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Ecological Security Evaluation System Integrated with Circuit Theory for Regional Ecological Security Pattern Construction: A Coordinated Study of Chang-Zhu-Tan Metropolitan Area in China

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Abstract: Rapid urbanization and land use changes have brought enormous pressure onto the ecological environment. Constructing ecological security patterns (ESPs) contributes to scientifically utilizing ecosystem functions, maintaining biodiversity, and protecting the ecological environment. Thus, this study proposed a regional ESP construction framework, which integrated circuit theory with an ecological security evaluation system composed of a landscape connectivity analysis, an ecosystem service evaluation, and an ecological sensitivity analysis, to generate the ESP of the national-level Chang-Zhu-Tan Metropolitan Area (CZTMA). The results showed that (1) there were 22 ecological sources mainly consisting of woodlands, grasslands, and water bodies and distributed heterogeneously from the eastern to western CZTMA; (2) 48 ecological corridors connected the large-scale ecological patches such as rivers, lakes, wetlands, and woodlands in the CZTMA, and the average distance of the east side was shorter, while the distance of the west side was longer; and (3) 13 ecological pinch nodes and 28 ecological barrier nodes were identified as important nodes. On this basis, this research constructed a multi-level ESP consisting of "one center and multiple cores, one belt and two screens, multiple corridors and multiple nodes" for the CTZMA, which not only guarantees the stability of ecosystems but also maintains their efficiency in providing ecological services and their resistance to the pressure of human activities. Moreover, a series of specific recommendations for the optimization of regional ESPs were provided, including protection of ecological sources and enhancement of their habitat quality, improvement of ecological corridor connectivity, maintenance of pinch nodes, and restoration of barrier nodes. Coordinated mechanisms at the provincial level were proposed. This study could help with ecological conservation and restoration, and strategic planning making in integrated nature–human systems that cross administrative boundaries.

Keywords: ecological security evaluation; ecological security pattern; circuit theory; metropolitan area

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1. Introduction

Rapid urbanization processes and intensive human activities have brought great pressure onto urban and regional ecosystems. The ecological environment is deteriorating

and experiencing severe problems like habitat fragmentation and loss of biodiversity [1–4]. Thus, ecological security gradually became a hot theme of sustainable development of human society and global ecosystem research in the early 1980s. In the 1990s, the concept and construction of an ecological security pattern (ESP) gained widespread attention as an effective way of scientifically regulating ecological processes [5] and enhancing human well-being [6,7]. Models, methods, and tools for its construction have been continuously improved.

The construction of ESPs aims at identifying crucial ecological elements in ecological processes, which could be used for ecological restoration and rehabilitation [5]. The core content for regional ESP construction usually includes extracting ecological sources, constructing resistance surfaces, and identifying key corridors [8–10]. Land use functions like nature reserves, forest parks, scenic spots, or land use patches with a large area of woodlands or water bodies are qualitatively selected as ecological sources due to their ecological attributes [11,12]. Many researchers have adopted Morphological Spatial Pattern Analysis (MSPA), which focuses on structural correlations, to extract ecological sources in recent years [13,14]. At the same time, the InVEST model was proposed and has been widely utilized [15,16]. Some scholars have also synthesized multiple methods and constructed a comprehensive indicator system from multiple perspectives [17–19]. For example, source areas were identified by simultaneously considering the risk of ecological degradation and the significance of ecological function in areas of rapid urbanization [1]. Li and others constructed an analytical framework from three aspects: the importance of ecosystem services, eco-sensitivity, and landscape connectivity, providing necessary references for identifying sources in this study [20]. Resistance surfaces are generally constructed by weighting various landscape types [21]. However, it is difficult to finely reflect the heterogeneous resistance surfaces under various land use patterns because of diverse land use and complex ecological processes. Therefore, some scholars constructed resistance surfaces by integrating natural and anthropogenic factors [18,22]. General theories and methods for ecological corridor extraction mainly include circuit theory [14,23], graph theory [24], and the minimum cumulative resistance model [25–27], which make the construction of ecological networks more scientific and intelligent. Among them, circuit theory is widely used because it has advantages in quantifying movements in corridor systems by taking the redundancy of networks into account.

Along with the expansion of large cities, metropolitan areas have become the main carriers of regional urbanization, human activities, and socio-economic development. Moreover, metropolitan areas are also the most suitable scale for optimizing the territorial spatial pattern and coordinating regional development according to the guiding opinions issued by the Chinese government in 2019. Land use changes caused by rapid urbanization and industrialization and their negative environmental effects in metropolitan areas have posed lots of challenges to the sustainable spatial development of ecosystems. Current research on the construction of ESPs has been focused on different levels of undivided administrative regions [15,28], and important ecological function areas [5,7,16]. However, the construction of ESPs in metropolitan areas by considering the surrounding ecological environment as integrated nature–human systems are few. Moreover, more attention should be paid to the conflicts between ecological areas and construction space [29].

Accordingly, this research selected the Chang-Zhu-Tan Metropolitan Area (CZTMA), located within Hunan province in south-central China, as the coordinated research area. Some studies selected indicators to quantitatively evaluate the ecological network or ecological quality of this region, to reveal its evolutionary characteristics, and to explore the linkages between specific factors and it [30,31]. In addition, Deng et al. integrated the ESP construction into the PLUS model to simulate the ecological security-oriented

land use change under four scenarios in the CZTMA [32]. The factors and methods adopted in the above studies for the construction of ESPs were relatively homogenous due to the different research focuses of the studies. In this study, an integrated evaluation framework by integrating an ecological security evaluation (ESE) system with circuit theory was proposed for regional ESP construction and optimization, which could be used to guide ecological network construction and collaborative ecological and environmental governance in metropolitan areas. The contributions of this research are three-fold. First of all, the ESE system was built to ensure that the selected ecological sources could not only favor the stability of the natural ecosystem but also maintain their efficiency in providing ecological services and their resistance to disturbance under the pressure of human activities. Additionally, circuit theory was adopted to explore the distribution of corridors and nodes to further estimate the importance of relevant ecological elements. Last but not least, the coordinated mechanisms for regional ecological environment governance, as an important means to effectively implement the research results of ESPs in areas that cross administrative boundaries, have received much attention in our research.

2. Study Area and Materials

2.1. Research Area

The CZTMA is located in the eastern Hunan Province of south-central China, which is formed by three large cities of Changsha, Zhuzhou, and Xiangtan with 19 county-level administrative units (Figure 1). According to the seventh national census data, this study area covers approximately 18,900 km^2 and is highly urbanized, with a permanent population of 14.68 million, occupying 22.1% of the province's population with just 8.9% of the province's territorial area.

This area has large ecological barriers, with the Xuefeng–Wuling Mountain Range on the west and the Luoxiao–Mufu Mountain Range on the east, as well as a complex network of water systems. The strategy plan of the CZTMA was officially approved by the Chinese government in 2022, which made this area the fourth national-level metropolitan area and the first one in central China. The CZTMA is rich in ecological resources, will be playing an important role in supporting regional development, and has urgent needs with regard to ecological environment protection and management.

2.2. Materials

The data used in this area and its sources are as follows: (1) Land cover data in 2020 were obtained from the National Center for Basic Geographic Information (https://www.ngcc.cn/, accessed on 3 August 2021). (2) Digital Elevation Model (DEM) data were obtained from the ASTER GDEM digital elevation dataset of the geospatial data cloud platform (https://www.gscloud.cn/, accessed on 15 September 2023). Slope data could be generated from these DEM data. (3) Vector data including railroad and highway network, administrative district boundaries, natural protected area boundaries, and forest park boundaries were sourced from the National Geographic Information Resource Catalog Service System (https://www.webmap.cn/main.do?method=index, accessed on 15 September 2023). (4) Normalized difference vegetation index (NVDI) data, and evaporation and precipitation data were derived from the Resource and Environmental Science and Data Center (RESDC) (http://www.resdc.cn/, accessed on 15 July 2024). (5) Soil information was derived from the National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn/home, accessed on 15 July 2024). All the above datasets were projected onto a unified reference system and resampled to the same spatial resolution for spatial calculations and analysis.

