

## Article

# Prioritization of Ecological Conservation and Restoration Areas through Ecological Networks: A Case Study of Nanchang City, China

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**Abstract:** Rapid urbanization has led to ecosystem fragmentation, conversion, and degradation, posing great threats to natural habitat and biodiversity. The utilization of ecological networks has gained importance in ecological restoration planning to mitigate the negative impacts of urbanization on ecosystems. This study focused on Nanchang City, China, as a case study area to examine the application of integrated ecological networks in 2000, 2010 and 2020. This study analyzed the dynamic characteristics and spatial differences in landscape connectivity, providing evidence-based support for ecological conservation and restoration. The results indicate the following: (1) a decrease in the number of ecological sources and corridors, especially general sources and corridors, along with a decreasing trend in their importance; (2) an increase in ecological barrier points and breakpoints over time, especially in the southeastern region of the study area; and (3) the identification of ecological conservation priority areas, ecological improvement priority areas, and ecological restoration points based on connectivity and dynamic analysis. Multiple priority actions were proposed, which remarkably improved network connectivity and strengthened biodiversity conservation. Our research provides a valuable reference for identifying ecological priorities and developing ecological protection and ecological restoration actions in highly urbanized areas.

**Keywords:** landscape connectivity; ecological network; ecological conservation; ecological restoration; priority area



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## 1. Introduction

Rapid urbanization and high-intensity land development have led to remarkable changes in land use patterns worldwide, resulting in adverse effects on urban landscapes and ecological sustainability. These changes, including habitat loss, landscape fragmentation, and impaired ecological functions, pose great threats to biodiversity and landscape connectivity [1], thereby endangering human well-being. In recognition of these challenges, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) released the ‘Global Assessment Report on Biodiversity and Ecosystem Services’ in 2019 [2], highlighting that the world is facing an unprecedented decline in nature and an accelerating rate of species extinction. It points out that ecosystem restoration is key to mitigating climate change and curbing species extinction. Ecological conservation and restoration are considered spatial solutions to enhance ecosystem integrity and connectivity [3]. They have become a global consensus to restore ecosystem functions and promote the coordination between ecological protection and urbanization [4,5]. In China,

rapid economic growth has been accompanied by ecosystem degradation, landscape fragmentation, and environmental problems [6,7], making nationwide ecological restoration implementation and sustainable development promotion imperative [8,9].

In response to increasing ecological environmental problems, ecological restoration projects have been continuously implemented worldwide at various scales. At the regional level, restoration projects aim to recover natural assets and ecosystem services in degraded ecosystems, such as China's Three-North Shelterbelt Development Program, Grain for Green Program [10], and Natural Forest Conservation Program; Vietnam's Five Million Hectare Reforestation Program [11]; and Sudan's National Adaptation Program [12]. At finer scales, ecological restoration focuses on specific ecosystem problems, such as mine wasteland reclamation [13], water management [14], and ecological restoration for heavy metal contaminated areas [15]. These ecological restoration projects demonstrate the theoretical and technological feasibility of restoring damaged ecosystems to their original ecological state.

Concurrently, scholars have conducted research on monitoring, assessing, and understanding the driving mechanisms of degraded ecosystems and ecosystem restoration, proposing pragmatic restoration strategies to facilitate regional development. Regarding ecosystem monitoring, scholars have emphasized the connections between ecological elements and socio-economic factors and highlighted the analysis of spatiotemporal change patterns of ecological elements caused by socio-economic development [16]. These approaches provide historical perspectives to diagnose regional ecological problems and accelerate the restoration process by systematically repairing degraded, damaged, or destroyed ecosystems [17].

Considerable progress has also been made in evaluating ecosystem services using various models and technologies. Conceptual models have been employed, such as "exposure-sensitivity-adaptive capacity", including essential variables of land use intensity, ecological land area, and ecosystem services [18] for vulnerability assessment; "pressure-state-response", including essential variables of economic development, agricultural production, environmental quality, topographical condition, proportion of investment into science, and education for ecological security assessment [19]; and "sensitivity-resilience-pressure", including essential variables of land-use land-cover change rate (LULC), growth rate of the population, built-up and road density (BD), proportion of forest land (PFL), landscape zoning and regulation (LZR) for ecological sensitivity and environmental vulnerability assessment [20]. These models and technologies contribute to the development of ecological restoration indicators and the exploration of driving mechanisms of degraded ecosystems and ecosystem restoration, leading to the formulation of suitable measures to ensure the effectiveness of ecological restoration [21].

Considering the theory of landscape ecology, ecological networks have provided new methods and perspectives for ecological conservation and restoration and have garnered considerable attention. Ecological networks emphasize the continuity and systematics of landscape elements, enabling the identification of critical ecological elements for regional ecological conservation and restoration, such as sources, corridors, and ecological nodes [22]. Current studies focus on exploring the spatial distribution and characteristics of sources, corridors, and degraded areas using networked static analysis, considering them as key areas and implementing measures to promote the ecological protection and ecological restoration efforts [23]. Prioritizing the protection and restoration of these key areas can effectively enhance ecosystem function stability and achieve optimal comprehensive benefits for ecology, economy, and society at the lowest cost [24].

However, existing studies on ecological networks have predominantly emphasized spatial patterns and distributions of sources and corridors, whereas the role of ecological networks in terrestrial ecological restoration requires further investigation. In particular, a gap remains in understanding how to prioritize conservation and restoration areas based on the connectivity of ecological networks. Connectivity is currently an important topic in global ecological conservation and restoration efforts. The challenge of these conservation

plans is how to identify key areas that play a crucial role in maintaining or restoring connectivity and promote ecological processes through the management of priority. In addition, research on integrating landscape configuration dynamics into ecological protection and ecological restoration strategies is limited. The dynamics help emphasize the effectiveness and rationality of ecological protection and ecological restoration actions. Therefore, it is imperative to emphasize and embed dynamic landscape connectivity when determining the priority areas for ecological protection and ecological restoration and provide targeted conservation and restoration efforts to enhance overall ecological restoration effectiveness. Thus, we proposed the following hypothesis for this study: The incorporation of dynamic landscape connectivity is capable of enhancing the precision and specificity of ecological conservation and restoration actions. Our study aims to address these gaps and seeks to answer the following research questions based on the hypothesis:

- (1) What are the dynamic characteristics of landscape connectivity in ecological networks?
- (2) How can we incorporate the landscape connectivity with the dynamics to contribute to the optimization of ecological conservation and restoration priority area determination?

