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A Framework for Developing Biodiversity Conservation Networks Based on Morphological Spatial Pattern Analysis and the Maximum Entropy Model: A Case Study of the Jianghan Plain, China

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Abstract: Constructing ecological networks in urban areas improves ecosystem stability and biodiversity protection. However, most studies focus on optimizing ecological environments through objective assessments, often neglecting species diversity. This study developed a biodiversity grading framework for the Jianghan Plain using species observation and ecosystem diversity data. Supported by ArcGIS, ecological sources were identified via MSPA and graded using the Guidelines and MaxEnt model. The MCR model was used to simulate connectivity barriers between ecological sources and calculate the minimum cumulative resistance distance, thereby generating corridors and ultimately constructing a hierarchical biodiversity conservation network for the Jianghan Plain. Our findings indicated the following: (1) The Jianghan Plain hosts 21 major ecological sources, primarily natural water bodies at the plain's edge, which can be classified into five primary and 16 secondary sources based on biodiversity grades. (2) The recessive corridors, comprising 10 primary and 95 secondary ones, are mainly concentrated in the central Jianghan Plain, with primary corridors located centrally and westward, characterized by a large overall span. (3) Changhu Lake and Honghu Lake, two critical water bodies with high-quality habitats and significant biodiversity, were identified as key ecological nodes from the ecological sources, bridging and guiding the central and southern corridors. (4) Based on the ecological network distribution and key nodes and corridors, a "three zones, three belts, and two points" strategy was proposed for optimizing the Jianghan Plain's ecological network. This study provides a novel framework and theoretical support for regional habitat, biodiversity conservation, and sustainable development.

Keywords: biodiversity conservation; ecological network; maximum entropy model; minimum cumulative resistance model; Jianghan Plain

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1. Introduction

Biodiversity underpins human survival and development [1], and biodiversity conservation is constantly put on the agenda of national and even world development [2]. However, urbanization has resulted in fragmented habitats, reduced connectivity, and degraded biodiversity [3–5]. The establishment of rational ecological networks between regional habitats is an important means of conserving biodiversity in response to the severe situation of biodiversity loss due to urbanization [6]; so, the related research has received great attention.

The primary research methodology for ecological networks involves the sequence of "source identification → corridor construction → network evaluation". Source identification serves as the foundation for network construction, with morphological spatial pattern analysis (MSPA) being recognized for its extensive application and scientific objectivity [7–9]. For corridor construction, various methods exist, with the minimum cumulative resistance (MCR) model, based on the "source-sink" theory, emerging as a mainstream method due to its flexibility [10–12]. Network evaluation is crucial for analyzing ecological networks and serves as key evidence for the rational construction and optimization of these networks.

Currently, scholars predominantly utilize methods such as the structural evaluation of landscape connectivity [13,14], the gravity model [15], graph theory [16], and circuit theory [17], among others, to evaluate and optimize ecological networks. These approaches are designed to assess the ecological environment objectively, focusing on factors such as the difficulty of connecting patches and corridors, the energy consumption of biological flows, and habitat quality. Nevertheless, existing network evaluation methodologies are not without limitations. For instance, the analysis of landscape patterns often involves the use of numerous landscape indices, which can result in data redundancy and a high degree of overlap in the expression of meanings [18]. Under these circumstances, the results of the analysis may not objectively reflect the ecological processes under study, potentially leading to biased conclusions [19]. Additionally, in terms of habitat assessment, the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model has been shown to have advantages due to its multi-module structure and the ease of accessing data [20,21]. This approach can serve as a surrogate indicator for biodiversity to some extent when species data are lacking, but it largely overlooks the subjective selection factors of organisms. Since obtaining spatial distribution data for species is challenging, habitat selection often relies on expert knowledge [22]. Consequently, the efficacy of the simulated ecological networks in protecting real target species remains to be tested. Constructing ecological networks based on the spatial distribution data of species significantly enhances the reliability of the network, particularly when focusing on the distribution of specific species within a defined landscape area [23].

The Yangtze River Protection Law of the People's Republic of China (2020) explicitly states the need to strengthen the protection and restoration of the ecological environment in the Yangtze River basin and to establish a comprehensive biodiversity protection standard system [24]. As an important geographical unit through which the Yangtze River passes, the Jianghan Plain plays a significant role in maintaining the ecological environment quality of the Yangtze River and has, therefore, been selected as a case study site. In recent years, the extensive exploitation of natural resources such as water, wetlands, and minerals has severely impacted the ecological stability of the Jianghan Plain, leading to a rapid decline in biodiversity [25]. Additionally, the Jianghan Plain has not yet established a biodiversity conservation system. In the context of the green development strategy of the Yangtze River Economic Belt, there is an urgent need to establish a complete ecological network to enhance habitat quality and protect regional biodiversity.

To promote regional sustainable development, China issued the Guidelines for Evaluating the Carrying Capacity of Resources and the Environment and the Suitability of Land and Spatial Development (Trial) (hereinafter referred to as "the Guidelines") in 2020 [26], which propose three levels of biodiversity evaluation criteria (ecosystem, species, and genetic resources). For the Jianghan Plain, ecosystem and species diversity effectively reflect its biodiversity, with data on these levels being more accessible and publicly available compared to the genetic level. Therefore, this study adopts the Guidelines and integrates data on ecosystem diversity and species observations. Using the Maximum Entropy Model (MaxEnt) and ArcGIS, we constructed biodiversity grades for the Jianghan Plain to assess the importance of ecological sources and corridors hierarchically. This approach aims to develop an ecological network and provide a scientific foundation for biodiversity conservation in the Yangtze River basin while optimizing regional ecological networks. Specifically, the objectives of this study were as follows: (1) to build a biodiversity assessment framework that integrates species data, landscape data, and models, while identifying and grading ecological sources; (2) to screen important ecological network nodes from ecological sources and determine key ecological corridors; and (3) to clarify the ecological network construction pattern, with a focus on biodiversity conservation.

