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Spatiotemporal Changes in Ecological Network Structure and Enhancing Territorial Space Management in Guilin, China

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Abstract: Accelerated urbanization and the excessive exploitation of the tourism industry are leading to a diminution of ecological spaces in tourist cities. Ecological networks are an effective method for improving patch connectivity and maximizing ecological space. However, previous research on ecological networks predominantly focuses on static snapshots, ignoring the fact that ecological networks are landscape entities with considerable spatiotemporal and structural dynamics changes. To fill this gap, we first constructed ecological networks of Guilin in 1990, 2000, 2010, and 2020, employing the integrated valuation of ecosystem services and tradeoffs (InVEST) model, the morphological spatial pattern analysis (MSPA) method, and circuit theory. Subsequently, we analyzed the spatiotemporal evolution of the ecological networks and proposed strategies for improving territorial space management. The results showed that ecological sources and corridors were generally decreasing in both number and areas (length), coupled with a notable increase in the number of ecological pinch points and barriers over the 30-year period. The spatiotemporal dynamics of ecological corridors, pinch points, and barriers were associated with ecological sources. Structural evaluation of the ecological networks revealed that during 1990~2020, the value of α (network closure) exceeded 0.7, the value of β (line point rate) surpassed 2, and the value of γ (network connectivity) was greater than 0.8, indicating robust overall connectivity within the ecological networks. The observed decline in these three indicators over time suggested a reduction in connectivity and the available dispersal pathways for species within the ecological networks, highlighting the need for protective measures and optimization strategies. Consequently, the ecological network conservation strategies and the development of ecological patterns were proposed to enhance ecological space management in Guilin. This study addresses a critical knowledge gap in the dynamics of ecological networks and offers valuable insights for mitigating habitat fragmentation and enhancing ecological space management of tourist cities.

Keywords: spatiotemporal changes; ecological space management; ecological networks; Guilin city

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1. Introduction

With the growing global population and the rapid progression of urbanization, urban areas are expanding worldwide [1]. Statistical data indicate that the global urban area increased by approximately 9687 km^2/yr from 1985 to 2015, outpacing the rate of population growth [2]. In addition, the recovery of tourism after the coronavirus disease (COVID-19) pandemic has been accompanied by a new wave of construction activity [3]. Although urbanization and tourism development contribute to enhancing land utilization efficiency and social productivity [4,5], the ongoing expansion of urban areas and tourism activities has resulted in significant environmental challenges, including landscape fragmentation, ecological space reduction, ecological function degradation, and increasing flood risk in floodplains [6–10]. Consequently, it is imperative to prioritize the implementation of ecological construction and restoration initiatives.

Ecological networks are supported by ecological sources, corridors, and nodes, which integrally connect decentralized ecological resources and ultimately establish a spatial landscape pattern analogous to a network structure [11,12]. They employ the concept of "anti-planning" to inform decision-making, aiming to achieve a balanced spatial development model that adheres to the limits of ecological sustainability (the minimum threshold) and socio-economic viability (the maximum target level for biodiversity conservation) [13]. Simultaneously, the ecological network exhibits robust spatial connectivity, permeability, and radiance, facilitating not only the integration of elements within the ecological space but also exerting influence on adjacent land areas through spatial overflow [14,15]. Consequently, as an effective approach for the restoration and sustainable development of ecological spaces, the ecological network holds considerable significance for the management of urban ecological space [16,17]. From the 1970s to the present, ecological networks are widely used in biodiversity conservation [18–20], green infrastructure construction [21,22], the planning of ecological security patterns [23,24], and ecological space management [25]. Current research on ecological networks encompasses multi-level investigations into the structure and function of an ecological network [14], ecological network construction [1], ecological network evaluation [26], ecological network optimization [27], and so on. Among them, ecological network construction is one of the most important directions of ecological network research.