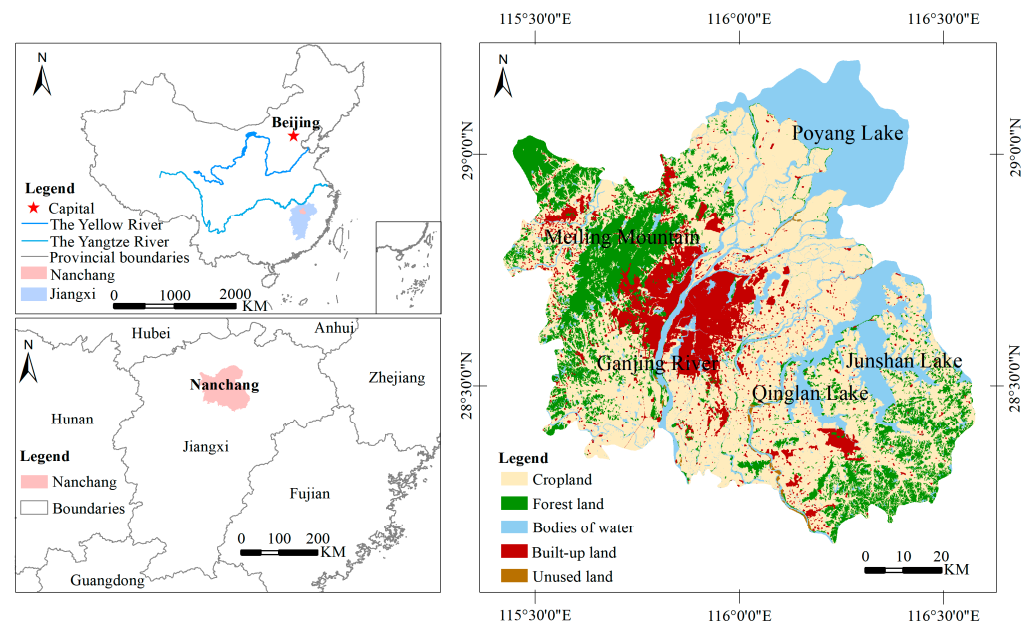
## 2. Materials and Methods

### 2.1. Study Area and Data Sources

The study area is Nanchang City, located in Central China and north-central Jiangxi Province, with geographical coordinates ranging from 115°27' E to 116°35' E and 28°09' N to 29°11' N. Covering a total area of 7195 km<sup>2</sup>, Nanchang is characterized by the Poyang Lake Plain, featuring flat terrain in the southeast and rolling hills in the northwest. There are abundant terrestrial resources such as forest, wetland and grassland, and the magnitude of biodiversity is high, such as birds, mammals, and aquatic animals. Nanchang is recognized as one of the fastest developing cities globally, with a gross GDP of 104.52 billion USD in 2022. Industries, such as automobile manufacturing, aircraft manufacturing, metallurgy, pharmaceuticals, and textiles, are prominent in the city. Various industrial zones have been designated in different parts of Nanchang to support and facilitate industrial activities.

However, in recent years, the rapid urbanization and economic development in Nanchang have caused severe forest degradation from Xishan to Meiling, as well as along the banks of the Gan River and Fu River. The forest degradation has led to extensive soil erosion in Nanchang. Landslides are the primary geological hazard in Nanchang, accounting for 66.67% of geological hazard sites, ranking the city sixth in China. Over the years, the government has placed a high priority on ecological environment protection and environmental management of Nanchang City [25]. The government has formulated the “Nanchang Municipal Land and Space Ecological Restoration Special Plan (2021–2035)”, which focuses on the key ecological issues, establishes the overall pattern, key areas, and major projects for ecological restoration, and proposes measures to ensure the implementation of the plan. At the same time, Nanchang is the capital city of Jiangxi Province and is also an important city in the Yangtze River Economic Belt. The implementation of ecological conservation and restoration in Nanchang is capable of promoting the development of ecological industries, driving the growth of eco-tourism, and advocating ecological civilization construction for the Yangtze River Economic Belt. It provides crucial support and an impetus for the sustainable development and green transformation of the Yangtze River Economic Belt.

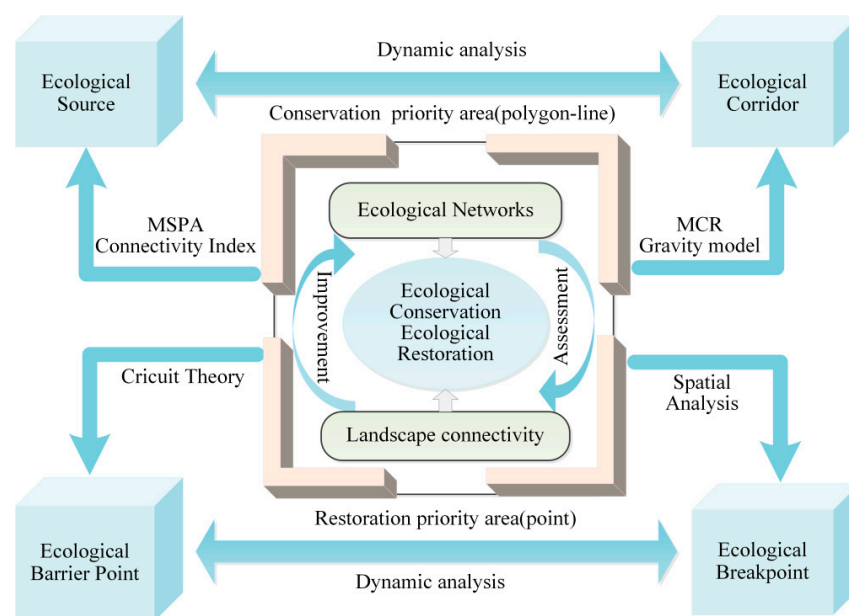
Land use data for the years 2000, 2010, and 2020, with a spatial resolution of 30 m × 30 m and accuracy over 80%, were obtained from the GlobeLand30 land use data (<https://www.webmap.cn/>) (accessed on 31 August 2021). The land use types were reclassified into five categories: cropland, forest, water, construction land, and others for subsequent analysis, as shown in Figure 1. Digital elevation model (DEM) data were downloaded from the Geospatial Data Cloud (<http://www.gscloud.cn/>) (accessed on 4 September 2021), and slope data were derived from the DEM data using spatial analysis methods. The road data were obtained from Open Street Map. The spatial resolution of all raster data was 30 m × 30 m.



**Figure 1.** Location of the study area.

## 2.2. Methods

This study aimed to identify ecological protection and ecological restoration priority areas in Nanchang City using ecological networks. The methodology consisted of several steps. First, ecological sources and ecological corridors, which are important components of ecological networks, were identified. The importance of the sources and corridors was determined using the landscape connectivity index and gravity model, respectively [26]. The details of the methods are shown in Sections 2.2.1 and 2.2.2. Second, ecological barrier points were identified using circuit theory (as shown in Section 2.2.3), and ecological breakpoints were determined through spatial analysis [9]. Finally, based on the dynamic landscape connectivity features, priority areas for ecological conservation and restoration were delineated [27], with specific recommendations tailored to each zone. The research framework was shown in Figure 2.



**Figure 2.** Methodological framework for ecological conservation and restoration.

### 2.2.1. Ecological Sources Identification for Ecological Conservation

Ecological sources is one of the most important landscape elements in ecological networks, which contribute greatly to maintaining ecological processes and functions. In recent years, the application of landscape connectivity methods for source identification has been widely recognized because it reduces the influence of subjective factors [8]. In this study, the morphological spatial pattern analysis (MSPA) and the landscape connectivity index were employed to improve the identification of ecological sources. MSPA, proposed by Vogt et al., is an image-processing approach that utilizes mathematical morphology algorithms and operations, including corrosion, expansion, opening operation, and closing, to analyze the geometry and connectivity of images in space [28,29]. It enables the measurement, identification, and partitioning of spatial patterns in raster images according to the eight-neighborhood method. MSPA accurately identifies habitat patches that contribute remarkably to landscape connectivity at the pixel level by considering landscape types and structures [30], which refers to the sizes, shapes and pattern of habitat patches. It categorizes these patches into core, island, bridge, ring, branch, edge, and perforation, which are seven non-overlapping landscape types, based on morphology [31]. In this study, land use types in 2000, 2010, and 2020 were converted into raster maps, where forest and water were regarded as the foreground and others as the background. The MSPA analysis was conducted using the eight-neighborhood method, as previously described.

The extraction of cores and calculation of their landscape connectivity index are also key steps in identifying ecological sources. Landscape connectivity reflects the extent to which patches contribute to promoting the ecological flow and species migration [32]. The landscape connectivity index assesses the landscape-level connectivity and assigns importance to each patch based on its contribution to connectivity [33]. The landscape connectivity index comprises the overall connectivity index (IIC), possible connectivity index (PC), and patch importance index (dPC), which can be calculated using the following formulas:

$$IIC = \left( \sum_{i=1}^n \sum_{j=1}^n \frac{a_i \times a_j}{1 + nl_{ij}} \right) / A_L^2 \quad (1)$$

where  $i \neq j$ ,  $n$  is the total number of forest and water areas in the landscape,  $a_i$  and  $a_j$  are the areas of patch  $i$  and  $j$ ,  $nl_{ij}$  represents the connection count for patch  $i$  and patch  $j$ , and  $A_L^2$  represents the habitat patches total area. Note that  $0 \leq IIC \leq 1$ , where  $IIC = 0$  indicates connection count is 0, and  $IIC = 1$  represents the entire landscape as a single cohesive habitat patch.

$$PC = \left( \sum_{i=1}^n \sum_{j=1}^n p_{ij}^* a_i a_j \right) / A_L^2 \quad (2)$$

where  $i \neq j$ ,  $p_{ij}^*$  is the maximum probability for ecological flow between patch  $i$  and  $j$ , and  $0 \leq PC \leq 1$ . A lower PC value indicates lower connectivity of the patch and less favorable conditions for species migration.

$$dPC = \frac{PC - PC_{\text{remove}}}{PC} \times 100\% \quad (3)$$

where  $PC_{\text{remove}}$  indicates the connectivity calculation result after the removal of a certain patch. dPC represents the importance of the habitat patch.