2. Materials

2.1. Study Area

The Jianghan Plain is located in Hubei Province, including eight county-level administrative districts of Jingzhou City, namely Jingzhou District, Shashi City, Jiangling County, Gong'an County, Jianli City, Shishou City, Honghu City, Songzi City, and three county-level cities directly administered by the province, namely Xiantao, Qianjiang, and Tianmen, as well as radiating the surrounding areas, such as Caidian District, Hanchuan City, Yingcheng City, Shayang County, Jingshan City, Zhongxiang City, Zhijiang City, and Yicheng City, with a total area of more than 46,000 square kilometers [27]. It has a subtropical monsoon climate, with the Yangtze River running through the area and a large number of lakes, water networks, and dykes. The varied topography and suitable temperature have created a natural ecosystem with rich species and diverse resources in the Jianghan Plain. Currently, 9.19% of the Jianghan Plain's land area is designated as part of the ecological conservation red line, which represents areas with critical ecological functions that require mandatory and strict protection. These include multiple national nature reserves such as the Shennongjia National Nature Reserve, the Wufeng Houhe National Nature Reserve, the Shishou Elk National Nature Reserve, etc. Additionally, the plain is home to several nationally protected wildlife species, including the Yangtze River dolphin, Milu deer, and finless porpoise, making it a valuable region for biodiversity research.

2.2. Data Sources and Processing

The data used in this study mainly include the following: (1) Land-use data for 30 m in 2020 from GlobeLand 30 (http://www.globallandcover.com, accessed on 19 February 2024). (2) Ecosystem diversity data from the Ecosystem Assessment and Ecological Security Database (https://www.ecosystem.csdb.cn, accessed on 22 February 2024). (3) Species observation data from the Global Biodiversity Information Platform (https://www.gbif.org, accessed on 22 February 2024) for the period of 2010-2020, for a total of 40 species of birds, including black-necked grebes (*Podiceps nigricollis*), the Chinese sparrowhawk (*Accipiter soloensis*), and other national second-grade protected animals. (4) The Digital Elevation Model (DEM) from the Geospatial Data Cloud (http://www.gscloud.cn, accessed on 27 February 2024). (5) The China meteorological background dataset from the Resource and Environmental Science Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn, accessed on 27 February 2024). (6) Normalized Vegetation Index (NDVI) data and the 2010 population density data from the Global Change Research Data Publishing & Repository (http://www.geodoi.ac.cn/, accessed on 27 February 2024). (7) Vector data for rivers and roads from the National Catalogue Service for Geographic Information (https://www.webmap.cn, accessed on 27 February 2024). Referring to related studies [12], all the above data were resampled using ArcGIS with a uniform spatial resolution of 30 m, and the rest of the data and information were obtained from government portals.

3. Methods

Building upon the ecological network framework of "source identification—corridor construction—network evaluation" mentioned in the Introduction section, we constructed a biodiversity grade model for the Jianghan Plain (Figure 1), which forms the basis for our study of the ecological network in the region.

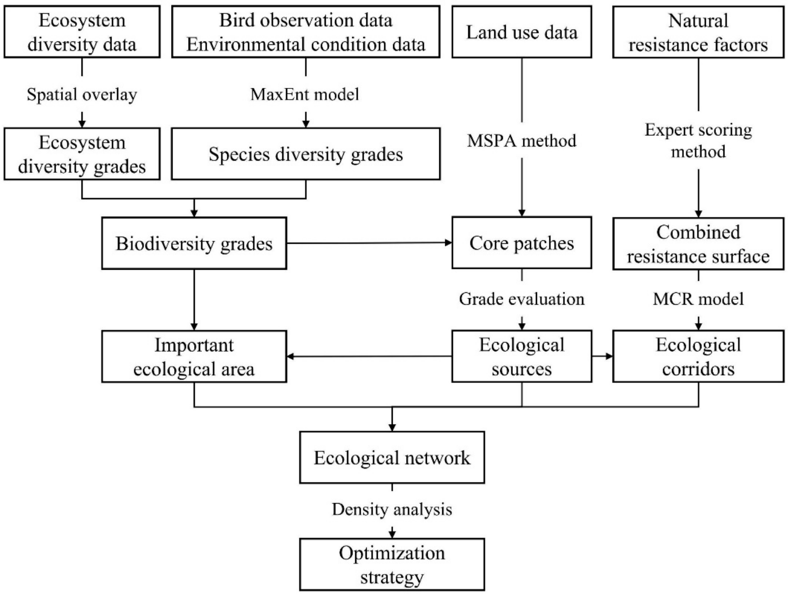

Figure 1. The implementation procedure of ecological network construction.

3.1. Biodiversity Assessment

3.1.1. Grading of Ecosystem Diversity

At the ecosystem level, based on the Guidelines, ecosystems with high authenticity and integrity that require priority protection, such as forests, shrublands, grasslands, inland wetlands, deserts, and marine ecosystems, are classified as areas of extremely important biodiversity conservation. Other ecosystems requiring protection are classified as areas of important biodiversity conservation [28]. The grading method and specific list of ecosystem diversity levels were thus determined.

The data of forest, shrubland, grassland, desert, wetland, farmland, and other ecosystem types at the ecosystem level were obtained from the China Ecosystem Assessment and Ecological Security Database, and the vector files of the selected sources were cropped to obtain the ecosystem distribution areas in the study area. The extremely important areas of ecosystem diversity (grade 2) were identified according to the priority conservation list in the Guidelines, and the remaining areas were defined as important ecosystem areas (grade 1), resulting in the ecosystem diversity grades (Figure 2a).