At present, ecological network construction has formed a typical paradigm of "source identification --> corridor extraction --> node extraction" [28,29]. The identification of ecological sources is a critical step in ecological network assessment, necessitating a variety of methods and considerations. Current studies have extensively proposed topics for determining the spatial extent, location, and structural characteristics of ecological sources, as well as for prioritizing them according to their relative importance [30,31], sensitivity/vulnerability [32], morphology, and connectivity [33,34]. In most studies, large nature reserves or forest parks are used as ecological sources. However, this method is too subjective and lacks valid data [35,36]. Several studies also employ MSPA methods or target species-oriented identification of ecological sources [31,37]. Nonetheless, these methodologies often overlook the ecological service value and the integration of multiple methods that are essential for ecological source identification. Ecological corridors, defined as linear or ribbon-like zones that interconnect ecological sources, are essential for species migration and dispersal. Presently, methodologies such as the minimum cumulative resistance (MCR) model and circuit theory are employed to delineate corridors [38,39]. Although the MCR model is proficient in extracting corridors with minimal resistance between sources, it is inadequate in pinpointing ecological nodes [40]. Conversely, circuit theory leverages the electrons' random mobility within a circuit to simulate the stochastic movement of species, thereby identifying corridors and nodes of species migration that more accurately reflect biological characteristics [41]. Ecological nodes encompass both ecological pinch points and barriers. Ecological pinch points represent essential elements within ecological networks, playing a pivotal role in enhancing ecosystem connectivity and facilitating species migration [42]. Conversely, ecological barriers serve as impediments that obstruct the movement and dispersal of fauna [43]. Presently, the identification of ecological pinch points and barriers predominantly relies on the application of circuit theory.

Currently, relatively few studies have directly addressed the spatiotemporal changes in ecological networks as an object of study, but previous studies have involved the spatiotemporal changes in ecological networks from the perspective of resilience evaluation. Huang et al. also mentioned existing ecological networks, ignoring the fact that ecological networks are landscape entities with considerable spatial range in their study of the spatiotemporal evolution of ecological network resilience [44]. Additionally, although the existing research on ecological network construction has formed a relatively mature research paradigm, a multi-dimensional and more scientific identification method still requires further in-depth exploration to enhance the scientific rigor and effectiveness of the nodes and corridors. To address the limitations of prior research, the following im-

provements have been made in this study: (1) The four-phase ecological networks in 1990, 2000, 2010, and 2020 were constructed through an integrated multi-method approach that combines InVEST, MSPA, the gravity model, and circuit theory. (2) The spatiotemporal evolution and structural evaluation of ecological networks were analyzed to investigate their dynamic changes and structural characteristics. (3) The application of ecological network findings to enhance territorial space management. The findings of this study contribute to addressing a knowledge gap in the dynamics of ecological networks and offer valuable insights for mitigating ecospatial fragmentation and promoting the sustainability of tourist cities.

2. Materials and Methods

2.1. Study Area

Situated in the northeastern region of the Guangxi Zhuang Autonomous Region, Guilin encompasses a total land area of 27,800 km^2 and administers 6 districts, 10 counties, and 1 county-level city (Figure 1). Renowned globally for the Li River system and karst landscapes, Guilin has earned recognition as an international tourist destination boasting exceptional landscapes, a nationally famous historical and cultural city with profound heritage, and an ecologically conscious city offering a pleasant living environment [45]. The geological structure of Guilin is characterized by complexity, resulting in a diverse array of geomorphological features due to the presence of various rock compositions, with karst landforms being the most prominent. Despite the high-quality landscape resources, karst areas in Guilin are ecologically fragile, leading to significant ecological and environmental challenges [46]. Furthermore, functioning as a central nexus for regional human activities, the principal urban center promotes a variety of production and habitation modalities that may intensify land development pressures in the region. This escalation could lead to environmental challenges, including the encroachment upon ecological spaces and the fragmentation of ecological land. Consequently, it is imperative to enhance ecological space management in Guilin by exploring the spatiotemporal changes in ecological network structure.