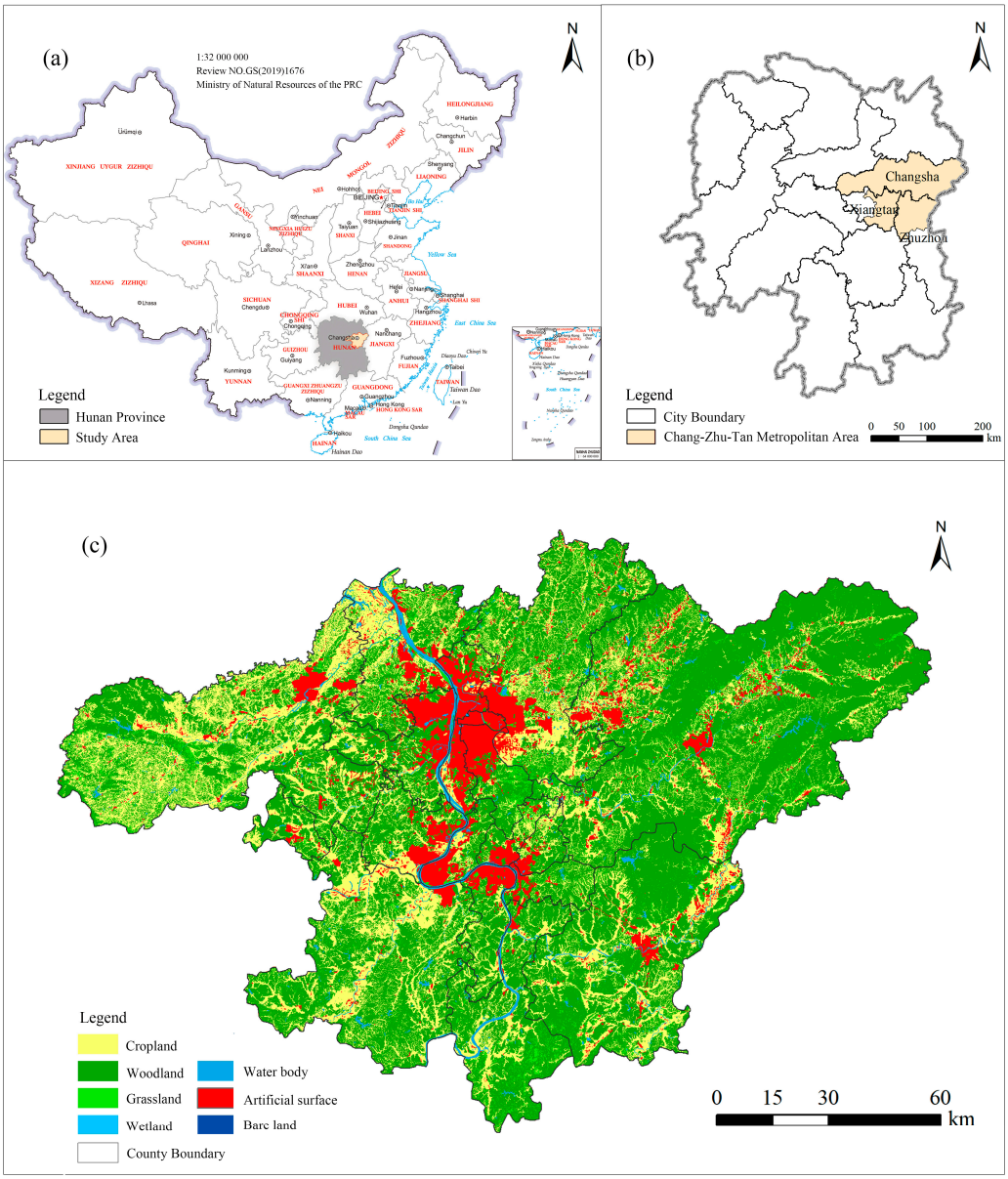


Figure 1. Geographical location and land cover type of the research area. (**a**) Location of Hunan province; (**b**) location of the CZTMA in Hunan province; (**c**) land cover types of the CZTMA in 2020.

3. Methodology

The following Figure 2 illustrates the technical route of the research. Firstly, an ESE system composed of a landscape connectivity analysis, an ecosystem service evaluation, and an ecological sensitivity analysis was proposed for extracting ecological sources in the CZTMA. Secondly, principle natural and social factors were weighted to generate resistance surface. Thirdly, ecological corridors were recognized based on circuit theory. Through an evaluation of the cumulative current density map, the importance levels of the sources and corridors were classified, and ecological pinch nodes and barrier nodes were further identified. Lastly, the regional ESP of the CZTMA was systematically built according to the extracted ecological elements, and corresponding ecological restoration and planning strategies were proposed.

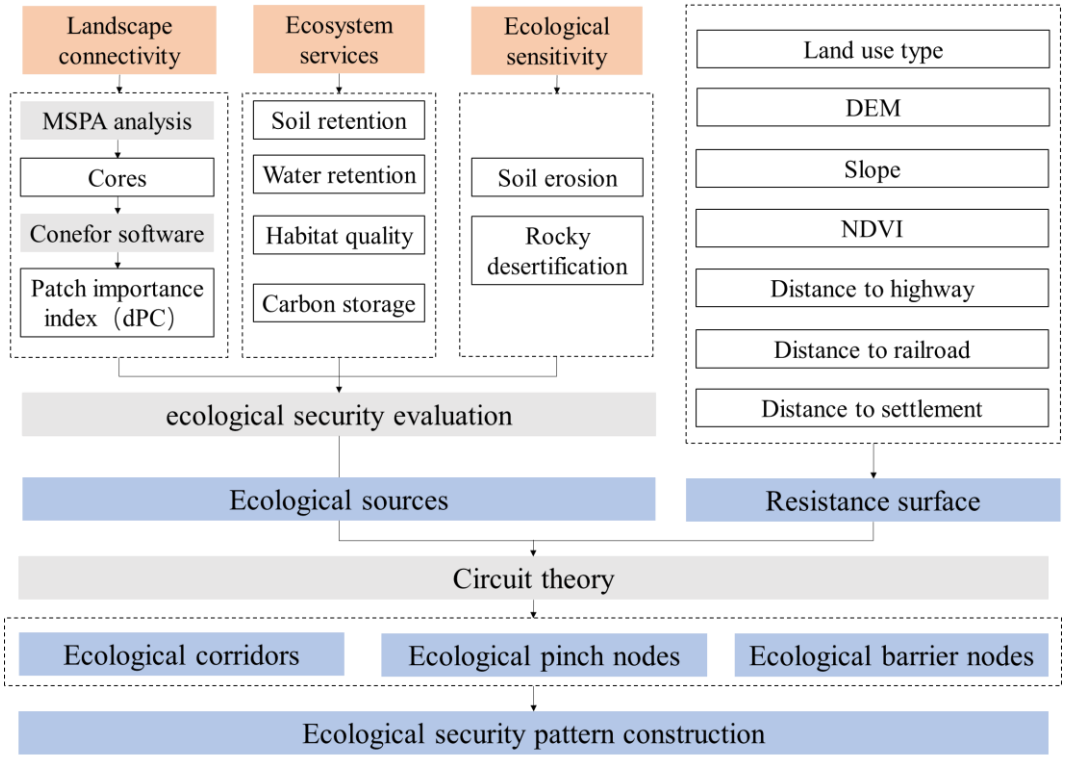


Figure 2. Technical route of the study.

3.1. Identification of Ecological Sources

Ecological sources are patches with good habitat quality, strong ecological functions, and high ecological service value, which play decisive roles in regional ecological processes and biodiversity conservation [15]. Ecological sources were extracted based on the ESE system composed of landscape connectivity, ecosystem service, and eco-sensitivity in this study [20]. The weights of each layer and factor were assigned by the Delphi method and the Analytic Hierarchy Process (AHP). Judgment matrices based on the indicator system were established at first. Eight experts in urban and rural planning, landscape architecture, and land resource management were invited to compare and score the importance of indicators and factors. After geometrically averaging the scores of the experts, AHP was used for analysis. The CR values were all less than 1, indicating that the results have passed the consistency test. The ESE index system and weights are demonstrated in Table 1.

Table 1. Layers and weights of the proposed ESE system.

Layer	Weight	Factor	Weight
Landscape connectivity	0.27	Landscape connectivity	0.27
Ecosystem service importance	0.43	Habitat quality	0.13
		Soil retention	0.08
		Carbon sequestration	0.11
		Water retention	0.11
Ecological sensitivity	0.30	Soil erosion	0.16
		Rocky desertification	0.14

3.1.1. Landscape Connectivity Analysis

MSPA is generally used to extract landscape types that are morphologically and functionally connected at the level of image elements [33]. Landscape connectivity analysis quantifies circulation degrees of ecological elements among different land use patches [34]. Land cover data were transformed to a binary raster image, in which the woodlands,

grasslands, shrublands, wetlands, and water bodies were set as the foreground layer, and the remaining land use types were the background layer. MSPA was carried out on the Guidos Toolbox 3.3 platform, and seven landscape classes were generated, of which cores are large natural patches with high connectivity and were extracted for subsequent landscape connectivity analysis.