3.1.2. Grading of Species Diversity

The MaxEnt model can simulate the regional distribution possibilities of target species using species observation data under multiple environmental condition constraints [29,30]. As the Jianghan Plain is rich in bird resources and distributed with numerous wetlands, it is an important station and habitat for bird migration from East Asia to Australasia [31]. Additionally, compared to other species, birds are more easily observable and possess strong migratory abilities [11,32], which enable them to represent the habitat usage distribution patterns of most species. Therefore, birds were chosen as the representative species for this study. Considering habitat requirements, urban environmental disturbances, and the related literature [33,34], and based on the actual conditions of the Jianghan Plain, three categories of environmental variables were selected: bioclimatic factors, habitat factors, and disturbance factors. Bioclimatic factors include the aridity index and humidity index. Elevation, slope, and land-use type represent habitat characteristics, while the distance from rivers and NDVI indicate food and other resource availability. The distance from roads assesses potential habitat disturbances from urban environments, and population density serves as a proxy for human activity intensity, which could affect bird breeding and survival. To ensure consistency, all environmental variables were resampled in ArcGIS 10.7, unified under a consistent coordinate system and a spatial resolution of 30 m × 30 m. Based on these nine environmental variables, the MaxEnt model was applied to predict bird distribution areas in the study region. The model achieved an AUC (area under the curve) value of 0.931, indicating a high level of accuracy.

Then, the ArcGIS 10.7 software was used to overlay the results of all the possible distribution areas of birds to obtain the distribution map of species diversity, and finally, the natural breakpoint method was used to classify the two levels of high species diversity (grade 2) and average species diversity (grade 1) (Figure 2b).

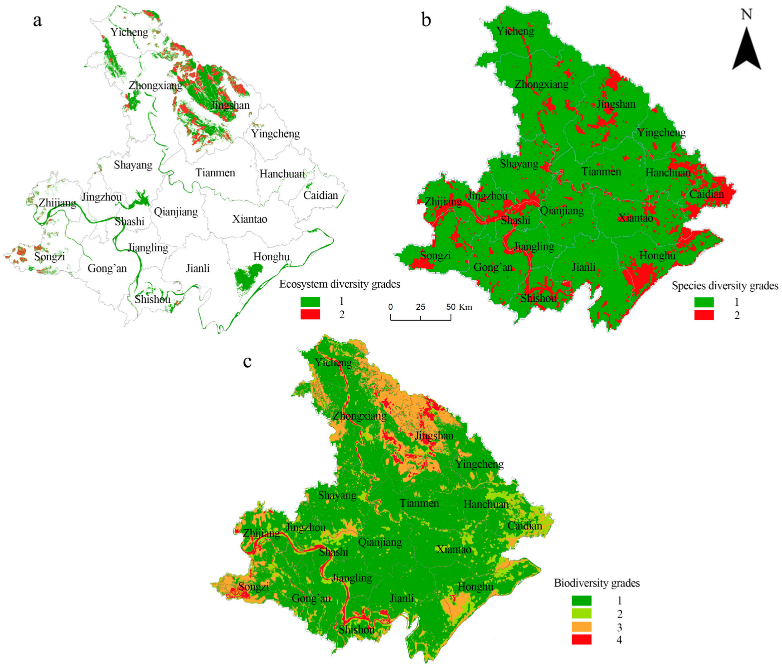

Figure 2. The composition of Biodiversity Grading Evaluation in the Jianghan Plain. (**a**) Ecosystem diversity grades. (**b**) Species diversity grades. (**c**) Biodiversity grades.

3.1.3. Biodiversity Grading Framework

The ecosystem diversity grades and species diversity grades obtained above were spatially overlaid using ArcGIS, from which the results of the Jianghan Plain biodiversity grades were obtained (Figure 2c), ranking 1, 2, 3, and 4 from low to high, respectively.

3.2. Ecological Network Construction

3.2.1. Ecological Source Identification Based on the MSPA Method

Based on land-use data and the current status of biological distribution and activities in the Jianghan Plain, four landscape types of forest land, grassland, wetland, and water bodies were extracted as the foreground, and cultivated land, construction land, and bare land as the background. The Guidos 3.0 software was employed to conduct a morphological spatial pattern analysis using the eight-neighborhood method, resulting in the identification of seven landscape types [8]. Among them, the core area is the larger habitat patch in the foreground image element, which can provide larger habitats for species and is important for the conservation of biodiversity. A set of criteria for selecting ecological sources in the Jianghan Plain was established based on the scientific literature [35] and expert evaluations: (1) these key sources should support species survival, reproduction, and ecosystem stability within the plain's ecological network; (2) larger habitats are more susceptible to landscape fragmentation, making them priority targets for connectivity [36,37]; and (3) patches should be evenly distributed within the target area, as overly clustered sources can reduce the ecological effectiveness of urban networks [38]. After multiple rounds of pre-screening, patches with core areas greater than 10 km^2 were identified as ecological sources, playing a critical role in biodiversity conservation in the study area.

We utilized the vector files of selected ecological sources to crop the biodiversity results of the Jianghan Plain, thus obtaining the biodiversity grades for the chosen sources. The focus of identifying important ecological source areas lies in extracting regions with higher habitat quality and a greater probability of species distribution [30]. Consequently, we define ecological source areas with grade 4 biodiversity as primary sources, while all other source areas are categorized as secondary sources.

3.2.2. Ecological Corridor Construction Based on the MCR Model

(1) Ecological resistance surface construction

The natural geographical conditions of a region affect the difficulty of biological migration and population expansion. Therefore, land-use type, slope, elevation, and the normalized vegetation index were selected as the natural resistance factors to construct an ecological resistance surface evaluation system (Table 1). We invited eight experts with extensive experience in biodiversity research to score each factor. The average scores were calculated to determine the weights of each factor. Then, the natural breaks method was used to assign values ranging from 1 to 5. Finally, a weighted sum was applied across the grid to generate the ecological resistance surface for the Jianghan Plain (Figure 3).