The ecological sources were determined by calculating the dPC value for cores with an area greater than 0.2 km<sup>2</sup>. In this study, a distance threshold of 1000 was set, and a possibility of connectivity of 0.5 was considered. On the basis of the dPC analysis, extracted patches with a dPC value greater than 0.5 were defined as ecological sources. The importance levels of ecological sources were classified as follows: extremely important ( $dPC \geq 10$ ), important ( $1 \leq dPC < 10$ ), and general ( $0.5 \leq dPC < 1$ ).

### 2.2.2. Formation of Ecological Networks for Ecological Conservation

Ecological corridors connect isolated key ecological patches and contribute greatly to improved landscape connectivity. The identification of ecological corridors involves the selection of ecological sources and the formation of resistance surfaces. The selection of ecological resistance factors is a critical step in constructing the resistance surface. On the basis of existing research [26,34,35] and the nature and urbanization characteristics of Nanchang, several factors were employed, namely, elevation, slope, land use type, distance from railways, distance from expressways, distance from trunk roads, and distance from minor arterial roads.

The minimum cumulative resistance (MCR) model, initially proposed by Kaaapen et al. [36], is used to calculate the minimum cumulative cost for biological migration, species diffusion, and other phenomena. It reflects the patterns of species migration and the level of connectivity between patches. The MCR model is particularly suitable for constructing ecological corridors that promote material, energy, and information flows, especially for animal migrations [37]. The formula is as follows:

$$\text{MCR} = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i) \quad (4)$$

where MCR represents the value of minimum cumulative cost,  $f$  is the proportional function relationship,  $D_{ij}$  represents the spatial distance from patch  $j$  to  $i$ , and  $R_i$  represents the resistance coefficient that the corresponding landscape unit  $i$  presents to the movement of species.

Corridor importance analysis was also regarded as valuable evidence for prioritizing ecological conservation measures. The gravity model is utilized for the formation of the interaction matrix and quantitatively analyzing the interaction intensity between sources [38]. A stronger interaction intensity indicates higher connectivity of ecological corridors, emphasizing their significance. In this study, important corridors ( $G_i \geq 100$ ) and general corridors ( $G_i < 100$ ) were defined according to the gravity model. The formula is as follows:

$$G_{ab} = \frac{(N_a \times N_b)}{(D_{ab})^2} = \frac{\left[ \frac{1}{P_a} \times \ln(S_a) \right] \left[ \frac{1}{P_b} \times \ln(S_b) \right]}{\left( \frac{L_{ab}}{L_{\max}} \right)^2} = \frac{(L_{\max})^2 \ln(S_a) \times \ln(S_b)}{(L_{ab})^2 \times P_a \times P_b} \quad (5)$$

where  $G_{ab}$  reflects the interaction intensity, indicating the corridor  $a - b$ 's importance. The weight coefficients  $N_a$  and  $N_b$  are derived from the resistance value ( $P_a$ ) and patch area ( $S_a$ ) of different habitat patches.  $D_{ab}$  is the resistance of the corridor  $a - b$ ,  $L_{ab}$  is the cumulative resistance value for corridors  $a - b$ , and  $L_{\max}$  is all of the corridors' maximum resistance value.

The method of network analysis, frequently used in conjunction with graph theory, is extensively applied to examine the internal structure and connectivity of ecological networks, as well as to assess the ecological processes occurring within them. Key metrics such as network closure ( $\alpha$ ), line-point rate ( $\beta$ ), and network connectivity ( $\gamma$ ) are utilized to measure the connectivity of these ecological networks [39]. The corresponding formulas are as follows:

$$\alpha = \frac{A - B + 1}{2B - 5} \quad (6)$$

$$\beta = \frac{A}{B} \quad (7)$$

$$\gamma = \frac{A}{3(B - 2)} \quad (8)$$

where  $A$  and  $B$  are respectively the number of corridors and sources and the  $\alpha$  index reflects the networked circuitry degree, with a higher value indicating smoother material and

ecological flow within the network. The index  $\beta$  indicates the number of connections, or lines, associated with each node, while  $\gamma$  also reflects the overall degree of connectivity among all of the nodes within the network.

### 2.2.3. Spatial Priority for Ecological Restoration

Ecological barrier points refer to areas where ecological flow and processes are hindered. Identifying and rehabilitating ecological barriers can significantly diminish ecological resistance and greatly enhance the landscape connectivity of ecological networks [40]. In this research, circuit theory was employed to map the spatial distribution of these ecological barrier points. The types of ecological barrier points were determined by overlaying the current status of land use. The improvement score represents the contribution of impairing the barriers to improving landscape connectivity. An elevated improvement score signifies a more substantial enhancement in connectivity [41]. The formulas are as follows:

$$\Delta LCD = LCD_0 - LCD_1 \quad (9)$$

$$IS = \Delta LCD / D \quad (10)$$

where  $LCD_0$  and  $LCD_1$  are respectively the minimum cost distance before and after repairing the barriers,  $\Delta LCD$  represents the difference of the minimum cost distance before and after repairing the barriers, and  $IS$  is the improvement score.

Ecological breakpoints occur at the intersections where roads and corridors meet, causing discontinuity in the corridor and remarkably reducing the landscape connectivity of ecological networks [42]. Ecological breakpoints, such as road and corridor intersections, significantly impede the natural flow of ecological processes between different habitats. Moreover, they elevate the risk of injury or mortality for wildlife during migration due to vehicle traffic, thereby jeopardizing the flow of matter, energy, and information within the ecological network. Therefore, restoration of ecological breakpoints is urgently needed. Using the GIS method, breakpoints were the intersection of corridor and traffic roads.

## 3. Results

### 3.1. Landscape Pattern Analysis Based on MSPA

The data were analyzed using the eight-neighborhood rule for the MSPA. The outcomes of the landscape pattern analysis, based on the MSPA approach, are presented in Figure 3 and detailed in Table 1.