The overall connectivity index (*IIC*) and probable connectivity index (*PC*) of the cores were calculated in Conefor 2.6 software [35]. The importance index (*dPC*) for every single patch was determined by the decrease in *IIC* when a patch was destroyed [36]. The three indexes were calculated as follows:

$$IIC = \frac{\sum_{x=1}^{n}\sum_{y=1}^{n}\frac{a_x a_y}{1+nl_{xy}}}{A_L^2}$$

$$PC = \frac{\sum_{x=1}^{n}\sum_{y=1}^{n}P_{xy}^{*}a_x a_y}{A_L^2}$$

$$dPC = \frac{PC - PC_{remove}}{PC} \times 100\%$$

where n is the sum of patches; $x \neq y$; a_x and a_y denote the area of patches x and y, respectively; nl_{xy} denotes the sum of links between patches x and y; A_L is the total area of landscape; and P_{xy}^{*} represents the probability that a species spreads between patches x and y. The values of both *IIC* and *PC* range from 0 to 1. A larger value means better connectivity. PC_{remove} indicates the overall connectivity index of remaining patches after the detachment of one, and *dPC* measures the significance of each patch by a change in *PC*.

3.1.2. Ecosystem Service Evaluation

Ecosystem services are regarded as profits that human societies can obtain from ecosystems, such as food, water, climate regulation, disaster control, and cultural services [3,4,37], which depend on the prevention and provision of ecosystems [1]. Land use types in the CTZMA are dominated by woodlands (57.3% in 2020), with rich landscape resources and good ecological background conditions. However, under the pressure of urban expansion, ecological land use has decreased and habitat fragmentation has increased in recent years [30]. Considering the land use characteristics and ecological conditions of the region, also referring to existing research [29,36,38,39], the ecological service functions of habitat quality, soil retention, carbon sequestration, and water retention were measured by combining with the InVEST model. The related results would be weighted and overlayed to obtain a comprehensive ecosystem service evaluation after normalization.

(1) Habitat quality

Habitat quality can be recognized as a continuous variable that is positively correlated with the resources provided for human survival [40]. In general, habitat quality is higher when it is less affected by human disturbance, i.e., when it is farther away from human land use [41]. It was computed by the Habitat Quality analysis panel embedded in the InVEST 3.14.2 software with the following formula:

$$Q_{nj} = H_j\left(1 - \frac{D_{nj}^2}{D_{nj}^2 + k^2}\right)$$

where Q_{nj} represents the habitat quality of cell n in land cover type j; k denotes the semi-saturation parameter; H_j represents the ecosystem suitability of j; and D_{nj} is the ecosystem degradation degree of cell n in land cover type j.

This study considered railroads, highways, artificial surfaces, croplands, and bare grounds as threat elements, while other land use types in land cover data as ecosystems. The settings of relevant parameters referred to InVEST 3.14.2 User's Guide and the related literature [39].

(2) Soil retention

Soil retention was computed by the Revised Universal Soil Loss Equation [42,43]. With the help of the Soil Delivery Ration (SDR) analysis panel, embedded in the InVEST 3.14.2, total potential soil erosion and total actual soil erosion were measured respectively, and substituted into the following equation for calculation:

$$A_c = A_P - A_r = R \times K \times LS \times (1 - C \times P)$$

where A_c means soil retention; A_P and A_r refer to the total amount of potential and actual soil erosion, respectively; R is the rainfall erosion factor; K indicates the soil erodibility factor; LS indicates the topographic factor; C indicates the vegetation cover and management factor; and P is the soil and water retention factor.

(3) Carbon sequestration

Carbon sequestration refers to approaches of increasing the carbon content of carbon pools other than the atmosphere, which helps maintain the balance of carbon dioxide, reduce the greenhouse effect, and protect biodiversity. Carbon sequestration was estimated with the following formula:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$$

where C_{total} indicates the total amount of carbon sequestration; C_{above} is the carbon sequestration over ground; C_{below} is the carbon sequestration below ground; C_{soil} is the carbon sequestration of the soil; and C_{dead} is the carbon sequestration of dead organic matter. Carbon densities of each pool were set by referring to an existing study [44].

(4) Water retention

Water retention indicates the ecosystem's ability to intercept, infiltrate, and store precipitation, which is mainly manifested in moderating surface runoff, replenishing groundwater, stagnating floods and supplementing water during the dry season, and ensuring water quality. The Annual Water Yield (AWY) analysis panel in the InVEST 3.14.2 was applied to compute the water yield and subtract the corresponding surface runoff; water retention can be calculated as follows:

$$Y_n = \left(1 - \frac{AET_n}{P_n}\right) \times P_n$$

$$WR_n = Y_n - P_n \times C_j$$

where Y_n indicates the annual water yield of cell n; AET_n is the annual evapotranspiration; P_n indicates the annual precipitation; WR_n represents the water retention; and C_j represents the surface runoff coefficient of land cover type j.

3.1.3. Ecological Sensitivity Analysis

Ecological sensitivity indicates the adaptive capacity of ecosystems to external pressures or disturbances and the recovery capacity when damaged [45]. Highly sensitive regions that are hard to recover can be figured out through targeted assessment. According to the "Guidelines for Delineation of Ecological Protection Red lines" issued by the national ministries and commissions of China, soil erosion and desertification were selected for

ecological sensitivity assessment taking the topography, geomorphology, and geological disasters of the CZTMA into account. The calculation methods are displayed below:

$$SS_i = \sqrt[4]{R_i \times K_i \times LS_i \times C_i}$$

where SS_i denotes the soil erosion sensitivity of assessment area i; R_i denotes the rainfall erosivity factor; K_i denotes the soil erodibility factor; LS_i is the terrain relief amplitude; and C_i represents the surface vegetation coverage.

$$S_i = \sqrt[3]{D_i \times P_i \times C_i}$$

where S_i is the sensitivity index of rocky desertification in assessment area i and D_i, P_i, and C_i indicate the sensitivity classifications of ecosystem type, topographic slope, and vegetation cover in assessment area i, respectively.

Then, the above results were normalized and superimposed to obtain a comprehensive result of ecological sensitivity, which was ranked into five levels by the natural breakpoint method (NBM).

3.2. Construction of Resistance Surface

Ecological flows between each ecological source are affected by ecological resistance [33], which is required for determining ecological corridors. Ecological resistance is usually calculated by key factors such as land use type, DEM, NDVI, and so on. Moreover, human activities could cause much disturbance to the ecosystem [46,47]. The smaller the value of ecological resistance, the easier for creatures to pass. Referring to existing studies [39,48,49], the following factors were chosen to assess the resistance of each grid cell. The weights of each factor were assigned by the AHP (Table 2).

Table 2. Classification and weights of ecological resistance factors.

Factors	Resistance Value					Weights
	1	2	3	4	5	
Land cover type	Woodland, Water body and wetland	Grassland	Cropland	Bare ground	Artificial surface	0.30
DEM	<100	100~400	400~800	800~1200	>1200	0.13
Slope (°)	<5	5~15	15~20	20~30	>30	0.15
NDVI	0.84~0.90	0.76~0.84	0.65~0.76	0.50~0.65	0.16~0.50	0.18
Distance to highway (km)	>5	3.5~5.0	2.0~3.5	0.5~2.0	<0.5	0.06
Distance to railroad (km)	>10	5~10	3~5	1~3	<1	0.06
Distance to settlement (km)	>3	2.0~3.0	1.0~2.0	0.5~1.0	<0.5	0.12

3.3. Identification of Ecological Corridors and Nodes

Ecological corridors undertake many ecosystem services, for example, biodiversity conservation, pollutant filtration, and erosion control, which are important in maintaining ecological functions, sustaining ecological processes and energy flows, and preserving the regional pattern of ecological security [26]. Circuit theory has good performance in simulating the species' movements in heterogeneous environments on account of the random walk characteristics of electric charges through circuit links [50,51]. In this theory, species are considered electrons, while the resistance surface is considered a conductive surface. Landscapes that promote ecological processes have relatively low resistance, while

those that prevent ecological processes have relatively higher resistance. The equation for calculating is demonstrated below:

$$I = \frac{U}{R}$$

where I is the current; U denotes the voltage; and R represents the resistance. In this study, I is the net frequency of species movement; U reflects the net probability of biological migration from one ecological source to another; and R refers to the impedance encountered by biological migration in habitats. In this study, links with high current values will be selected as ecological corridors.

Ecological corridors and nodes were identified based on the Linkage Mapper 3.1.0 software and the Circuitscape 4.0.7 toolbox. The Linkage Pathway Tool was selected to model the least-cost path (LCP) and cost-weighted distance (CWD). Then, it was able to judge the connectivity performance of corridors according to the ratio of CWD to LCP. A smaller ratio indicates stronger connectivity between ecological sources [28,52]. Ecological corridors are categorized into three types in terms of their connectivity.