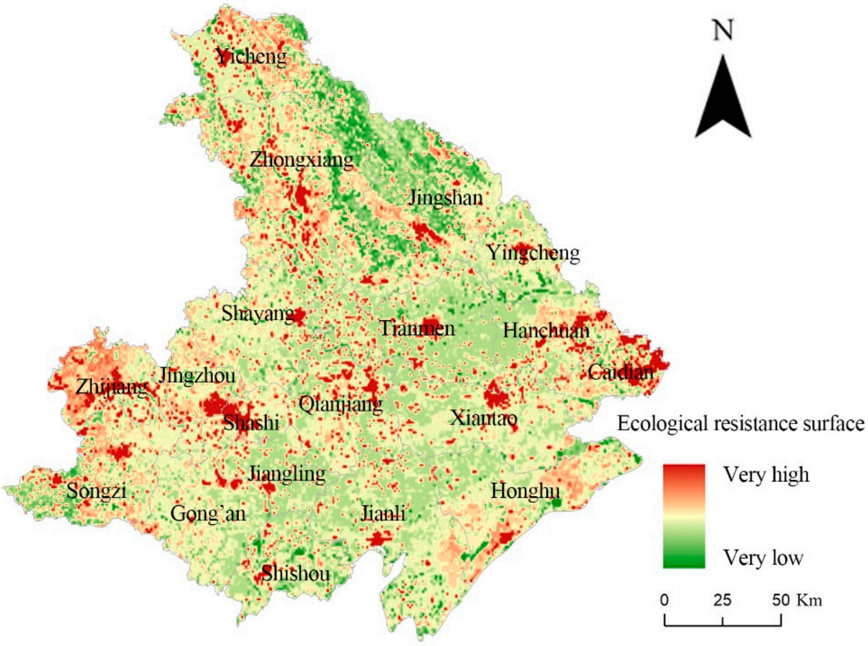

Figure 3. Ecological resistance surface of the Jianghan Plain.

Table 1. Evaluation index system of ecological resistance.

Weight	**Index System**	**Resistance Value**				
		1	**2**	**3**	**4**	**5**
0.5	Land use	Wetlands and forest land	Grassland and waters	Cultivated land	Bare land	Building land
0.15	Slope (°)	<3	3–8	8–15	15–25	>25
0.15	DEM (m)	<40	40–90	90–250	250–450	>450
0.2	NDVI	>0.82	0.72–0.82	0.58–0.72	0.38–0.58	<0.38

(2) Ecological corridor identification

The ecological corridor is composed of the dominant corridor (such as rivers, ditches, etc.) and the recessive corridor. The recessive corridor is an invisible network suitable for the migration and exchange of organisms underground or in the air, which can enhance connectivity between sources and improve biodiversity [39]. Based on the resistance surface formed by various landscape elements, the paths between two ecological source site nodes were calculated using the cost distance analysis method, and the recessive ecological corridors in the study area could be obtained by removing the duplicate paths. The formula is as follows:

$$MCR = \int_{min} \sum\nolimits_{j=n}^{i=m} \left(D_{ij} \times R_i\right) \tag{1}$$

where MCR is the minimum cumulative resistance value, D_{ij} refers to the spatial distance from source j to landscape unit i, and R_i refers to the resistance value of landscape unit i.

During the modeling process, to highlight the importance of corridors, this study simulated corridors between primary sources, between primary and secondary sources, and between secondary sources. These were classified as primary, secondary, and tertiary corridors, respectively.

4. Results

4.1. Ecological Source Analysis

Based on the biodiversity classification and the size of the area, 21 important ecological source sites were selected as source patches for constructing the ecological network (Figure 4a), and they were numbered. Among these, five are classified as primary ecological sources, and 16 as secondary ecological sources (Figure 4b).

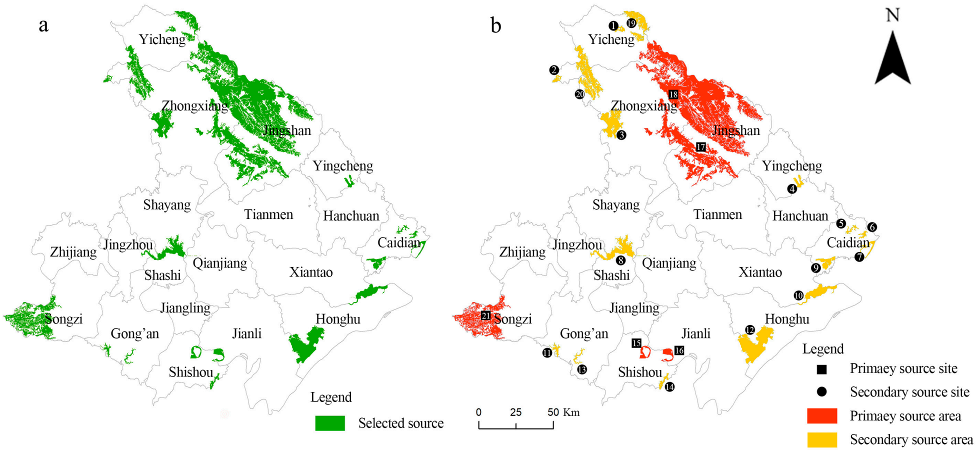

Figure 4. Distribution of ecological sources (**a**) and their grades (**b**) in the Jianghan Plain.

