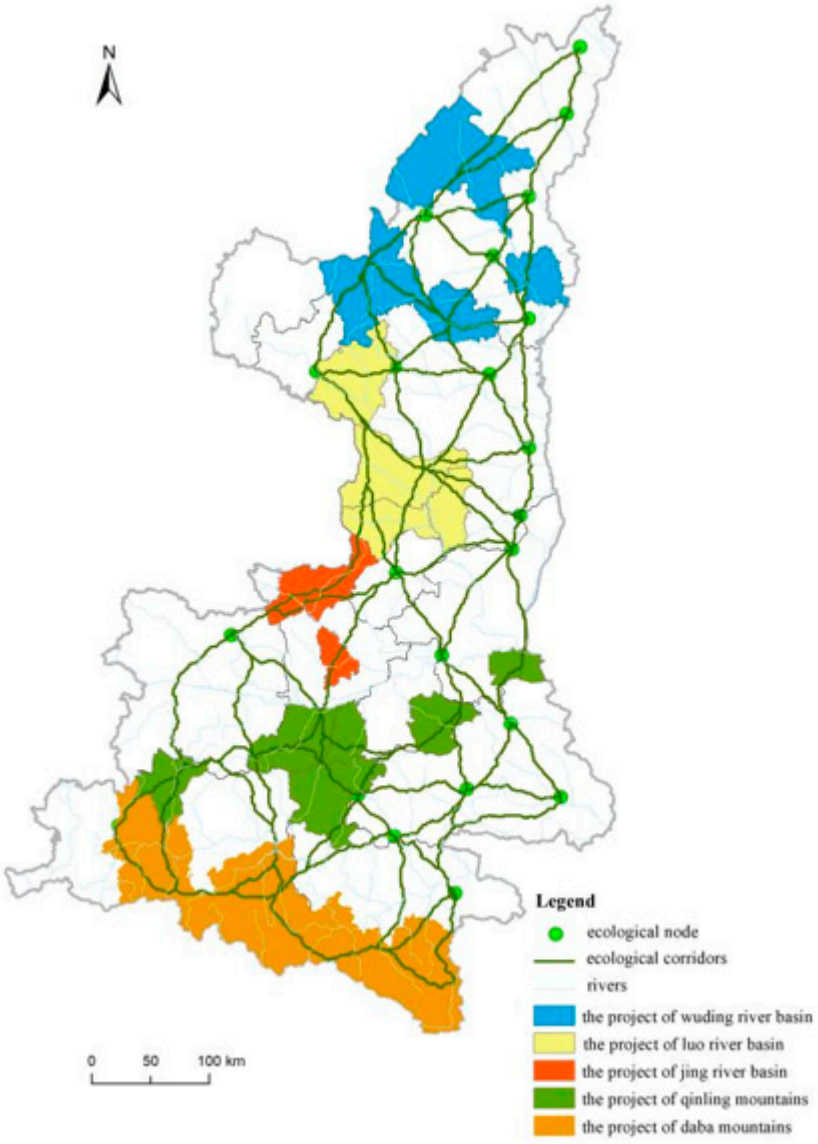



**Figure 10.** Scope of the ecological corridor construction and restoration projects in the Shaanxi Province.

First, the ecological corridor construction and restoration project in the main river course of the Yellow River Basin should be implemented in the Wuding, Luohe, and Jinghe River Basins. The proposed restoration of ecological corridors mainly focuses on the Suide County, Fuxian County, Weibin District, Linwei District, Wugong County, Xingping City, and Binzhou City, while the protection of ecological corridors is mainly concentrated in the Zhidan County and Zichang City. The main task here is to build the Yellow River's green landscape corridors and ecological isolation belts. Local conditions should be taken into account to select suitable native tree and grass species, and the ecological rules must be strictly followed to fulfill the ecological functions of landscape corridors. The primary strategy is continuously improving the green open space along the south and north banks of the Yellow River to form a continuous ecological landscape pattern on the basis of existing waterfront leisure functions.