In addition, a number of strategic nodes are placed in ecological links, including ecological pinch nodes and barrier nodes [15]. Ecological pinch nodes are critical nodes in ecological processes with the highest cumulative current values [53]. The Pinchpoint Mapper tool in the Circuitscape 4.0.7 toolbox was applied to generate cumulative current value maps, which were categorized into three levels by NBM. The highest level was identified as ecological pinch nodes. Ecological barrier nodes are places where animals and energy flows are blocked from moving between ecological sources [54]. Ecological barrier nodes in corridors were extracted through the Barrier Mapper module in the Circuitscape 4.0.7 toolbox. The cumulative current recovery values were categorized into three levels, in which the highest level was identified as barrier nodes.

4. Results

4.1. Spatial Distribution Pattern of Ecological Sources

4.1.1. Spatial Distribution Pattern of Landscape Types and Connectivity

In this study, seven landscape types were finally obtained through MSPA, as shown in Figure 3a and Table 3. Among them, the cores of CZTMA are 5435.42 km^2, which are larger habitat patches in the foreground elements, and account for 44.59% of the whole territorial space. The majority of the cores are concentrated in the eastern and southern parts of the CZTMA, especially in the eastern JiuLing Mountain and Xianyu Ridge, where the woodland patches are densely distributed. The area of bridges occupies 28.9% of the foreground layer, indicating better connectivity between landscapes.

Table 3. Statistics of landscape type in the CZTMA.

Types	Core	Islet	Edge	Perforation	Bridge	Loop	Branch
Area (km^2)	5435.42	484.51	1381.21	98.40	3523.76	618.18	649.66
Percentage (%)	44.59	3.97	11.33	0.81	28.90	5.07	5.33

Since the cores varied greatly in size and had significant fragmentation characteristics, a total of 106 core area patches over 5 km^2 were further screened out to calculate landscape connectivity. Multiple simulation tests were conducted on the Conefor 2.6. When the connectivity threshold exceeded 5 km^2 and the connectivity probability was 0.5, the IIC and PC were stable enough. Then, the dPC of each patch was measured; meanwhile, the spatial distribution of landscape connectivity in the study area was acquired. It is shown in Figure 3b that connectivity over the medium level was usually located in the eastern half of the CZTMA divided by the Xiangjiang River, and the proportion of high and relatively

high connectivity areas was 8.9% and 5.5%, respectively. There were only a few small areas with medium-level connectivity distributed in the western half.

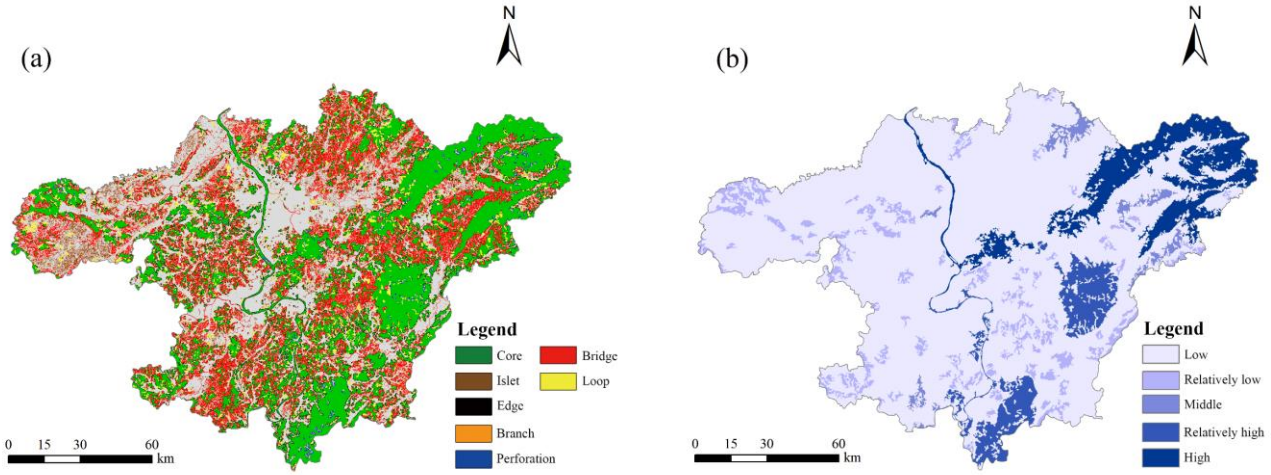


Figure 3. Distributions of landscape types and connectivity. (**a**) Landscape types; (**b**) landscape connectivity.

4.1.2. Spatial Distribution Pattern of Ecosystem Service Importance

The results of the four ecosystem services mentioned in Section 3.1.2 distributed heterogeneously in the CZTMA are shown in Figure 4. The ecosystem service distribution map was obtained by overlaying these four ecosystem service aspects (Figure 5). Overall, areas of high ecological service value were large areas of woodlands, which were distributed in the eastern and southern edges of the CZTMA, including the ridges located at the border of Liuyang City and Liling City, at the border of Lukou District and Liling City, and the mountain in the eastern part of Liuyang City. Moreover, woodlands were interspersed with agricultural lands, contributing to relatively high ecological service values, scattered in our research area. The ecological service of water bodies in this metropolitan area was generally low because of the small-scale water system formed by the tributaries of the Xiangjiang River, which is greatly disturbed by the built-up areas, roads, and railroads. Areas with the lowest ecosystem service were dominated by urban areas.

4.1.3. Spatial Distribution Pattern of Ecological Sensitivity

The spatial distribution patterns of ecological sensitivity are depicted in Figures 6 and 7. Five regions with different levels of sensitivity, from low to high, accounted for 27.62%, 35.01%, 21.68%, 11.95%, and 3.74% of the whole area in the CZTMA, respectively. The overall degree of ecological sensitivity of CZTMA was not high. The total proportion of high and relatively highly sensitive areas was only 15.68%, which was distributed on the easternmost and westernmost sides of this metropolitan area, and the land cover types were primarily woodlands and grasslands. These areas had larger terrain slopes and lower vegetation coverage and were prone to soil erosion and rocky desertification. The proportion of low and relatively low sensitive areas was close to 62.63%, usually spread in the western part of this area, for example, Ningxiang City, Xiangtan County, Lukou District, and Wangcheng District. The land cover types were mostly croplands, followed by woodlands.