4.1.1. Primary Source

The primary ecological sources are mainly distributed in the northern part of the Jianghan Plain, including Jingshan City, Zhongxiang City, and Yicheng City, as well as in the southern areas of Songzi City and Shishou City. In the north, ecological sources 17 and 18 are part of the Great Hongshan Scenic Area, which was designated as a national key scenic area by the State Council in 1988. In the south, ecological source 21 is the Weishui Scenic Area, which began development as a tourist destination in 1996 and was approved as a national 4A-level tourist attraction in 2016. Ecological sources 15 and 16 are part of the Tianezhou Baiji National Nature Reserve of Yangtze River, established with official approval in 1992. The No. 18 source area is the largest, and the areas of grade 3 and 4 biodiversity are also the largest (Table 2), which proves that Jingshan City, Zhongxiang City, and Yicheng City, where it is located, are rich in biodiversity. Although the areas of No. 15 and No. 16 are the smallest among the primary sources, the area proportions of their grade 4 biodiversity are higher than 77%, far exceeding that of other primary sources, which indicates that the sources have very high habitat quality and rich biodiversity and also proves that the ecological environmental protection of the White-Flag Dolphin National Nature Reserve of Tian-e-Zhou Oxbow of Yangtze River in Shishou City has achieved remarkable results. The No. 21 source has the lowest biodiversity in its grade, and the conservation of biodiversity in the city of Songzi, where it is located, needs to be emphasized.

Table 2. Statistics on the area and biodiversity of ecological sources in the Jianghan Plain.

Grade of Source	Serial Number	Area (km^2)	Area of Grade 4 Biodiversity (km^2)		Area of Grade 3 Biodiversity (km^2)		Area of Grade 2 Biodiversity (km^2)		Area of Grade 1 Biodiversity (km^2)	
Primary source	18	1647.65	243.94	14.81%	1344.54	81.60%	56.24	3.41%	2.93	0.18%
	17	518.54	117.72	22.70%	395.92	76.35%	4.88	0.94%	0.02	0.003%
	21	333.00	97.59	29.31%	199.61	59.94%	35.80	10.75%	0.00	-
	15	25.64	19.87	77.47%	5.78	22.53%	0.00	-	0.00	-
	16	32.03	25.67	80.14%	6.36	19.86%	0.00	-	0.00	-
Secondary source	1	10.92	0.00	-	2.25	20.59%	8.67	79.41%	0.00	-
	19	99.72	0.00	-	80.25	80.47%	19.41	19.46%	0.07	0.07%
	2	11.15	0.00	-	0.00	-	7.37	66.05%	3.79	33.95%
	20	194.61	0.00	-	164.10	84.32%	24.67	12.68%	5.84	3.00%
	3	146.74	0.00	-	143.54	97.82%	3.19	2.18%	0.00	-
	4	20.78	0.00	-	13.19	63.45%	7.60	36.55%	0.00	-
	5	12.02	0.00	-	11.28	93.85%	0.74	6.15%	0.00	-
	6	10.64	0.00	-	10.57	99.40%	0.00	-	0.06	0.60%
	7	20.83	0.00	-	16.66	79.95%	0.00	-	4.18	20.05%
	8	131.61	0.00	-	123.30	93.69%	8.30	6.31%	0.00	-
	9	41.36	0.00	-	39.62	95.80%	1.72	4.16%	0.02	0.04%
	10	86.50	0.00	-	70.39	81.38%	10.45	12.08%	5.66	6.55%
	11	14.26	0.00	-	4.85	33.99%	5.73	40.21%	3.68	25.80%
	12	260.65	0.00	-	246.04	94.39%	14.61	5.61%	0.00	-
	13	12.66	0.00	-	6.21	49.07%	6.45	50.93%	0.00	-
	14	17.54	0.00	-	10.62	60.55%	6.91	39.42%	0.01	0.04%

4.1.2. Secondary Source

There are four ecological sources of 8, 9, 10, and 12 in the secondary source areas with water as the main body. Only the No. 8 source is located in the middle of the study area, which is Changhu Lake in Jingzhou City, and the rest of the secondary sources are located at the edge area of the study area (Figure 4). The No. 9 source consists of Yayuan Lake, Wangjiashe Lake, Chen Lake, and Zhangjiadahu Lake in Wuhan City, with the highest area proportion of grade 3 biodiversity, and the No. 10 source is located in Wuhu Lake in Xiantao City, with the lowest area proportion of grade 3 biodiversity. As can be seen from the satellite remote sensing images, although the two ecological sources are close to each other, the water area of source No. 9 is complete and less affected by human beings, while the water area of source No. 10 is divided by the highway and encroached upon by a large amount of cultivated land. Therefore, more attention should be paid to the ecological environment protection of Wuhu Lake in Xiantao City. The area of Honghu Lake in the No. 12 source is the largest, and its grade 3 biodiversity area is the largest among the secondary sources, which proves that Honghu City has fully protected the ecological environment of Honghu Lake and made it rich in biodiversity.

4.2. Recessive Corridor Analysis

A total of 276 corridors were obtained in this study, including 10 primary corridors and 95 secondary corridors (Figure 5a). The analysis shows that the recessive corridors span a large distance and there will be a greater energy consumption during the migration of organisms. The rapid urbanization in the eastern part of the Jianghan Plain and the drastic human impacts on the ecological environment have resulted in the absence of primary corridors, which is not conducive to biological migration [27].