Second, the ecological corridor construction and restoration project for biodiversity conservation of the Hanjiang River in the Daba Mountains should be implemented in southern Shaanxi. The proposed construction of ecological corridors is mainly concentrated in the Ziyang County and Zhenba County. Concerning the restoration of ecological corridors, the Hantai District, Mianxian County, Nanzheng District, and Xixiang County are the target areas. The protection of ecological corridors mainly focuses on the Zhenping County, Pingli County, and Langao County. This project's primary task is to fully strengthen the protection of unique species (such as pandas) and key habitats, build buffer zones and ecological corridors, and generally expand the living space for wildlife. The main strategy for realizing this is to restore the terrain along the course of the Hanjiang River to its prior state and restore or construct ecological corridors for the main stream of the Hanjiang River in the built-up areas.

Third, the ecological corridor construction and restoration project for biodiversity conservation in the Qinling Mountains would be implemented in the Qinling Mountains, Weihe River Basin, and Hanjiang River Basin. Tongguan County is the focus of the ecological corridors' construction, while the restoration of ecological corridors is mainly concentrated in the Ningshan County, Liuba County, Lantian County, Huayin City, and Huyi District. The protection of ecological corridors mainly targets Zhouzhi County. The primary task is to comprehensively strengthen habitat conservation and restoration for rare and endangered species (such as pandas, golden monkeys, and the crested ibis), and to expand the living space for wildlife. The main strategy relies on two approaches: (1) setting up different types of ecological corridors in areas subject to serious human interference, based on the nature-imitating channel construction technology; and (2) building a habitat conservation system with a reasonable layout, diverse corridor types, and complete functions. Further, biodiversity conservation networks should be established to strengthen the ecological security barrier of the Qinling Mountains.

## 5. Conclusions

Based on multi-source datasets and ecological security pattern theory, the important ecological structure elements of the Shaanxi Province were identified. We found 67,457 $km^2$ of ecological sources in the Shaanxi Province (32.8% of its total land area) in terms of ecological service importance and ecological environment sensitivity. In addition, a total of 32 ecological nodes were obtained at the center of important ecological sources and 72 ecological corridors were also found, spanning multiple county-level units from south to north. These ecological sources, nodes, and corridors constitute the ecological security pattern of "two barriers, three belts, and multiple corridors" in Shaanxi Province, which enables the continuation of ecological functionality and connectivity of landscape patches on a regional scale and ensures the conservation of the ecological environment as well as biodiversity.

By identifying the conflicts between human activities and ecological security pattern, we propose building a robust ecological security pattern characterized by "two barriers, three belts, and multiple corridors" for the Shaanxi Province. In order to alleviate the con-

tradiction between socio-economic development and ecological protection, we put forward the following suggestions for ecological restoration planning in Shaanxi. (1) Supplementing the ecological sources along the Great Wall in northern Shaanxi and improving the area and connectivity of that ecological land. (2) Protecting forest land resources in the Ziwuling area and improving the support function of ecological corridors for biodiversity conservation there. (3) Resolving the blockage of ecological corridors by urban agglomeration in the Guanzhong Plain; serially connecting urban green spaces, water bodies, and parks via road green belts and urban green roads; and enhancing their connectivity with existing ecological corridors. (4) Improving the quality and increasing the width of ecological corridors in the Qinba Mountains, and jointly building a network of ecological corridors linking the "mountains–waters–forests–cities" in the Shaanxi Province.

Limited by effective data and methods, this paper has only undertaken a preliminary analysis of the combination of ecological corridors and cultural corridors, and proposed the construction directions of integrated ecological and cultural corridors in different regions. However, the question of how to balance the relationship between the protection and development of cultural corridors and ecological corridors is still worth further consideration. It is necessary to combine more detailed historical data and investigate the subjective wishes of residents along the cultural corridors, so as to put forward a more feasible cultural–ecological corridor construction scheme. Moreover, in the follow-up research, we would like to make further optimizations of the ecological security pattern in the Shaanxi Province by depicting the width of ecological corridors, as well as by extracting ecological pinch points and ecological disturbances.

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