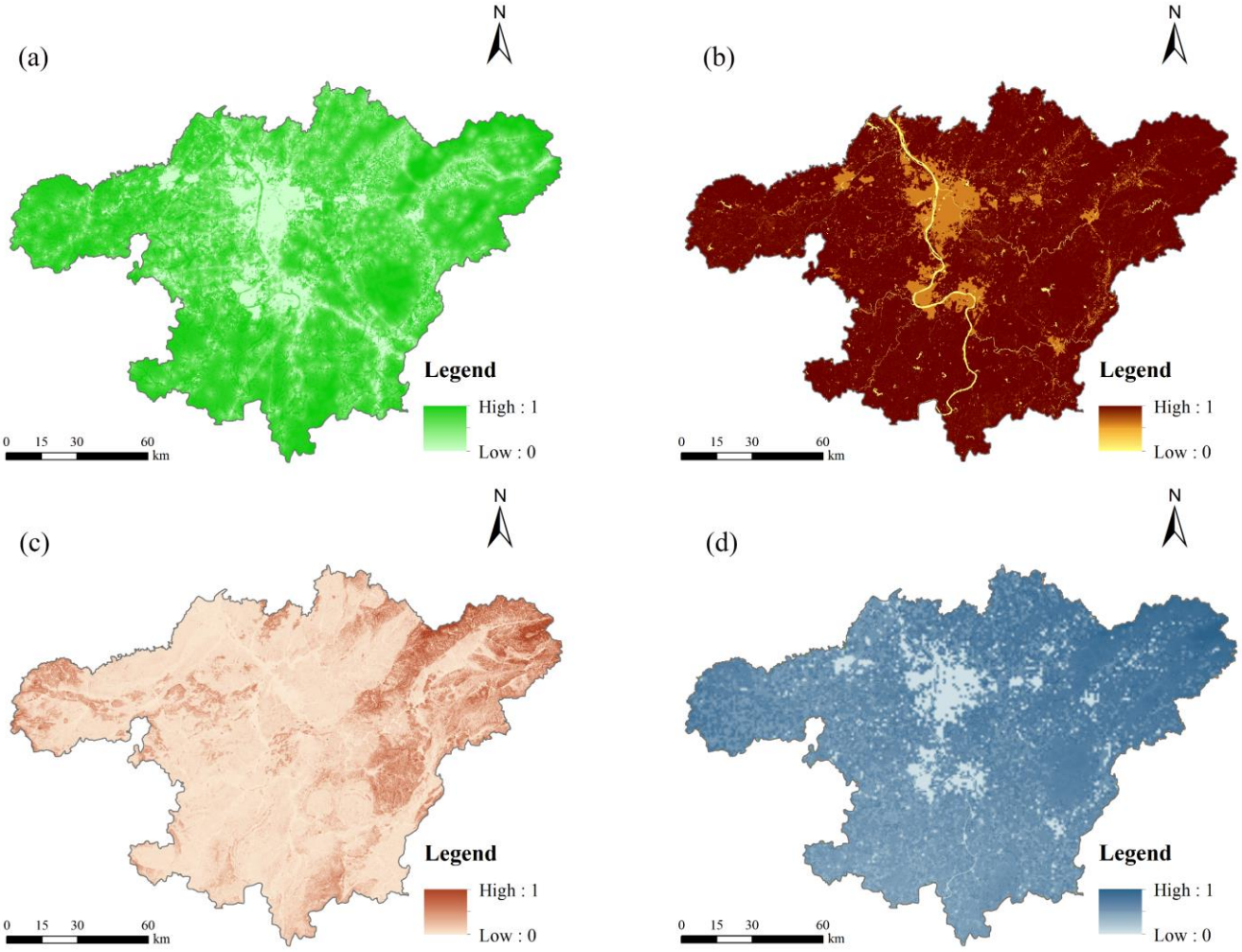


Figure 4. Evaluation results of ecosystem service importance. (**a**) Habitat quality; (**b**) carbon sequestration; (**c**) soil retention; (**d**) water retention.

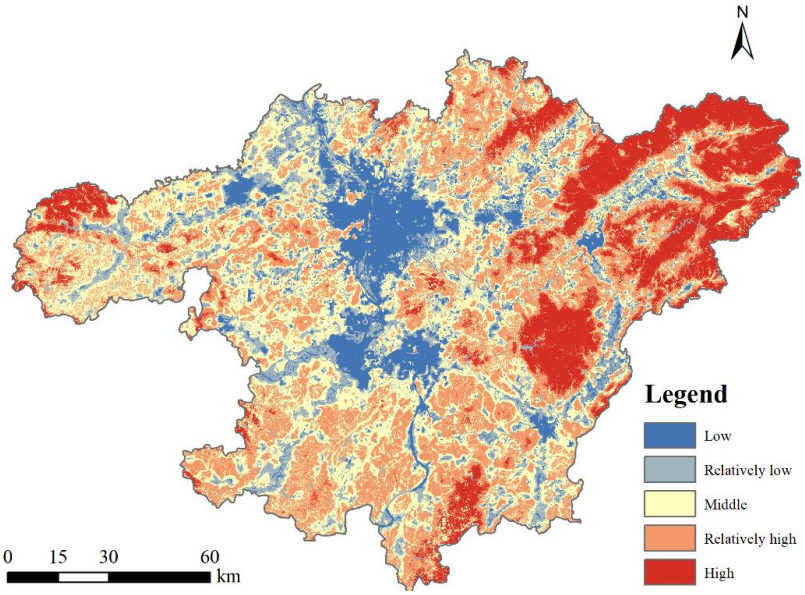


Figure 5. Comprehensive result of ecosystem service importance.

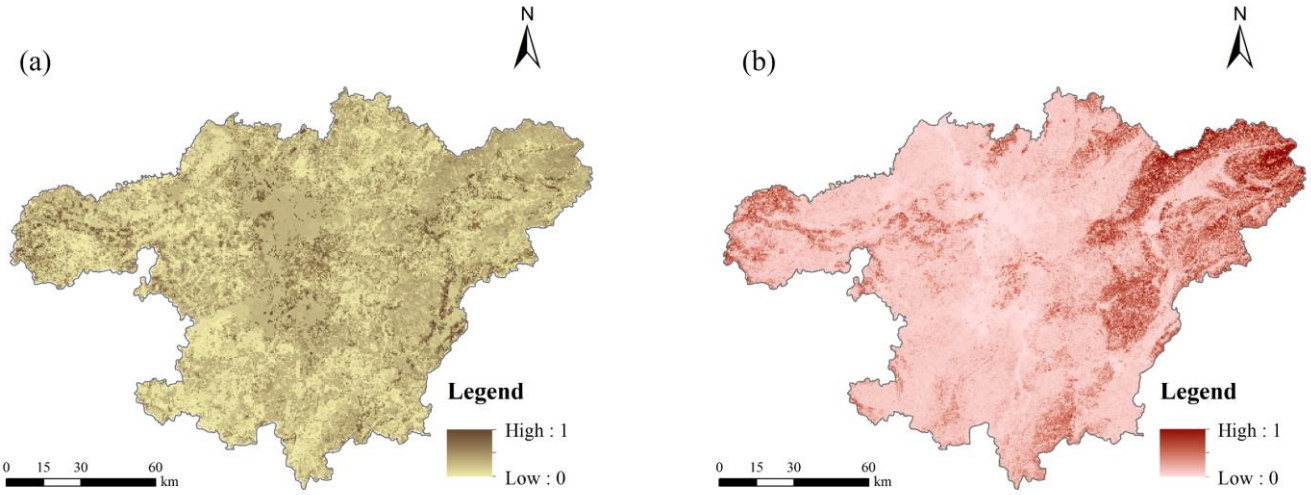


Figure 6. Results of ecological sensitivity. (**a**) Soil erosion; (**b**) rocky desertification.

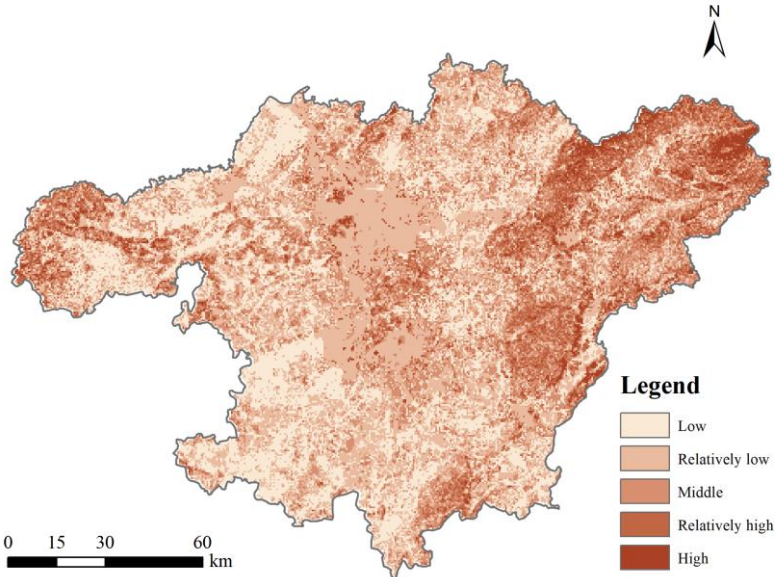


Figure 7. Comprehensive result of ecological sensitivity.

4.1.4. Comprehensive Result of ESE and Spatial Distribution of Ecological Sources

The result of the ESE was obtained after weighting and overlaying the above results of the landscape connectivity analysis, ecosystem service evaluation, and ecological sensitivity analysis (Figure 8). The areas with high and relatively high ecological security values were concentrated in the easternmost part of the area, which largely overlaps with the Mountain Range. The low and relatively low ecological security zones occupied 83.92% of the total area. Furthermore, 22 areas larger than 5 km^2 in the highest three levels were identified as the results of the sources (Figure 9). Compared with the list of nature reserves and forest parks above the provincial level within this metropolitan area, it was found that these ecological sources included Dawei Mountain Nature Reserve, Lion Mountain Forest Park, Zhaoshan Scenic and Historic Spot, Weishan Scenic and Historic Spot, and so on, which indicated that the method used for delineating the sources was feasible. The total area of extracted sources was about 2480.60 km^2, occupying 13.12% of the research area. The majority of land use types of the sources were woodlands, accounting for 95.24%. Other small amounts of land cover types were grasslands and water bodies. The ecological sources on the west side were concentrated in the northwest corner of Ningxiang City, which had small areas and sparse distribution, while the ecological sources on the east side

had large patches and dense distribution. The importance of ecological sources was ranked by the Centrality Mapper tool. Four of the top five were situated in the eastern and southern fringes of the CZTMA, concentrated in Liuyang City, Liling City, and Lukou District. There was another one situated in the geographic center of the CZTMA surrounded by urban areas of the three large cities, which is the ecological "green heart" to be jointly protected.