**Table 1.** Proportion of landscape elements in MSPA analysis (%).

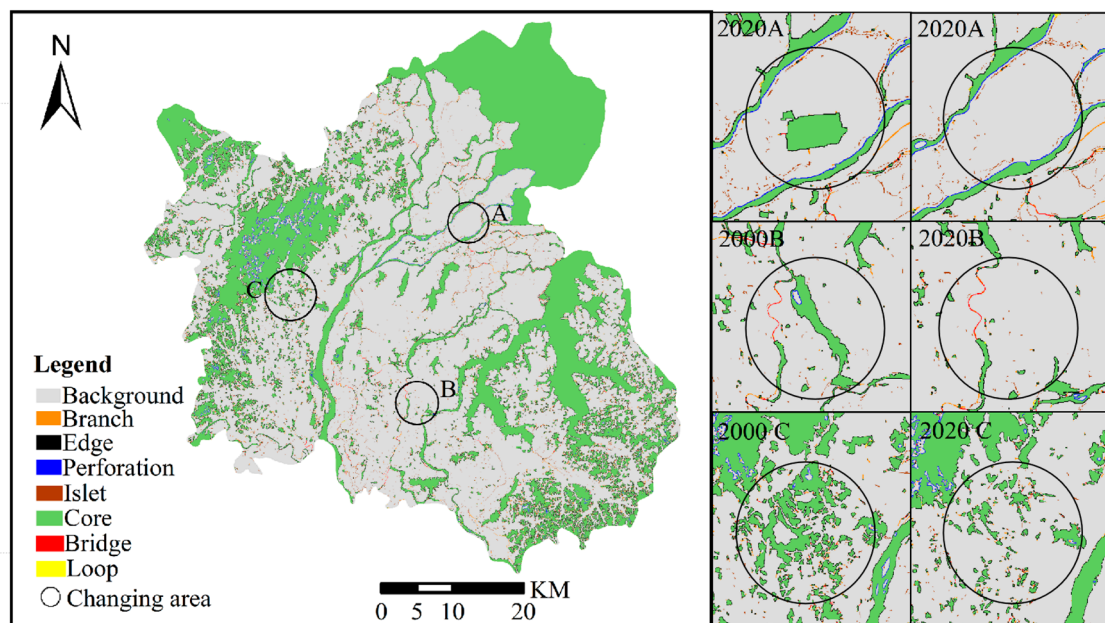
| Type        | 2000                    |                | 2010                    |                | 2020                    |                |
|-------------|-------------------------|----------------|-------------------------|----------------|-------------------------|----------------|
|             | Area (km <sup>2</sup> ) | Proportion (%) | Area (km <sup>2</sup> ) | Proportion (%) | Area (km <sup>2</sup> ) | Proportion (%) |
| Core        | 2326.45                 | 83.56          | 2319.19                 | 83.54          | 2323.40                 | 84.36          |
| Bridge      | 16.32                   | 0.35           | 16.36                   | 0.35           | 13.85                   | 0.29           |
| Edge        | 325.30                  | 12.01          | 324.33                  | 12.01          | 307.66                  | 11.48          |
| Branch      | 60.86                   | 2.19           | 60.83                   | 2.19           | 53.93                   | 1.96           |
| Islet       | 28.34                   | 1.02           | 28.44                   | 1.02           | 25.39                   | 0.92           |
| Loop        | 5.63                    | 0.09           | 5.56                    | 0.08           | 5.93                    | 0.08           |
| Perforation | 21.37                   | 0.80           | 21.56                   | 0.80           | 24.14                   | 0.91           |

As shown in Figure 3 and Table 1, the cores, which are crucial to networked connectivity, are primarily located in the northern, eastern, and western parts. They include several large woodlands, rivers, and lakes, such as Meiling Mountain, Poyang Lake, Ganjing River, Fuhe River, Junshan Lake, and Qinglan Lake. The areas and proportion of the cores increased from 2000–2010, accounting for more than 2300 km<sup>2</sup> and 83% of habitat patches. Significant loss of cores was observed in certain areas, such as circles A and B, indicating substantial landscape fragmentation.

Bridges serve as essential structural corridors connecting different core patches in the landscape. The proportion of bridges was less than 0.5% and showed a decreasing trend from 2010 to 2020. This suggests poor connectivity and a lack of essential landscape connections between cores, which is detrimental to the dispersal of species and the exchange of energy and materials. And the branch account for 2.19%, 2.19%, and 1.96% from 2000 to 2020, which indicates the connection was interrupted.

The edges, serving as transitional zones between the core areas and the peripheral non-green landscape regions, accounted for 12.01%, 12.01%, and 11.48% of the total area from 2010 to 2020, respectively, which can reduce the impact brought by the external environment and human disturbances. Perforations are inner edges of the cores that often experience vegetation degradation due to natural factors or human activities, accounting for 0.80%, 0.80%, and 0.91% in 2000, 2010, and 2020, respectively. The edges showed a decreasing trend, whereas the perforations showed an increasing trend. This indicates that the edge effect was declining gradually in the study area, which is not conducive to resisting external interference and maintaining ecosystem stability.

Isolated ecological patches known as islets can act as stepping stones for species migration. The proportion of these islets diminished from 1.02% in 2000 to 0.92% in 2020, and they were dispersed in fragments around the core areas. Additionally, the loops, which facilitate shortcuts for animal movement within patches and aid in species migration within the same patches, are present in very small proportions.



**Figure 3.** Map of landscape pattern analysis based on MSPA. Note: the left is the landscape pattern based on MSPA in 2020. The circles A, B, and C are the representative change areas we chose, which changed a lot from 2000 to 2020. The right is the change areas, circles A, B, and C, in 2000 and 2020. We enlarged the circles A, B, and C from 2000 to 2020 so their change characteristics could be represented clearly.

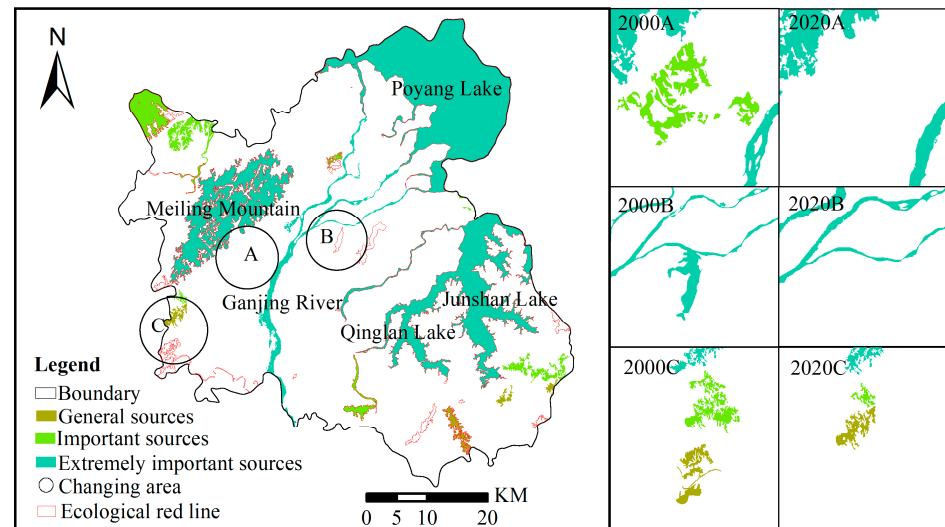
### 3.2. Characteristics and Spatiotemporal Changes in Ecological Networks

The ecological networks in 2000, 2010, and 2020 were constructed using the MSPA and MCR models. On the basis of the importance of the ecological networks, the ecological sources were categorized into extremely important sources, important sources, and general sources, and the corridors were classified as important corridors and general corridors.

#### (1) Ecological sources

Figure 4 illustrates the spatial distribution of ecological sources. Overlapping with the ecological red line area of Nanchang, most identified ecological sources, particularly

extremely important sources, were located within the ecological red line area, indicating the credibility and reasonableness of the sources identified through the MSPA method and landscape connectivity index.



**Figure 4.** Spatial distribution of ecological sources. Note: the left is the spatial distribution of ecological sources in 2020. The circles A, B, and C are the representative change areas we chose, which changed a lot from 2000 to 2020. The right is the change areas, circles A, B, and C, in 2000 and 2020. We enlarged the circles A, B, and C from 2000 to 2020 so that their change characteristics could be represented clearly.

Table 2 presents the data on ecological sources, revealing that the number of ecological sources decreased from 28 in 2000 to 24 in 2010, and further down to 20 in 2020. This indicates a decreasing trend in the number of ecological sources over time. The mean ecological source area was 62.88 km<sup>2</sup> in 2000, 72.52 km<sup>2</sup> in 2010, and 88.78 km<sup>2</sup> in 2020. This indicates there were some achievements for the conservation of key habitat patches. Figure 4 shows the sources located in the northern, western, and southeastern of Nanchang. The distribution of ecological sources is uneven, with extremely few identified in the central region. This is attributed to intense urban expansion encroaching on a large amount of ecological land, resulting in a decline in habitat patches. The loss of sources was remarkable in Nanchang from 2000 to 2020. For example, in circle A, circle B and circle C, sources experienced remarkable loss from 2000 to 2020. These findings indicate that the rapid urban development between 2000 and 2020 has caused serious damage to the ecological sources. Furthermore, the area and importance of sources decreased, as shown in circle C, indicating a severe decline in landscape connectivity in Nanchang.