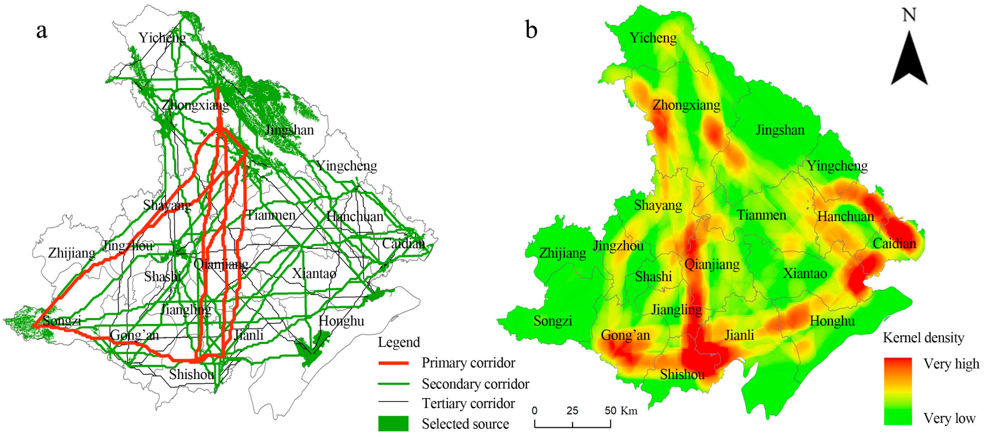

Figure 5. Recessive ecological network (**a**) and kernel density analysis (**b**) of the Jianghan Plain.

4.3. Important Network Nodes and Key Ecological Corridors

Kernel density analysis was performed based on the ecological network map formed by the simulated primary, secondary, and tertiary ecological corridors. The results of this study show that there are three important ecological network areas in the Jianghan Plain, namely the mountain forest area in the north, the water area in the south, and the urban area in the east (Figure 5). The northern mountain forest includes Yicheng City, Zhongxiang City, and Jingshan City and has a large ecological source area, high biodiversity richness, and excellent habitat quality. The southern water area is composed of old river channels that have been diverted from the upper reaches of the Yangtze River and lakes in the basin, including Songzi City, Shishou City, Jianli City, Honghu City, and Gong'an County. This area has a medium ecological source area but a high overall biodiversity richness. The eastern urban area includes Caidian District, Xiantao City and Xiaogan City and has a small ecological source area, low biodiversity richness, and average habitat quality.

There are currently two ecological corridor clusters of a certain scale in the Jianghan Plain, one of which is a cluster of ecological corridors from the mountain forest to the water area that runs through Jingmen and Jingzhou City, and the other is a cluster of ecological corridors along the Yangtze River that runs through Jingzhou City to Xiantao and Wuhan City. The number of corridors within these two clusters is large in number and high in quality. In addition, there is a corridor cluster from the northern mountain forest area to the eastern urban area that has not yet formed a certain scale.

Kernel density analysis identified two critical nodes in the Jianghan Plain's ecological network: source No. 8 and source No. 12. These nodes represent areas with a high density of corridors and require special attention due to their roles in anchoring the overall ecological network and bridging different ecosystems. Specifically, Source 8, Changhu Lake, is located in the central Jianghan Plain and exhibits high network density (Figure 5b). However, as indicated by Table 2, despite its large area, the biodiversity richness of Changhu Lake remains relatively low. Source 12, Honghu Lake, is a central node within the Yangtze River ecological corridor system. Its significance lies in its role as a hub connecting ecological corridors anchored by the Yangtze River. These corridors extend along the river and expand inland into the Jianghan Plain, thereby sustaining and safeguarding biodiversity in the region. The prioritization of these two nodes for conservation stems from their substantial source area, coupled with the relatively low proportion of high-biodiversity zones within them. Therefore, enhancing biodiversity richness in these areas is essential for strengthening the ecological network and preserving the ecological integrity of the Jianghan Plain.

4.4. Strategy of Ecological Network Construction

Based on the analysis of the current status of biodiversity and the ecological network in the Jianghan Plain, we propose an ecological network construction pattern of "three zones, three belts, and two points" to maintain and enhance the biodiversity of the Jianghan Plain (Figure 6). It is important to emphasize that although this study uses birds as the case study, given their role as key indicator species in the Jianghan Plain's ecological network, the proposed strategies can also inform the protection of other animal species.

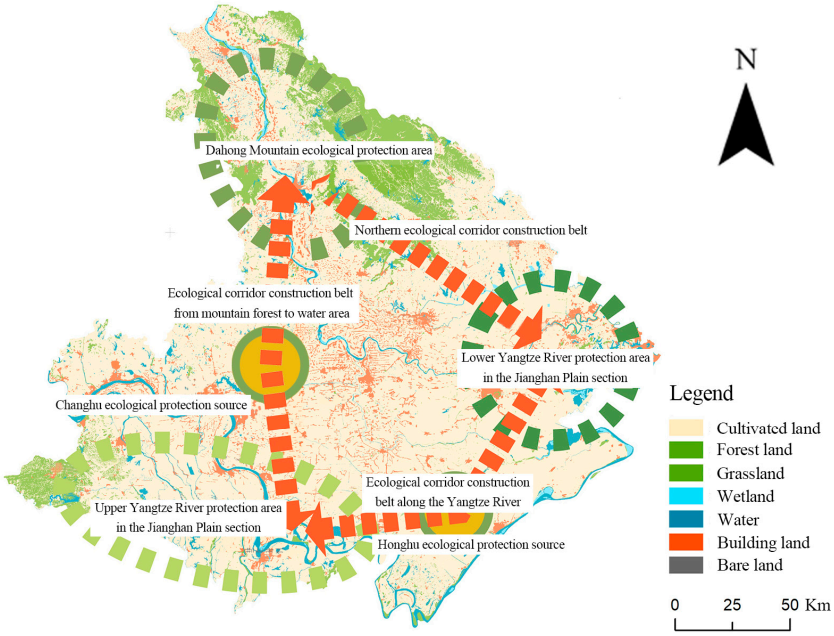

Figure 6. Construction of the ecological network in the Jianghan Plain.