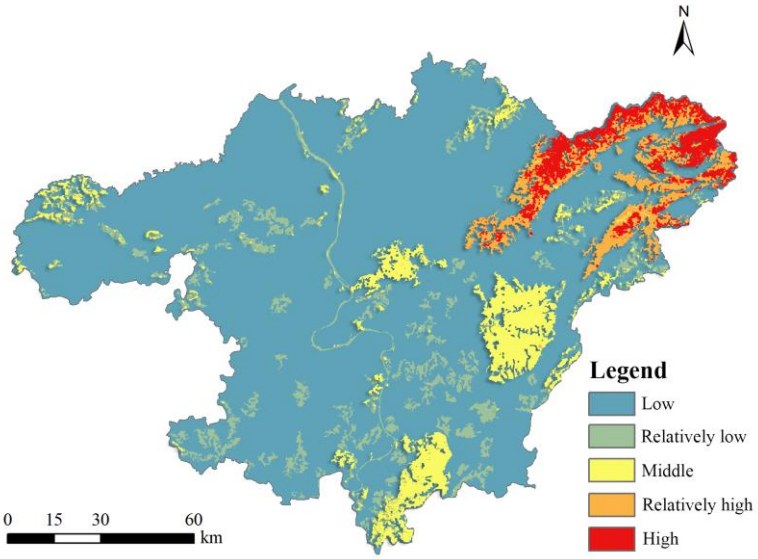


Figure 8. Result of the ecological security evaluation.

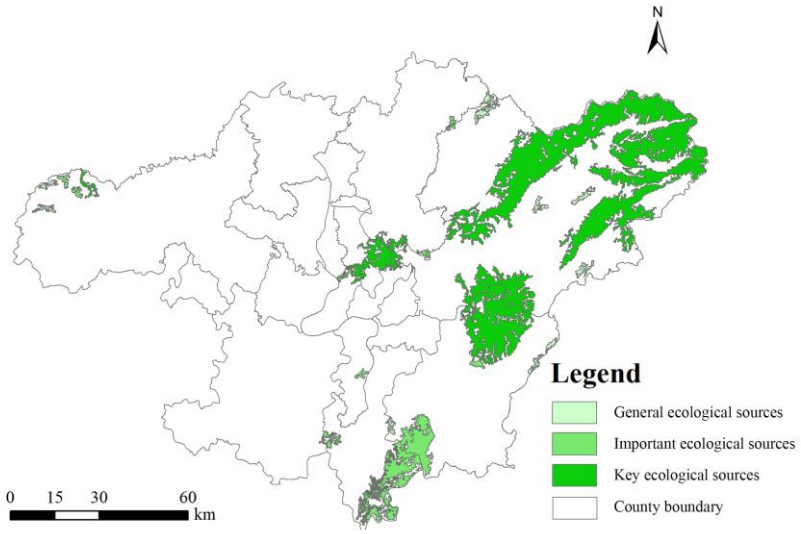


Figure 9. Distribution of ecological sources.

4.2. Resistance Surface and Spatial Pattern of Ecological Corridors

According to the method mentioned in Section 3.2, various natural and anthropogenic factors were superimposed to depict the resistance surface result of the CZTMA (Figure 10). The average value was 1.93, and the standard deviation was 0.65. High resistance values were concentrated on the urban built-up areas of Changsha, Zhuzhou, and Xiangtan, which were situated in the central part of the CZTMA. These three cities had frequent human activities in the built-up area and a well-connected transportation network, which easily disturbed the ecological processes. The low-resistance areas were mainly distributed in the east and south parts of the metropolitan area, including Liuyang City, Liling City, Lukou District, and Xiangtan City, which matched the geospatial distribution of ecological sources well.

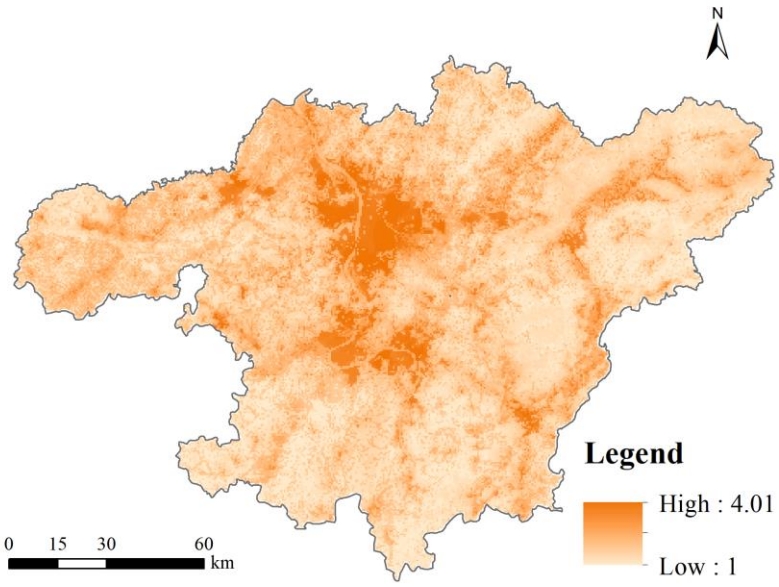


Figure 10. Resistance surface of the CZTMA.

There were 48 ecological corridors constructed by the Linkage Mapper tool, with a total length of 1270.36 km and an average length of 26.47 km (Figure 11). The longest one is 136.69 km, which is located in the northern metropolitan area, running east to west and connecting Weishan Mountain in Ningxiang City in the northwest with a small piece of ecological source area at the border of Changsha County and Liuyang City in the northeast. Overall, the corridors on the west side of the metropolitan area had a longer average distance, which were the crucial corridors for long-distance migration of species, while the ecological corridors on the east side had a shorter average distance, which connected ecological sources with relatively large scales and centralized distribution. The selected corridors were separated into different levels in terms of the ratio of CWD to LCP. Thirteen key ecological corridors of the greatest significance were scattered in the middle and in the eastern and western marginal areas of the CZTMA, which connected a few relatively fragmented sources with short distances in the northwestern, northeastern, and southern parts of the metropolitan area. Twenty-two important ecological corridors were identified, which mainly connected the large-scale sources with the ecological "green heart". Ecological corridors at the importance level had long distances on the northern and western sides. The remaining ecological corridors of general importance were distributed vertically and horizontally in the CZTMA.

4.3. Spatial Distribution of Ecological Nodes

After eliminating or merging the fine pinch nodes with an area of less than 0.5 km^2, 13 ecological pinch nodes in the CZTMA were extracted, with a total area of 265.25 km^2 (Figure 12). The land cover types of the ecological pinch nodes were mainly woodlands, croplands, and water bodies, occupying 64.6%, 27.2%, and 5.1% of the whole area of pinch nodes, respectively. Larger ecological pinch nodes were mainly distributed in ecological corridors in the northwest direction, for instance, from the central ecological "green heart" to the northwest edge of Weishan Mountain. Other pinch nodes with an area of more than 5 km^2 were located in the central and eastern parts of the CZTMA and distributed along the corridors connecting the ecological "green heart" with several large ecological sources in the east. Landscape resistance values around the ecological pinch nodes were high, indicating high risks of ecological degradation and negative impacts on the connectivity of the landscape system.

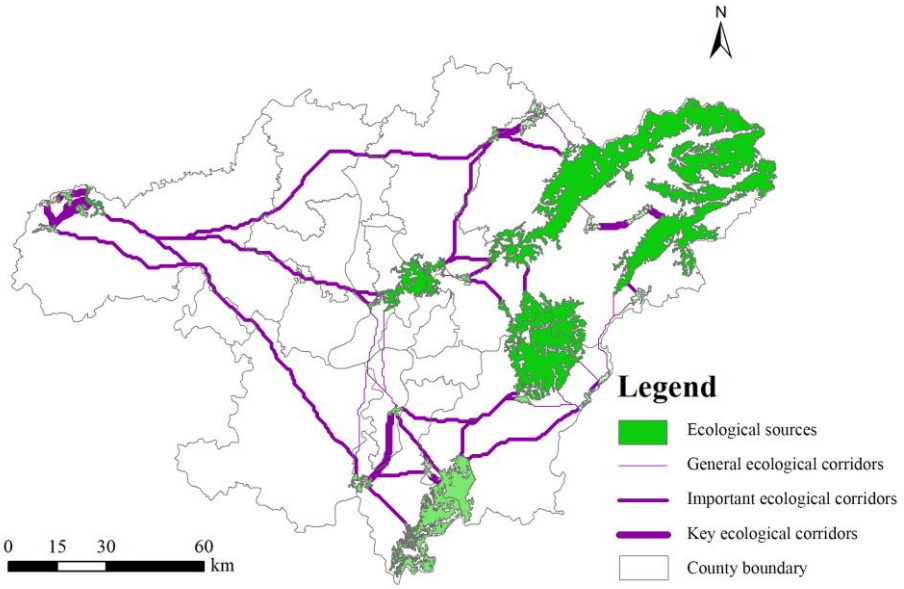


Figure 11. Distributions of ecological sources and corridors.