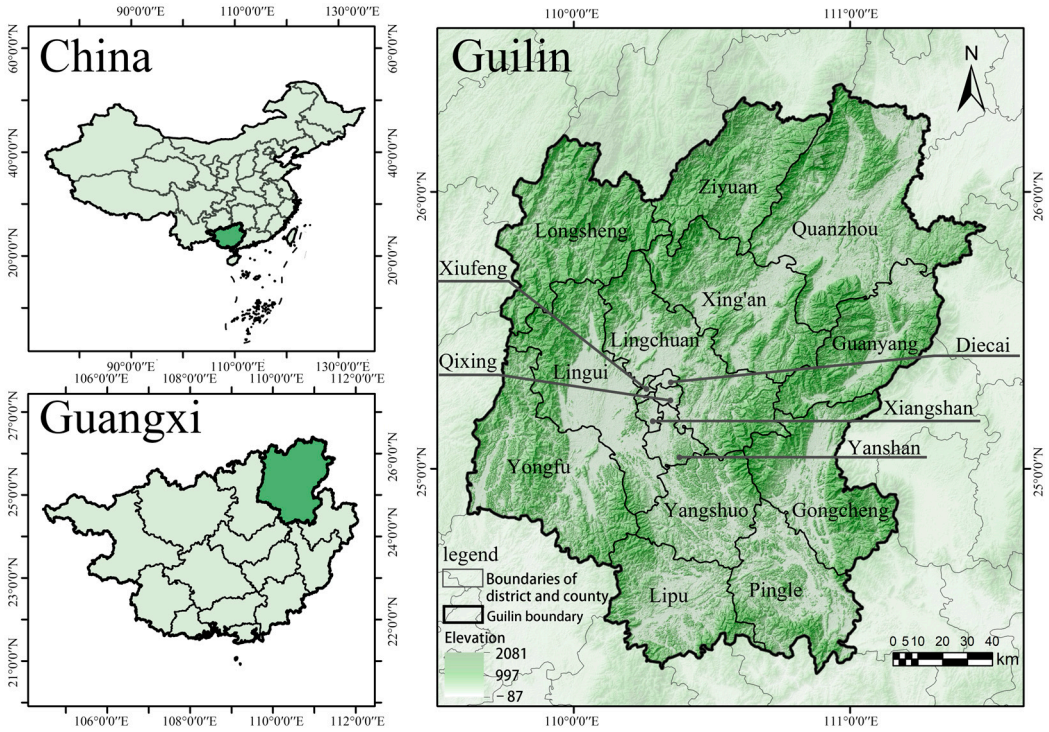


Figure 1. Location of the study area.

2.2. Data Sources and Pre-Processing

The datasets utilized in this study are listed in Table 1. Aligned with the Resource and Environmental Science Data Platform, land use in Guilin was classified into six distinct types: cultivated land, forest land, grassland, water body, construction land, and unused land. All data were consistently projected onto a coordinate system, WGS_1984_UTM_Zone _49N, and resampled to a 30 m resolution using ArcGIS 10.2.

Table 1. Data sources and description.