As shown in Figure 4, extremely important ecological sources are characterized by important woodlands and waters, including Meiling Mountain, Poyang Lake, Ganjing River, Junshan Lake, and Qinglan Lake. The extremely important ecological sources are the key habitat patches in Nanchang with strong ecological foundations and abundant species. These sources deserve considerable attention in ecological planning, biodiversity protection, and urban development. Important ecological sources are located around extremely important ecological sources, with areas of 198.86, 176.44, and 162.37 km<sup>2</sup> in 2000, 2010, and 2020, respectively. The area of important ecological sources showed a decreasing trend, reflecting high landscape fragmentation in Nanchang. General sources were mainly found in the peripheral regions and were far from other sources, making a limited contribution to the entire networked connectivity.

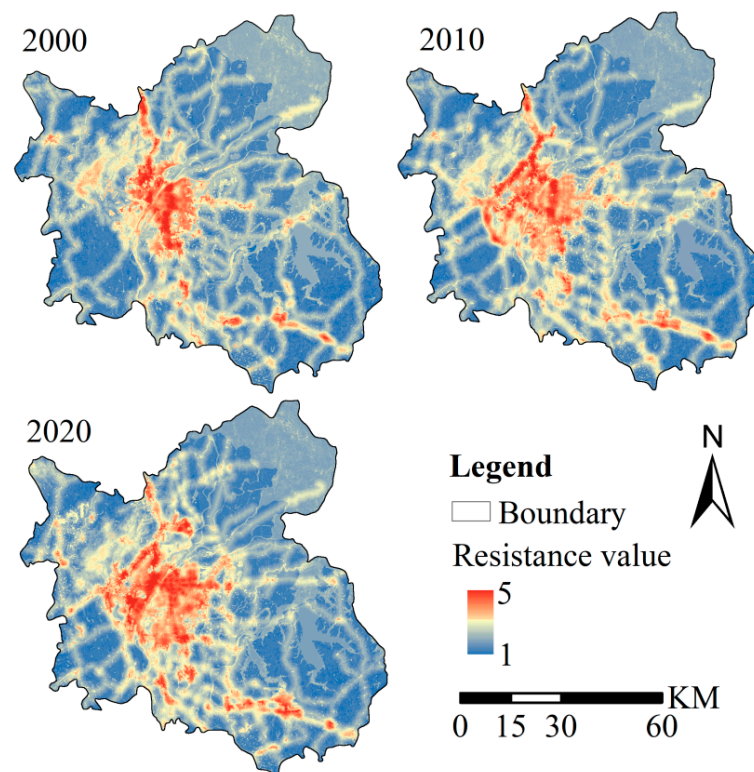
**Table 2.** Statistics of ecological sources in 2000, 2010, and 2020.

| Year | Number | Area (km <sup>2</sup> ) |        |       | dPC  |       |      |
|------|--------|-------------------------|--------|-------|------|-------|------|
|      |        | Mean                    | Max    | Min   | Mean | Max   | Min  |
| 2000 | 28     | 62.88                   | 800.64 | 21.47 | 6.09 | 62.3  | 0.59 |
| 2010 | 24     | 72.52                   | 802.05 | 82.93 | 5.60 | 59.07 | 0.51 |
| 2020 | 20     | 88.78                   | 840.72 | 21.22 | 7.91 | 62.75 | 0.51 |

## (2) Ecological corridors

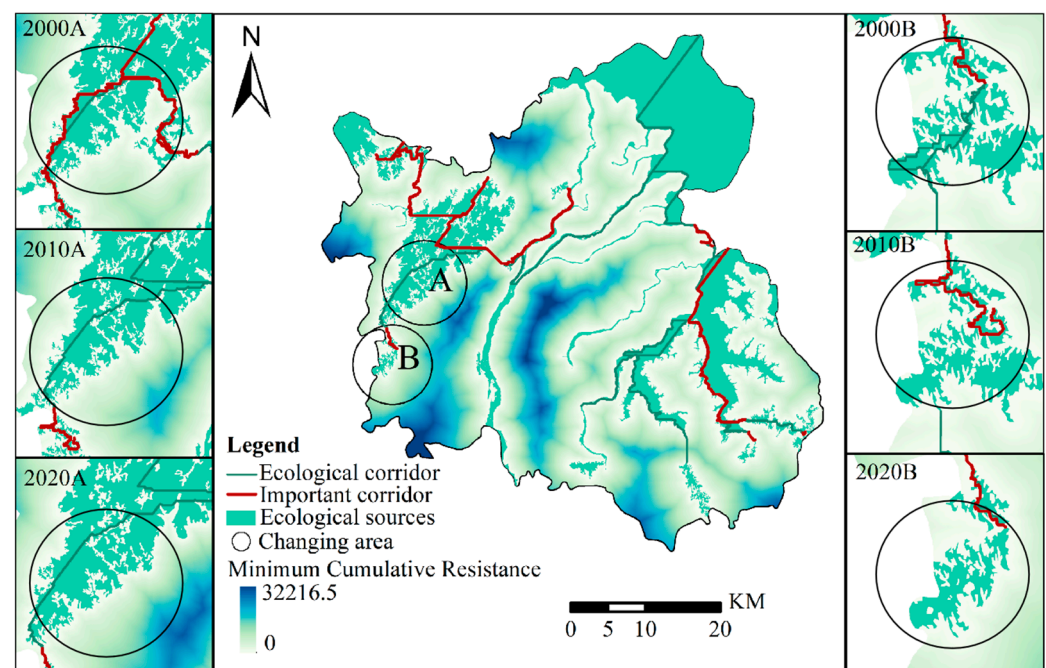
The comprehensive resistance surface in 2000, 2010, and 2020 was calculated by considering the weights of different factors, as shown in Figure 5. The spatial distribution of the comprehensive resistance surface exhibited a characteristic pattern of “middle high, low around” throughout the three periods. High-resistance areas were predominantly found in the central urban zones and the construction lands of surrounding towns. These areas, characterized by high-density human disturbance, hindered landscape connectivity and impeded material and energy flow. Moreover, the southeastern part of the study area had several high-resistance areas due to the presence of railways and highways, posing remarkable obstacles to species migration. Over time, the extent of high-resistance areas expanded, indicating the growing impact of urban development and high-density human activity on ecological processes. Hence, promoting ecological protection and ecological restoration becomes crucial to enhance landscape connectivity and facilitate ecological flow in these areas.

Furthermore, low ecological resistance values were predominantly observed in the peripheral areas of the study area, which are distant from the central urban region. These areas are characterized by high vegetation cover, plentiful water resources, and excellent ecological condition, providing a conducive environment for species habitat, survival, and dispersion.



**Figure 5.** Spatial distribution of comprehensive resistance surface. Note: The colors from blue to red represent the resistance values from low to high. The blue represents low resistance value and the red represents high resistance value.

On the basis of the analysis of ecological sources and the comprehensive resistance surface, the spatial distribution and classification of ecological corridors are shown in Figure 6. Ecological corridors exhibited predominant distribution in the northern, western, and eastern regions of the study area. This pattern can be attributed to the high density of ecological sources and favorable natural conditions in these regions, facilitating strong connectivity between the core patches and promoting frequent ecological flow. Conversely, the central region had a scarcity of ecological corridors due to high levels of human disturbance and landscape resistance. This resulted in a scarcity of ecological sources and stepping stones. Additionally, the southern region had a reduced number of corridors, leading to poor network connectivity in the southeast and southwest of Nanchang. Thus, it is necessary to add corridors and stepping stones to strengthen the landscape connectivity and optimize the spatial network layout.



**Figure 6.** Spatial distribution and classification of ecological corridors. Note: the picture in the middle represents the spatial distribution and classification of ecological corridors in 2020. The circles A and B are the representative change areas from 2000 to 2020. The left pictures are of circle A in 2000, and the right pictures are of circle B in 2020. We enlarged circles A and B in 2000 and 2020 so that the change characteristics could be represented clearly.