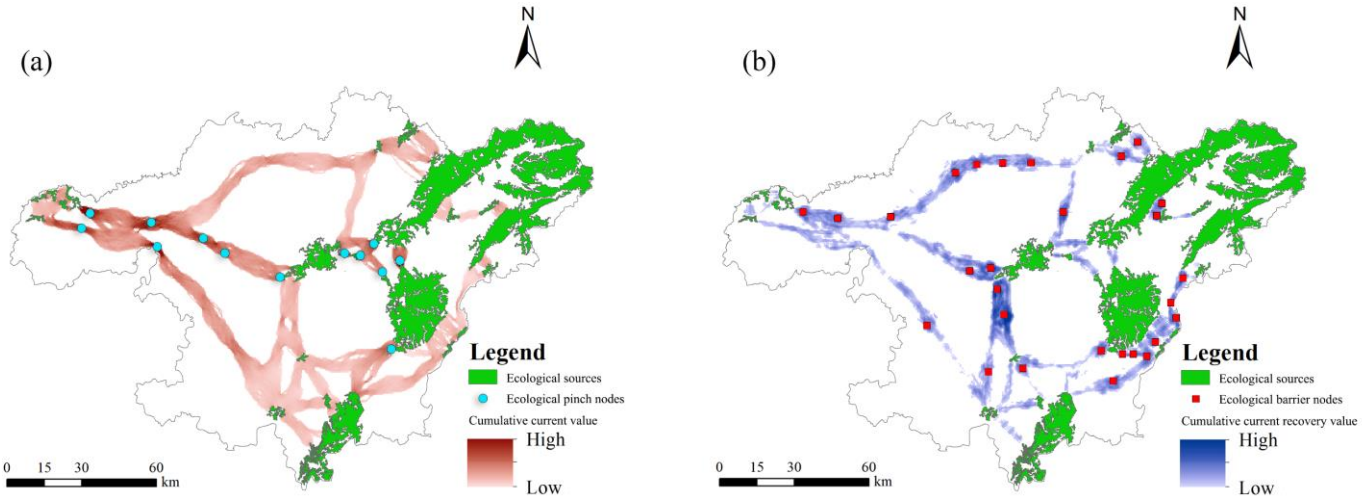


Figure 12. Distributions of ecological nodes. (**a**) Pinch nodes; (**b**) barrier nodes.

The ecological barrier nodes with high cumulative current recovery values were extracted to be prioritized for restoration (Figure 12). The larger the value is, the more beneficial from the restoration of the barrier nodes for improving and upgrading the ESP. After removing or merging the fragmented patches with an area less than 0.5 km^2, our study obtained 28 barrier nodes, with a total area of 235.75 km^2. They were relatively scattered and distributed in the Tianxin, Yuetang, and Tianyuan districts. The majority of land cover types were woodlands, croplands, and artificial surfaces, occupying 33.7%, 29.2%, and 27.8% of the whole area of barrier nodes. Among them, there were four barrier nodes with an area of more than 10 km^2, two of which were located at the junction of the construction sites of Changsha, Zhuzhou, and Xiangtan, and the other two were located in Wangcheng District and Changsha County. These areas had more serious ecological broken fragments, were affected by the urban construction land, and were nearly in a state of fracture. This study also found that a small number of barrier nodes overlap with ecological pinch nodes, such as the ecological obstacle near the Weishan Mountain in the northwest, which was the only biological corridor connecting ecological sources, and was in urgent need of ecological restoration.

4.4. Construction of ESP

The elements obtained above are the foundation of ESP construction. Thus, this study proposes to construct a regional ESP of "one center and multiple cores, one belt and two screens, multiple corridors and multiple nodes" for the CZTMA according to the identified ecological elements, and the natural geographic characteristics of the metropolitan area (Figure 13). "One center" refers to the ecological green center located at the intersection of the three largest cities in this metropolitan area. "Multiple cores" refers to the ecological cores formed by several important ecological sources. "One belt" is the ecological axis along the Xiangjiang River, which runs through the whole area from south to north. "Two screens" refers to the ecological barriers on the eastern and western sides, which are the Luoxiao–Mufu Mountains in the east and the Xuefeng–Wuling Mountains in the west. "Multi corridors" refers to the ecological corridors that are crisscrossed with ecological sources. "Multiple nodes" include 13 pinch nodes and 28 barrier nodes, which are the most crucial nodes for future ecological conservation and remediation in this metropolitan area.

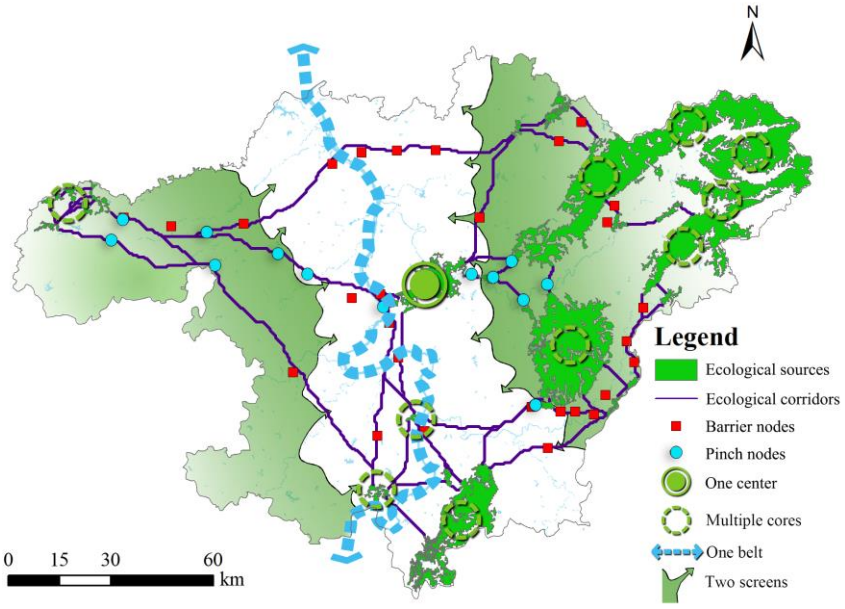


Figure 13. ESP of the CZTMA.

5. Discussion

5.1. The Rationality of ESP Construction

Since the concept of an ESP was proposed in 1996, after 30 years of development, the methodological basis of related research has become relatively mature, from empirical judgment to multi-indicator analysis and from a simple ecologically oriented goal to multi-objective balancing [55]. Scholars have also adopted various technical approaches for specific research objects and objectives. The research found that different area thresholds, evaluation indicators, and methods lead to significant differences in the quantity, location, and proportion of ecological elements. For example, in Deng et al.'s study on the CTZMA, 61 ecological sources were determined through MSPA and landscape connectivity analysis, almost completely including 22 ecological sources identified in our research. However, their percentage of the total study area significantly exceeded that of this study [32]. Additionally, based on the analysis of the results, some scholars have proposed using buffer zones to expand ecological sources [29,56]. In the study by Wang et al., ecosystem service evaluation, ecological sensitivity evaluation, and circuit theory were also used for this region, and the selected research scope was smaller than this study. The identified ecological sources, ecological corridors, and nodes also differed from those of this study [57]. Therefore, it

is particularly important to carefully consider developing a research plan based on the research objectives. Scholars generally believe that identifying various ecological elements in the construction of an ESP is essentially a process of balancing ecological conservation and socio-economic development [8,58], especially in rapidly urbanized areas with high human activity intensity. Excessive areas result in high ecological conservation costs and further limit the effective utilization of land resources [55]. However, a small area cannot achieve the basic goal of ecological security protection. It is necessary to comprehensively take the factors that affect ESE into account and give serious consideration to the ecological bottom line and ecological service value as much as possible, in order to seek more targeted and rational results.