The "three zones" refer to the three key ecological source protection and construction zones formed according to the distribution of the sources to play an aggregation effect. (1) Dahong Mountain ecological protection area. This region exhibits a high overall richness of biodiversity, but the terrain results in high resistance to biological movement; thus, there is a certain level of obstruction to species migration along the ecological corridors. In the future, it is recommended that while continuing to maintain the ecological environment, efforts should focus on constructing more ecological corridors between Yicheng City, Jingmen City, and Tianmen City. This would ensure the migration of forest species to the plains, promoting the unified development of regional biodiversity. (2) Upper Yangtze River protection area in the Jianghan Plain section. The biodiversity richness of this region is extremely high, with several primary sources distributed here, but the source area is small. The ecological corridors in this area are mostly based on water bodies, which makes it easy for organisms to migrate. In the future, we suggest expanding the area of ecological sources to enhance the biocapacity, while building ecological corridors along the Yangtze River to efficiently drive biodiversity in the basin. (3) Lower Yangtze River protection area in the Jianghan Plain section. This region exhibits a lower richness of biodiversity, with insufficient protection of ecological source areas, and human activities severely impacting wildlife conservation. In the future, we propose to reduce the impact of human interference on ecological sources and control the environmental impact of economic development. Additionally, the quality of habitats should be improved and the connectivity of the source areas should be enhanced to provide a good ecological base for the migration and settlement of organisms.

The “three belts” refer to three key ecological corridor construction belts to enhance the connectivity of sources. (1) Ecological corridor construction belt from mountain forest to water area. This corridor mainly connects the Dahongshan ecological protection area and the upper Yangtze River protection area in the Jianghan Plain section, running through Jingmen City and Jingzhou City. The corridor has high biodiversity and a strong demand for biological flows, so it needs to be constructed as a priority. It crosses the agricultural development area of the Jianghan Plain, so it needs to pay attention to minimizing the interference of human factors on biological migration. (2) Ecological corridor construction belt along the Yangtze River. This corridor connects the source areas of the upper and lower reaches of the Yangtze River and has high biological mobility. In the future, the waters and surrounding green areas should be incorporated into the construction of ecological source areas to promote the role of the corridor in expanding biological habitats. (3) Northern ecological corridor construction belt. This corridor construction belt mainly connects the Dahongshan ecological protection area and the Wuhan urban area. The terrain of the area creates a greater resistance to biological migration, while the corridor is too long and there is no large, high-quality habitat as a bridging point in the middle of the corridor, all of which contribute to the poor biodiversity of the area. We suggest that future development should involve the construction of ecological corridors along rivers or forest belts, with enhanced ecological conservation measures to form a corridor zone of a certain scale, thereby facilitating biological migration.

The “two points” refer to the two ecological sources that play a guiding and bridging role in the ecological corridor construction belt. The areas of the Changhu ecological protection source and the Honghu ecological protection source are large and the habitat quality is high, but their current biodiversity richness is not high enough to fully assume the roles of guiding and bridging ecological corridors and biological migration stations. In the future, we suggest reducing the development and protecting habitats with the long-term goal of increasing biodiversity, thereby upgrading the grade of the source area and driving the development of the overall ecological network.

5. Discussion

Despite the extensive use of the MSPA method in constructing green ecological networks [10,14], the identification of ecological sources based on the biodiversity of key species observed has often been overlooked [40]. Previous efforts to grade ecological sources have primarily relied on landscape pattern analysis and ecosystem service assessments [17,21], but these approaches have typically lacked data on key species. To address these gaps, and considering the specific context of the Jianghan Plain, this study adopted an integrated approach to biodiversity conservation network design. Specifically, the MaxEnt model was employed to predict the potential distribution of bird species. The construction process leveraged various functionalities of the ArcGIS software, including the following key steps: first, ecological sources were classified by integrating ecosystem and species diversity; second, ecological corridors were identified using the MCR model based on the constructed resistance surface; and finally, key nodes within the ecological network were selected using kernel density analysis. Previous studies relied solely on habitat quality and ecological sensitivity assessments to construct networks [15,41], which may fail to capture the distribution of key species in the absence of empirical data. Our method overcomes this limitation. Furthermore, by using the categorization of "extremely important" and "important" ecological protection areas from the Guidelines as the foundation for ecosystem classification, this approach also mitigates the potential overestimation of species distributions by the MaxEnt model [42,43]. As a result, the graded ecological sources more accurately reflect regional biodiversity distribution patterns, providing robust support for the development of reliable and practical methods to construct regional ecological networks in the context of national spatial planning.

Some studies on ecological network construction still focus on provincial or municipal scales, highlighting the characteristics of highly urbanized ecological networks [12,30,38]. In this study, 21 ecological sources in the Jianghan Plain were identified based on the biodiversity framework, providing a scientific foundation for biodiversity conservation and ecological space optimization in plain areas. The results indicate that the identified ecological sources are primarily distributed along the edges of the plain, which aligns with the ecological security pattern of the Jianghan Plain designed by Sun et al. [25]. This may be because the periphery of the plain serves as a transitional zone between different terrains and habitats. These edge areas are often subject to greater protective measures, such as the establishment of nature reserves, and are characterized by higher habitat diversity and quality. Additionally, compared to central regions, edge areas experience lower levels of anthropogenic disturbance, allowing for the preservation of more natural habitats that facilitate wildlife migration. Notably, compared to previous approaches based solely on area size [44], incorporating biodiversity levels provides a better indicator of the ecological importance and the value of patches within a network. For example, despite their smaller size, sites 15 and 16 in Shishou City were classified as primary sources due to their exceptionally high biodiversity. This reflects their critical role in ecological network construction as national nature reserves. Conversely, site 20 in Zhongxiang City, despite its large size, was categorized as a secondary source because of its relatively low biodiversity. This area is actually a common mountainous forest with a relatively simple ecosystem and community, making it less capable of assuming a core role in corridor network establishment. Thus, future ecological conservation and planning efforts should focus on a comprehensive assessment of regional biodiversity conservation status and trends, rather than merely targeting area, quantity, or protection ratios [45].