Data	Sources	Description
Land use	Resource and Environmental Science Data Platform (http://www.resdc.cn, accessed on 9 May 2022)	Raster, 30 m × 30 m, in 1990, 2000, 2010, and 2020
World soil types	Food and Agriculture Organization of the United Nations (http://www.fao.org/soils-portal, accessed on 15 September 2022)	Raster, 1:1,000,000
Meteorological data (annual average rainfall and temperature)	Resource and Environmental Science Data Platform (http://www.resdc.cn, accessed on 15 December 2022)	Raster, 1 km × 1 km
Monthly potential evapotranspiration	National Tibetan Plateau Data Center (https://www.tpdc.ac.cn/home, accessed on 20 December 2022)	Raster, 1 km × 1 km
Digital evaluation model (DEM) and normalized differential vegetation index (NDVI)	The National Aeronautics and Space Administration (NASA, http://search.earthdata.nasa.gov, accessed on 20 September 2022)	Raster, 30 m × 30 m
Nighttime light data	Harvard Dataverse (https://doi.org/10.7910/DVN/YGIVCD, accessed on 16 September 2022)	Raster, 500 m × 500 m
Road data	Sinomap press (1990 and 2010); College of Urban and Environmental Sciences, Peking University (2000, https://www.ues.pku.edu.cn/old/index.htm, accessed on 17 September 2022); OpenStreetMap (2020, https://www.openstreetmap.org/#map=5/35.588/134.380, accessed on 18 September 2022)	Vector, in 1990, 2000, 2010, and 2020
River network	National Earth System Science Data Center (http://www.geodata.cn/, accessed on 19 September 2022)	Vector
Statistical yearbook	Guangxi Zhuang Autonomous Region Bureau of Statistics (http://tjj.gxzf.gov.cn/, accessed on 18 December 2022)	Text
Relevant planning materials	Guilin Municipal People's Government (http://www.Guilin.gov.cn, accessed on 17 December 2022) and Guilin Natural Resources Bureau (https://zrzyj.guilin.gov.cn/xwzx/tzgg/, accessed on 18 December 2022)	Text

2.3. Research Framework

The study was conducted using a framework comprising four stages: source identification, corridor extraction, network assessment, and strategy proposal (Figure 2). First, we identified ecological sources utilizing the InVEST model, the MSPA method, and functional analysis. Then, we extracted ecological corridors, pinch points, and barriers using the MCR model, gravity model, and circuit theory. Finally, we analyze the spatiotemporal evolution and network structure of ecological networks. According to the aforementioned findings, we proposed strategies for enhancing ecological space management.