In Figure 6, the identified ecological corridors decreased in number from 62 in 2000 to 46 in 2010 and further to 43 in 2020, indicating a decline in landscape connectivity within the study area. The spatial complexity of the ecological corridors showed a constant decline, with a tendency toward a more single structure, particularly observed in the northern and western regions, such as circle A. This decreasing complexity suggests a reduction in accessible paths for species migration, which poses challenges to biodiversity conservation. Thus, protecting these corridors and preventing their fragmentation is crucial to strengthen ecological flow. Losses of corridors in 2000, such as circle B in 2000, highlight the fragility of the ecological linkages between the sources, resulting in difficulties for species migration. Therefore, it is urgent to implement ecological protection and restoration actions for enhancing corridor connectivity and improving the allocation of ecological space.

The gravity model was employed to compute the interaction force between the linked ecological sources via the ecological corridors, thereby assessing their respective significance levels. Important corridors ( $G_i \geq 100$ ) and general corridors ( $G_i < 100$ ) were identified.

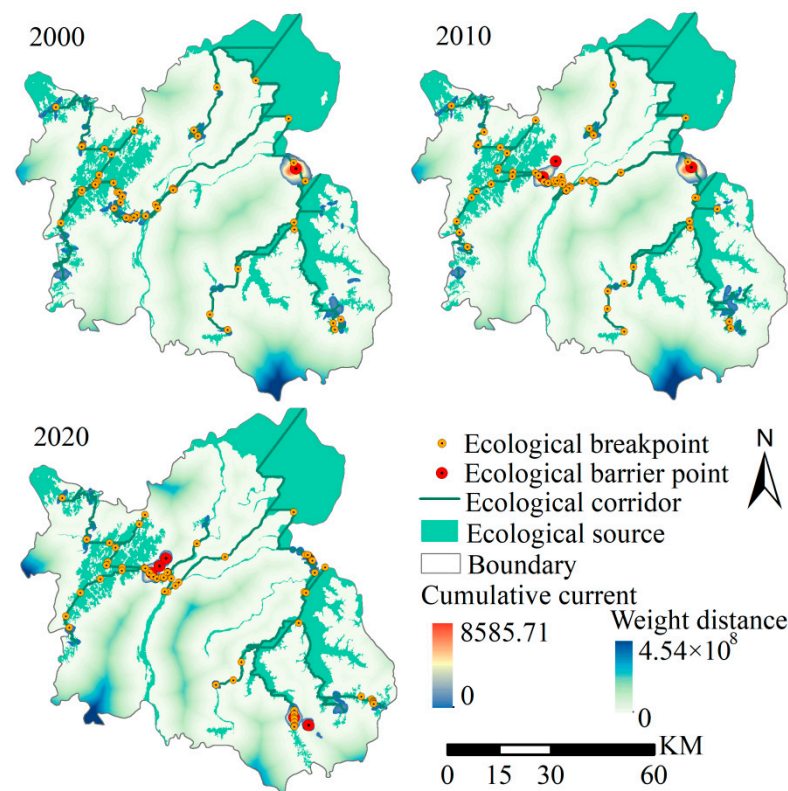
As depicted in Figure 6, key corridors were predominantly situated in the northern, western, and southeastern areas. These corridors served as vital connections between extremely important ecological sources, including Meiling Mountain, Poyang Lake, Ganjing River, Junshan Lake, and Qinglan Lake, characterized by favorable natural conditions and strong connectivity. The number of important corridors decreased from 43 in 2000 to 33 in 2010 and further to 21 in 2020, indicating a decline in interaction intensity and corridor connectivity between sources. These important corridors are essential for enabling species migration and facilitating energy flow among the primary ecological sources, thereby contributing to landscape connectivity and biodiversity conservation. Therefore, prioritizing the conservation and restoration of these important corridors is essential for future actions.

### *3.3. Identification of Key Areas for Ecological Restoration*

Enhancing regional ecological network connectivity can be achieved by restoring ecological barrier points, improving or removing barrier points, and reducing ecological resistance to ecological flow.

Most ecological barrier points are situated at the peripheries of ecological sources or within ecological corridors, where resistance values change. These barrier points primarily consist of arable lands and construction sites, signaling that intense human activity has disrupted the connectivity of natural ecological corridors and impeded species migration. In the study area, one ecological barrier was identified in 2000, three in 2010, and five in 2020, indicating an increase over time. The additional barrier points were mainly distributed in urban construction lands, roads, and highways, indicating that urban development in these regions has increased ecological resistance and threatened species mobility. Therefore, it is essential to prioritize the restoration of ecological barrier points. It is also recommended to propose ecological protection and restoration measures that take into account different land use types to ensure a more effective ecological restoration process.

Ecological breakpoints arise where ecological corridors intersect with major traffic arteries, pose a threat to biological migration and regional biodiversity conservation. Restoring ecological breakpoints is crucial for improving landscape connectivity and promoting ecological flow. As shown in Figure 7, the number of identified ecological breakpoints were 51 in 2000, 69 in 2010, and 79 in 2020. The number of ecological breakpoints has decreased over time. The spatial distribution of breakpoints showed that they are mainly located in the central built-up and eastern areas of Nanchang. These areas are distinguished by extensive transportation infrastructure, a dense network of roads, and a multitude of corridors, which results in a higher density of ecological breakpoints. Several increased breakpoints were observed in the southeastern area in 2020, indicating that the construction of railways and expressways has remarkably hindered species migration. Consequently, constructing wildlife migration corridors, including tunnel-like culverts, underpass culverts, and overpasses, is essential. It is necessary to facilitate species migration.



**Figure 7.** Spatial distribution of ecological barrier points and ecological breakpoints. Note: improvement score represents the recovery value for landscape connectivity after impairing the barriers. Weight distance represents the distance of cost path for species migration.

### 3.4. Ecological Conservation and Restoration Strategies Based on Ecological Networks

Ecological conservation and restoration research play a crucial role in supporting urban development and planning, ensuring that critical ecological areas are not encroached upon by future economic activities. On the basis of the dynamic landscape connectivity, the identified ecological sources, corridors, barrier points, and breakpoints were categorized into three priority areas: ecological conservation priority areas, ecological improvement priority areas, and ecological restoration points (Figure 8). Ecological conservation priority areas included extremely important sources and important corridors. Ecological improvement priority areas included important sources, general sources, general corridors, and increased sources and corridors. Ecological restoration points included ecological barrier points and breakpoints. Multiple ecological conservation and restoration strategies for priority areas were proposed, and the strategy framework was constructed, as shown in Figure 9. Integrating and restoring the three key ecological areas will significantly strengthen the connectivity of the ecological network, enhance biodiversity conservation, and promote urban sustainable development.

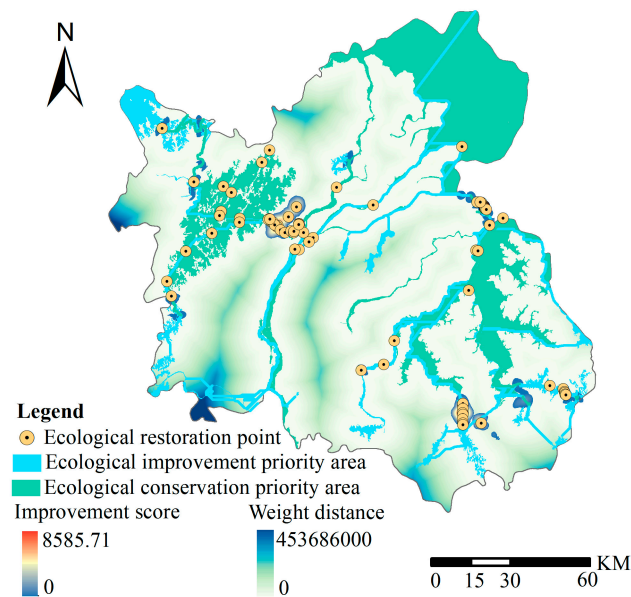


Figure 8. Spatial distribution of priority areas.