Using the MCR model, 276 corridors were identified, including 10 primary corridors and 95 secondary corridors. The considerable distance between source areas results in large spans for the ecological corridors, with a notable lack of significant corridors in the eastern region. This may be attributed to Wuhan's role as the core city in the Jianghan Plain, driving urbanization in the eastern areas. However, rapid industrialization and commercialization have profoundly affected the original ecological environment, creating challenges for land-use changes and biodiversity conservation [27,46]. Additionally, the differing topographies between the northern and eastern regions complicate the establishment of corridors between these areas. To address this, it is critical to incorporate additional ecological source sites as bridging points or to develop ecological corridors along rivers or forest belts to reinforce network stability. Our findings also highlight that water bodies and wetlands often dominate ecological networks as essential components. The continuity of waterways is crucial for maintaining habitats for local species and migratory birds, which significantly enhances biodiversity and facilitates species migration and dispersal [5,11]. Consequently, it is vital to strictly protect water corridors within key ecological networks.

The *Outline of the 14th Five-Year Plan (2021–2025) and Vision 2035 of the People's Republic of China* emphasize constructing a biodiversity conservation network to improve the overall quality of regional natural ecosystems [47]. Given the Jianghan Plain's significant ecosystem services within the Yangtze River Basin, we analyzed its ecological network structure and proposed the "three zones, three belts, and two points" strategy for construction and optimization. This strategy closely aligns with Hubei Province's resource allocation plan for the comprehensive ecological restoration project of the Jianghan Plain, ensuring the rational identification of ecological priority zones. Restoration strategies are tailored to different ecological zones based on biodiversity needs, maintaining ecological balance and security. The optimized network underscores the role of Chang Lake and Hong Lake as "stepping stones", forming a radial and circular corridor distribution pattern that facilitates species diffusion, migration, and exchange. This case study of the Jianghan Plain offers novel approaches to biodiversity conservation planning and provides scientific guidance for ecological restoration and sustainable development in plain regions.

In future research, several aspects should be considered: (1) Determination of resistance factors and weights. In constructing the ecological resistance surface, this study included only four natural resistance factors—land-use type, slope, elevation, and NDVI. However, migration is also influenced by human factors, such as road blockage and construction land interference. Thus, the rationality of the selected resistance indicators requires further validation. Additionally, the use of expert scoring for quantifying resistance factor weights introduces subjectivity. Future studies should incorporate objective data to support expert judgments whenever feasible. (2) Criteria for constructing ecological corridors. This study focused solely on birds as the target species, excluding other terrestrial animals like reptiles and mammals from the ecological source identification and protection network. This exclusion may overestimate regional biodiversity conservation. Unlike birds, these species face additional migration challenges, such as terrain, water availability, and predators, increasing risks during transit. Additionally, studies have shown that different bird species exhibit variations in habitat distribution and corridor layout depending on habitat preferences and urbanization tolerance [34,48]. Therefore, categorization based on species similarity could be more targeted. Furthermore, corridor width was not considered due to the lack of established standards for ecological corridor construction [49]. Since different species require different corridor widths based on their ecological needs, behaviors, and physical characteristics, future research should develop a comprehensive habitat suitability evaluation system, including optimal corridor widths, to better protect regional habitats and biodiversity. (3) Portability and applicability of biodiversity framework. The Jianghan Plain provides comprehensive species observation data and large-scale ecosystem information, offering strong support for biodiversity assessments. The ecological source scale in this study aligns well with the region's geographical and ecological features, making the proposed framework applicable to biodiversity management and green space planning in other plains with similar characteristics. However, in dense urban areas, data limitations may require finer-scale adjustments for identifying ecological sources. Additionally, using birds as representative species may not fully reflect the diversity of other ecosystems. Future studies should consider local key species and adapt the framework to different ecological contexts to enhance its broader applicability.

6. Conclusions

From the perspective of biodiversity conservation, the ecological network of the Jianghan Plain was constructed and optimized, with the following key findings:

(1) We developed a grading framework for ecological sources that integrates both ecosystem diversity and species diversity. Using the MSPA method and MaxEnt models, we identified 21 large ecological sources in the Jianghan Plain, including five primary and 16 secondary sources. These ecological sources are predominantly located at the edges of the plain and are mainly water bodies. This underscores the importance of prioritizing biodiversity conservation in the identification of ecological sources, ensuring that ecological protection and planning efforts are comprehensive and effective.

(2) The MCR model was applied to construct the ecological network of the Jianghan Plain, identifying 276 ecological corridors, including 10 primary and 95 secondary corridors. These corridors span a large area, with primary corridors concentrated in the central and western regions of the plain. Due to natural and human-induced factors, there is a notable lack of significant ecological corridors in the eastern part of the plain. Consequently, there is an urgent need to strengthen the construction and protection of ecological corridors, particularly those dominated by water bodies.

(3) To optimize the ecological network, we proposed the construction pattern of "three zones, three belts, and two points". Specific strategies include dividing different ecological zones, focusing on key construction areas for ecological corridors, and enhancing the role of important ecological patches as "stepping stones". These strategies provide a decision-making reference for habitat network planning in plain regions, with a focus on biodiversity conservation.

In conclusion, this study developed a biodiversity conservation network in the Jianghan Plain to provide scientific support for local policymakers. The findings lay an ecological foundation for advancing regional high-quality development and serve as a crucial reference for integrating biodiversity conservation into national spatial planning.

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