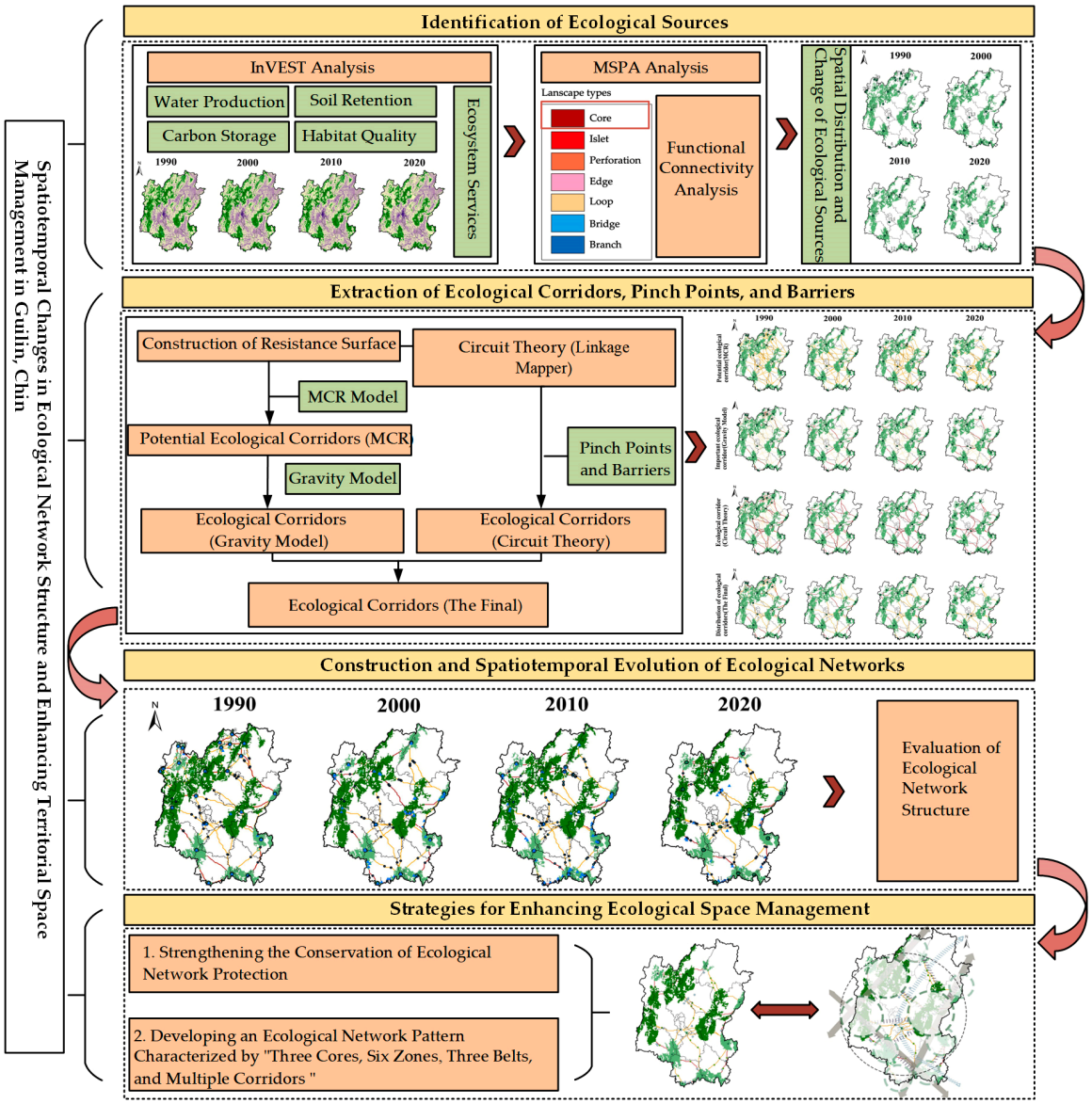


Figure 2. Research framework.

2.4. Identification of Ecological Sources

Ecological sources are essential for maintaining ecosystem stability and landscape pattern integrity, thereby providing a foundational guarantee for regional ecological security [37]. This study employed a synergistic approach, integrating the InVEST model with the MSPA method, to improve the precision and scientific robustness of the selection of ecological sources. Initially, the outputs from the InVEST model—specifically pertaining to water production services, soil conservation services, habitat quality, and carbon storage—were normalized. Referring to a related study [47] and in combination with the

ecological status of Guilin, these normalized results were aggregated using a weighted overlay method, assigning weights of 0.3, 0.3, 0.2, and 0.2, respectively, to derive the overall assessment of ecosystem service importance. Then, core areas exceeding 5 km^2 were identified using the MSPA methodology and subsequently overlaid with patches representing the top 25% of ecosystem service importance values. Finally, the connectivity of these superimposed patches was evaluated using the Conefor 2.6 quantitative connectivity metric. Patches with a dPC index greater than 0.1 were subsequently identified as ecological sources.

2.4.1. InVEST Analysis

The InVEST model possesses the capability to simulate variations in both the quantity and value of ecosystem services across diverse landscapes and cover scenarios. In this study, we quantified the value of four categories of ecosystem services—water production, soil retention, carbon storage, and habitat quality—using the annual water yield, sediment delivery ratio, carbon storage and sequestration, and habitat quality modules within the InVEST model. The formulas employed for these calculations were detailed in Table 2 [48]. Referring to a related study [47] and combining with the ecological status of Guilin, the results of the ecosystem service importance analysis were obtained by superimposing the weights of 0.3, 0.3, 0.2, and 0.2, respectively.

Table 2. Indicators of ecosystem services.