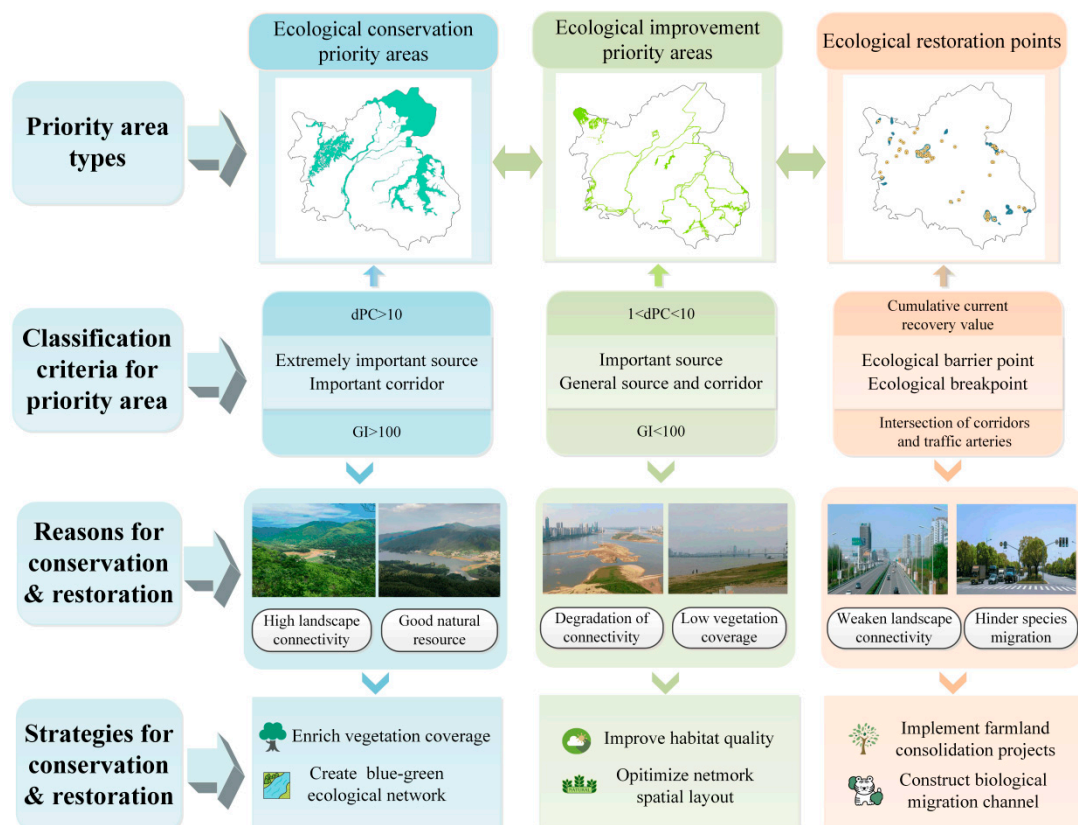


Figure 9. Strategies for ecological conservation and restoration in priority areas. Note: dPC represents the importance value of ecological sources; GI denotes the importance value of ecological corridors.

### 3.4.1. Ecological Conservation Priority Areas

Ecological conservation priority areas encompass fundamental ecological spaces with abundant ecological resources and important ecological functions, including extremely important sources and important corridors. These priority areas are primarily located in Meiling Mountain, Poyang Lake, Ganjing River, Junshan Lake, and Qinglan Lake, which are the key areas of future ecological conservation. However, our results indicate a decline

in the number and importance of important corridors. Thus, addressing the decline in important corridors and restoring connectivity are crucial. For extremely important sources, high-intensity human disturbance, land use change, and urban construction activities that are inconsistent with the primary functional orientation must be strictly avoided to safeguard ecosystem stability and security. Enriching the vegetation community structure and vegetation coverage is also essential to maintain biological reproduction and support rich biodiversity.

Furthermore, enhancing the development of crucial corridors stands out as the most direct strategy to safeguard natural landscapes and enhance landscape connectivity. The establishment of ecological corridors should extend beyond urban landscape construction and cultural recreation, focusing instead on biodiversity preservation, ecological functionality enhancement, and landscape connectivity maintenance as the primary goals of ecological conservation. Furthermore, focusing on integrating terrestrial ecological corridors with river corridors is important for creating a blue-green ecological network system [34] that aligns with the geographical features and the requirements of Eco-Spatial Planning in Nanchang.

### 3.4.2. Ecological Improvement Priority Areas

Ecological improvement priority areas serve as important ecological security barriers in the Eco-Spatial Planning of Nanchang. These areas encompass important sources, general sources and corridors, mainly located in Dagongling Mountain and Qiaoling Mountain. The dynamic analysis of ecological networks revealed a decreasing trend in the number of important sources, with general source areas located in fringe areas exhibiting poor connectivity and a remarkable loss of general sources. Strengthening the ecological function and improving the landscape connectivity of important sources are essential for attaining the strategic objectives of ecological conservation and fostering sustainable development. Measures, such as returning farmland to forest and prohibiting deforestation, should be implemented to protect forest resources and expand the scope of important sources. Additionally, the haphazard distribution and proliferation of industrial enterprises and construction zones should be strictly avoided to protect biological diversity and maintain ecosystem stability. For general sources and corridors, the focus should be on enhancing ecological protection and promoting ecosystem management. More efforts should be devoted to promoting comprehensive management of forest and grass ecosystems [43], including actions such as enriching vegetation coverage, optimizing the vegetation structure, strictly prohibiting land use changes for other commercial purposes, and avoiding the loss of high-quality forestland. Regarding water corridors located in the Ganjing River, Fuhe River and Qinglan Lake, establishing ecological shelter forests along river and lake shorelines and strengthening pollution control and water quality monitoring are essential [44].

Moreover, achieving more ambitious protection targets may be necessary for the spatial layout optimization of ecological networks [26]. The dynamic characteristics of ecological networks indicate a decreasing trend in regional landscape connectivity due to the loss of sources and corridors, resulting in poor network connectivity between the southeast and southwest regions. Therefore, increasing the number of sources and corridors is important to improve landscape connectivity and the spatial layout of ecological networks. On the basis of the Ecological Red Line Area Protection Plan and Ecological Spatial Pattern Plan of Nanchang City, 22 sources were selected and 82 corridors were increased using the MCR model (Figure 8). Through network connectivity analysis, the values of  $\alpha$ ,  $\beta$ , and  $\gamma$  in the original ecological network were 0.68, 2.15, and 0.79, respectively, and the values of  $\alpha$ ,  $\beta$ , and  $\gamma$  in the optimized ecological network were 0.81, 2.5, and 0.87, respectively, showing an increase in the values of  $\alpha$ ,  $\beta$ , and  $\gamma$ . This increase signifies a significant enhancement in both the connectivity and the complexity of the ecological network.

### 3.4.3. Ecological Restoration Priority Areas

Ecological restoration priority areas encompass ecological barrier points and ecological breakpoints. Ecological barrier points are primarily represented by arable and construction land, which remarkably weaken landscape connectivity. Measures such as converting farmland to forestland or grassland and constructing shelter forests should be implemented to address arable land. These actions improve habitat quality and enhance landscape connectivity. Undertaking farmland consolidation projects, which involve improving rural infrastructure and promoting ecological agriculture, are also necessary. These initiatives strengthen ecological conservation efforts and promote the concept of ecological civilization. Regarding construction land, the focus should be on expanding green spaces, enriching vegetation coverage, and strengthening the construction of pocket parks, roof gardens, and greenways [45]. The analysis results show that ecological breakpoints severely hinder species migration and pose a threat to biodiversity conservation. Therefore, establishing biological migration channels such as underpasses, bridge culverts, tunnels, and air corridors as passages is essential to facilitate species migration. Additionally, the construction of light and sound insulation facilities and the implementation of dynamic monitoring systems for species migration are necessary. These measures effectively ensure regional ecological flow and ecological safety.