5.2. Suggestions for Optimizing ESP

This study proposes the following ecological restoration and control recommendations for ESP optimization in the CZTMA:

(1) The protection of ecological sources needs to be strengthened, and their habitat quality needs to be gradually improved. For the ecological sources with a small scale and a high level of fragmentation in the western part, their quality should be maintained and improved. For instance, new ecological reserves should be expanded upon and built based on Weishan Mountain, Shaoshan Mountain, etc., to enhance the ecological extension of the sources. For the large-scale ecological sources formed by the penetration of the Luoxiao–Mufu mountain system in the east, targeted ecological remediation should be put into practice to fill the "holes", and the low-quality arable lands should be returned to forests. At the same time, key protection measures, including the sealing of mountains and forests, and the reduction in human activities, should be provided to promote the prosperity of the vegetation and to maintain the functions of water retention and soil retention. The central part of the metropolitan area is dominated by centralized construction areas of cities and towns, with few scattered ecological sources, which had less prominent ecological functions. It is appropriate to focus on strengthening the preservation of natural ecological resources in the urban periphery, promoting the construction of green ecological networks, intensifying the efforts of pollution prevention and control, safeguarding the ecological quality of cities and towns, and improving the human living environment. The ecological red line of the ecological source between the three cities, namely the "green heart" mentioned above, should be strictly controlled. For the ecologically fragile areas of the "green heart", the three cities should fully collaborate with each other to optimize the mechanism of coordinated diagnosis, treatment, and restoration of the ecological environment and actively implement the ecological restoration of abandoned mines, comprehensive improvement of water environment, construction of ecological flood storage and retention area, and so on.

(2) Restoration measures for ecological corridors are centered on improving corridor connectivity. For ecological corridors where ecological space has been partly occupied by human activities and normal ecological processes cannot be maintained simply by protection, restoration projects for ecological breakpoints should be carried out, and passages with low resistance value and high connectivity should be constructed gradually. By superimposing the ecological corridors with highways and railroad lines, we obtained 48 intersections with highway lines and 46 intersections with railroad lines (Figure 14). It is necessary to implement ecological restoration projects for ecological corridors blocked by human activities in a targeted way, such as constructing culverts, tunnels, and other facilities to connect them. Meanwhile, the alignments of high-level roads should minimize the blockage of ecological corridors. For corridors that are too long to take on the risk of vulnerability, it is necessary to add ecological steppingstones, to enhance greening along the way, so as to improve their resilience to risks. The Xiangjiang River and Yangtze River

tributary systems are weak in terms of habitat quality and water conservation. It is important to emphasize the roles of water bodies and wetlands in preserving regional ecosystem diversity and regulating hydrological processes. Blue lines for protecting water bodies should be established, and the management of river and lake shorelines needs to be reinforced. Wetland restoration and greening, sewage removal and interception, wastewater treatment, and other restoration measures for water bodies need to be carried out.

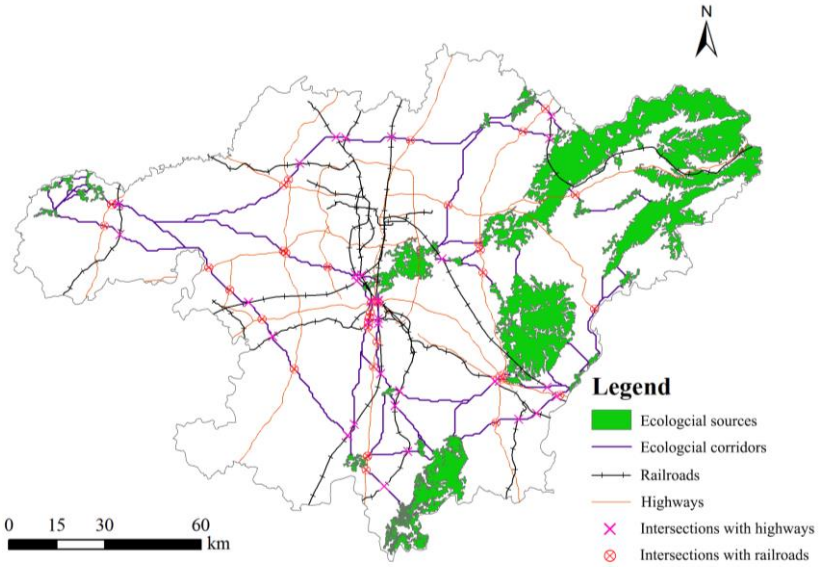


Figure 14. Intersections between ecological corridors and highways/railroads.

(3) The overall connectivity of the ecological network can be improved by maintaining ecological pinch nodes and restoring ecological barrier nodes. Pinch nodes are suggested to be restored naturally, with different natural conservation measures for various land cover types, for instance, the adoption of recreational crop rotation and on-site cultivation of fertilizers in arable land, the implementation of vegetation conservation in grasslands, the improvement of the forest manager system in woodlands, and the strict control of sewage discharges in watersheds, as well as the construction of vegetation protection belts. Ecological barrier nodes should try to prevent secondary damage to the ecosystem caused by the excessive intensity of human activities. Improvement measures for these sporadic barrier nodes mainly include vegetation cultivation and reduction in human activities to promote ecosystem self-repair and self-succession. Large barrier nodes adopt artificial restoration combined with natural conservation. Combined with the renovation of low utility land in the built-up areas of cities and counties and suburban areas, country parks, protective forests, and urban green corridors would be created.

5.3. Coordinated Mechanisms for Ecological Protection and Restoration

There are 19 county-level administrative units in the CZTMA with homogeneous and contradictory interests, which divides the whole ecosystem into different parts, and may indirectly lead to the loss of socio-economic and ecological benefits. Therefore, this study suggests establishing a coordinated mechanism at the provincial level, to strengthen the coordination and guidance of CZTMA development, improve the ability to coordinate the response to major ecological challenges, and minimize the unfair competition between different cities [32]. Firstly, a unified ecological environment governance leadership organization, with the participation of local municipal governments, should be established as a permanent institution. The decision-making and execution mechanisms of this organization should be gradually constructed and continuously improved. Secondly, it is

urgent that the consensus needs be reached regarding the goals of ecological protection and restoration by scientifically formulating ecological environment protection and governance plans. The ecological protection red line and ecological control line should be strictly delineated. In addition, it is also recommended to build a key engineering project library that embraces ecological elements, and a cost distribution and benefit-sharing mechanism for cross-border cooperation in the metropolitan area. Ecological compensation systems should be improved for key ecological functional areas, including nature reserves, national aquatic germplasm resource protection areas, key prevention and control areas of ecological services, centralized drinking water source protection areas, and watersheds.

5.4. Limitations and Future Study Directions

This research still has shortcomings and may provide some new insights and directions for future study:

Firstly, methods for identifying ecological sources and corridors need to be optimized and improved under different circumstances. Building a regional ESP is a complex process, in which the accuracy of determining the sources and rationality of constructing a resistance surface directly affect the final structure. Future studies could focus on evaluation approaches for the effectiveness of the ESPs according to practical feedback.

Secondly, this study paid less attention to the evolution of the ESP in the historical and future time scales. Currently, there are studies using the PLUS land use change model [7,32], which combines land use change simulation for constructing ESP. Relevant studies with multiple time periods and perspectives can also be carried out to provide references for facilitating ecological remediation of territorial spaces in the future.

Thirdly, the optimal scale of ESP construction needs to be further explored. Smaller scales are more suitable for refined management, while larger scales help eliminate the fragmentation of natural geographic patterns and ecological functional flows caused by administrative boundaries. It is believed that the construction of ESPs in different spatial scales could find various relevant issues in the ecosystems for vertical comparison [59].

6. Conclusions

Along with the development of city regionalization and regional urbanization, metropolitan areas have become one of the most vital spatial carriers for China to distribute the functions of megacities and promote new-type urbanization and regional coordinated development. Meanwhile, ecological security is urgently needed in the study of regional ESP construction because of its prominent ecological security problems and arduous ecological protection tasks. This study takes the CZTMA, a national and developing metropolitan area, as the research case and focuses on constructing a regional ESP by adopting an ESE system and circuit theory. The following results were obtained to verify the applicability of the technical framework brought forth in our research:

(1) Twenty-two ecological sources distributed heterogeneously from the eastern to western CZTMA, mainly consisting of woodlands, grasslands, and water bodies;
(2) Forty-eight ecological corridors connected large-scale ecological patches such as rivers, lakes, wetlands, and woodlands in the CZTMA, and the average distance of the east side was shorter while the distance of the west side was longer;
(3) Thirteen ecological pinch nodes and twenty-eight ecological barrier nodes were identified as important nodes.

Finally, this study constructed the ESP of the CZTMA as “one center and multiple cores, one belt and two screens, multiple corridors and multiple nodes”, forming a multi-level ecological spatial structure consisting of nodes, links, and surfaces. Meanwhile, suggestions

for optimizing the ESP and coordinated mechanisms for areas that cross administrative boundaries were further put forward.

This research helps to provide decision support for ecological and environmental protection and remediation, and the planning of ecological protection patterns and ecological network systems in the CZTMA. The construction of ESPs in metropolitan areas has great significance in the common preservation and governance of the ecological environment of cross-border areas, thus improving ecological services' value and providing foundations for the transition from passive restoration to active adaptation in the governance of national territorial space.

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Data Availability Statement: Data used in this study are publicly available, and their sources have been referenced in the manuscript. The raw data supporting the conclusions of this article will be made available by the authors on request.

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

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