## 4. Discussion

Incorporating ecological networks into the prioritization of conservation and restoration efforts offers a viable strategy for attaining sustainable urban development. The main drivers of ecosystem degradation, landscape fragmentation, and biodiversity loss in urban areas are high-intensity land development and urban construction [34]. Constructing networked ecological areas, improving landscape connectivity, and promoting biodiversity conservation should be the focal points of future ecological conservation and restoration efforts in cities. Nanchang, with abundant forest and water resources, possesses ecological sources that include crucial nature reserves, such as Poyang Lake, Ganjing River, and Meiling Mountain, and small-scale habitat patches with high connectivity, such as urban parks and gardens. These ecological sources greatly facilitate species migration and material energy exchange. Additionally, some ecological networks in Nanchang are adjacent to urban areas where the conflicts between production, living, and ecological space are most concentrated. Therefore, the spatial optimization of these networks should be a priority in the future. Determining key areas for ecological protection and ecological restoration, guided by network connectivity, helps define protection objectives and restoration priorities for different landscape elements, enabling differentiated conservation and restoration strategies.

Previous studies mainly focused on the role of individual landscape elements within ecological networks, ignoring the spatial configuration and connectivity between different elements during conservation and restoration actions [44]. This study emphasized the comprehensiveness and connectivity of various landscape elements to determine priority areas and highlighted multiple priority actions from holistic and systematic perspectives. First, on the basis of connectivity analysis for ecological networks, extremely important sources and important corridors were identified as ecological conservation priority areas. Extremely important ecological sources typically consist of crucial biological habitats and nature reserves, such as Meiling Mountain, Poyang Lake, Ganjing River, Junshan Lake, and Qinglan Lake. These sources play an important role in maintaining regional landscape connectivity and supporting biodiversity conservation. Important corridors greatly strengthen source connectivity and promote the ecological flow within regions, making them a focus of future ecological conservation efforts.

Second, ecological improvement priority areas encompass important sources, general sources, and corridors, considering their contribution to regional networked connectivity. These areas are crucial for regional ecological protection and ecological flow. However, the landscape connectivity has severely degraded, and the spatial distribution of the ecological

network is uneven due to urban development. Thus, improving networked connectivity and optimizing network spatial patterns should become the main focus of ecological improvement priority areas in Nanchang City.

Finally, ecological restoration priority areas were identified as ecological barrier points and breakpoints. These areas, characterized by damaged connectivity, seriously hinder species migration and exacerbate ecological risks. Thus, the restoration of ecological barrier points and breakpoints should be prioritized to improve regional connectivity and strengthen biodiversity conservation.

Integrating the dynamic characteristics of ecological networks into ecological conservation and restoration is essential. Rapid economic development, urbanization, and industrialization in recent decades have greatly changed regional landscape patterns and land cover, severely affecting the networked structure and characteristics [35]. This encompasses the degradation of ecological sources and a decrease in the quantity of corridors [8]. Precise ecological conservation and restoration measures are necessary for alleviating the contradictions between the economy, society, and ecology to fulfill the strategic objectives of ecological preservation and sustainable development [46]. Dynamic landscape connectivity should be emphasized and embedded in the determination of ecological conservation and restoration priority areas. Most studies on ecological conservation and restoration were primarily conducted from a static perspective, neglecting the dynamic characteristics of landscape elements. Analyzing the dynamic characteristics of ecological networks allows for an effective evaluation of changing trends and characteristics of landscape connectivity and an exploration of the impact of economic development on ecological elements. Strategies and suggestions for ecological protection and ecological restoration can then be proposed for different priority areas based on the network element optimization and restoration requirements [47].

Our analysis results revealed a decreasing trend in the number of sources and corridors from 2000 to 2020, particularly in the case of general sources and corridors. The importance of sources and corridors also declined over time. The complexity of corridors was also declining, indicating the paths for species migration were decreasing and the landscape connectivity of ecological networks was also declining. The more complex the structure of the corridors, the greater the number of corridors. This also indicates that there are more path options for species migration. If the complexity of the corridors decreases, it indicates a decrease in the number of corridors and that there are also fewer paths available for species to choose during their migration. For example, if there was a single corridor structure with only one corridor, species migration would be severely hindered when the corridor was disrupted due to human interference. Therefore, the more complex the structure of the corridors and the greater the number of corridors the better the landscape connectivity of the ecological network, which greatly facilitates species migration and ecological flow. Additionally, the number of ecological barrier points and breakpoints increased because of urban development and traffic road construction, further weakening the regional landscape connectivity [26,44]. Thus, the construction of ecological networks should extend beyond urban landscape construction. Ecological protection and restoration efforts must prioritize the conservation of biodiversity, the maintenance of ecological functions, and the improvement of landscape connectivity as their fundamental objectives. Ecological networks can be optimized, and ecological benefits can be maximized by integrating conservation and restoration strategies.

Scholars have reached a consensus that there is a need to systematically address current global ecological issues through ecological protection and restoration. Accurately determining the priority spaces for ecological protection and restoration is a prerequisite for taking specific actions. There is extensive research that has been conducted on this topic. In order to achieve systematic ecological protection and restoration actions, our research introduced landscape ecology theory into ecological protection and restoration research, which furthers the empirical studies in the aspects of biodiversity conservation and ecological space optimization. Differing from the traditional notion of “passive restora-

tion”, the implement of ecological protection and restoration through ecological networks focuses on “active adaptation” [48]. The most important thing for ecological protection and restoration efforts is to enhance overall ecological restoration effectiveness through the implementation of targeted measures in key areas. Therefore, it is essential to scientifically and accurately identify priority areas to minimize the costs and optimize the ecological restoration actions, which has already been justified in the previous studies of [44,49]. Besides, we considered the dynamic landscape connectivity characteristics in 2000, 2010, and 2020 to determine the zoning for ecological protection and ecological restoration, and proposed targeted measures for landscape elements within different zones, different from the studies of Chen [44] and Hou [49], which lacked the classification and zoning for priority areas. Our research emphasized the rationality and systematics of ecological conservation and restoration efforts, whereas the studies of Chen [44] and Hou [49] focused primarily on individual landscape elements, such as “point”, “line”, and “polygon” levels within ecological networks, ignoring the spatial configuration and connectivity between different elements during conservation and restoration actions.

However, this study has several limitations and uncertainties that need to be addressed. Initially, this study concentrated on pinpointing key areas for ecological conservation and restoration through the establishment of ecological networks and an evaluation of landscape connectivity. However, it did not consider the characteristics and habitat requirements for different species. Moving forward, establishing multispecies ecological networks across various scales will be essential to identify priority areas for ecological protection and restoration efforts. Second, the appropriate thresholds for distances, dPCs, and corridors, and their ecological benefits in different geographical contexts and spatial scales, should be considered in ecological network studies [26]. Therefore, further research should be conducted on the impact of different thresholds on ecological effects and biological flow. Ultimately, this study aimed to construct ecological networks from a systematic and holistic viewpoint. However, it overlooked the issue of scale nesting and failed to account for the variations and interconnections among landscape elements across different scales. Therefore, future research should concentrate on constructing ecological networks at different levels across scales [50].

## 5. Conclusions

In this study, an ecological network assessment framework was integrated on the basis of landscape ecology theory to identify priority areas for ecological conservation and restoration in Nanchang City. Multiple priority actions were provided on the basis of the findings. The results are as follows: Firstly, the ecological sources and corridors have shown a decreasing trend from 2000 to 2020 with 28.57% less ecological sources and 36.16% less ecological corridors. Secondly, the ecological barrier points and breakpoints increased over time, with four new ecological barriers and 54.9% more ecological breakpoints from 2000 to 2020. Finally, the identification of ecological conservation priority areas, ecological improvement priority areas, and ecological restoration points were determined based on dynamic connectivity analysis. Overall, this study addressed the lack of awareness regarding spatial connections of ecological elements in ecological restoration research and aimed to achieve ecosystem structural and functional stability and connectivity from systematic and holistic perspectives. The framework developed in this study is also suitable for identifying ecological priorities in other rapidly urbanizing regions in the future.

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