Indicators/ Weights	Formula	Parameter Meaning
Water production (WP, 0.3)	$w_{ij} = \left(1 - \frac{AET_{ij}}{P_i}\right) P_i$	w_{ij} represents the annual water yield; AET_{ij} denotes the annual average potential evapotranspiration of pixel i of land use type j; and P_i represents the annual precipitation of pixel i.
Soil retention (SR, 0.3)	$RKLS = R \times K \times LS$ $USLE = R \times K \times LS \times P \times C$ $\mathrm{SD} = RKLS - USLE$	$RKLS$ is potential soil erosion; R represents the rainfall erosivity factor; K is the soil erodibility factor; LS denotes the slope length gradient factor; $USLE$ represents potential soil loss; P denotes the factor of soil and water conservation measures; C represents the factor of vegetation management; SD represents soil retention.
Carbon storage (CS, 0.2)	$C_x = \sum_{j=1}^{j} A_{xj}\left(C_{aj} + C_{bj} + C_{sj} + C_{dj}\right)$	C_x represents the carbon storage; A_{xj} denotes the area of land cover type j in region x; C_{aj}, C_{bj}, C_{sj}, and C_{dj} are the aboveground carbon density, belowground carbon density, aboveground carbon density, and belowground carbon density of land cover type j, respectively.
Habitat quality (HQ, 0.2)	$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{W_r}{\sum_{r=1}^{n} W_r}\right) \times r_y \times i_{rxy} \times \beta_x \times S_{jr}$ $Q_{xj} = H_{xj}\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^z}\right)\right]$	D_{xj} is the degree of habitat degradation; R is the number of threat factors; Y_r is a set of raster on the r threat raster map; w_r denotes the threat factor weight; r_y is the threat factor value of raster y; i_{rxy} denotes the extent to which the threat factor r of raster y affects the habitat raster x; β_{xc} is the level of accessibility of the threat factor; and S_{jr} stands for the sensitivity of habitat type j to the threat factor r's sensitivity; Q_{xj} is the habitat quality of grid x in land use type j; H_{xj} is the habitat adaptability of grid x in land use type j; K denotes the half-saturation constant.

2.4.2. MSPA Analysis

MSPA is an image processing technique employed to segment spatial elements within raster images, grounded in mathematical morphological principles such as erosion and expansion, which help to enable the precise delineation of landscape types and structures [49]. Utilizing the Guidos Toolbox 3.0 software, this study identified seven distinct landscape types—core, islet, edge, perforation, bridge, loop, and branch. Considering the situation of Guilin, forest land, grassland, and water body were utilized as foreground image elements, while cultivated land, construction land, and unutilized land served as background data for the MSPA analysis. The core areas were specifically extracted as ecological patches for further assessment of connectivity.

2.4.3. Functional Connectivity Analysis

Landscape connectivity is a crucial factor in analyzing the migration and dispersal of species, as well as in evaluating the stability of ecosystems [50]. In this study, a total of 51 significant core patches (area > 5 km^2) were identified through MSPA to serve as the foundation for the computation of the overall connectivity index (IIC), the potential connectivity index (PC), and the patch importance index (dPC) using the Conefor2.6 software (Equations (1)–(3)) [51]. Previous research has indicated that maintaining consistency in the importance of each habitat patch leads to a more rational setting of the distance threshold [52]. Consequently, this study has established a distance threshold of 1000 m and a connection probability of 0.5 after multiple iterations.

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^{*}}{a_i a_j p_{ij}^{*}} \quad (1)$$

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

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

where n denotes the habitat patch number; a_i and a_j represent the areas of habitat patches i and j, respectively; p_{ij}^{*} is the maximum path connectivity for direct movement between patches i and j; A_L is the total area; nl_{ij} denotes the number of links in the shortest path between patches i and j; dPC quantifies the importance of each patch in sustaining landscape connectivity by evaluating changes in the PC. PC_{remove} represents the connectivity potential of the landscape, recalculated after the exclusion of a specific patch.

2.5. Extraction of Ecological Corridors, Pinch Points, and Barriers

This study delineates the process of identifying ecological corridors into four distinct phases. Firstly, we constructed a resistance surface and identified the potential ecological corridors using the MCR model. Secondly, we optimized these potential corridors by employing the gravity model to ascertain their significance and conservation priority. Thirdly, we identified the ecological corridors, pinch points, and barriers by determining the most cost-effective routes for organism migration between adjacent ecological sources, utilizing circuit theory. Finally, we extracted the final ecological corridors at four time points in 1990, 2000, 2010, and 2020, superimposing the optimized ecological corridors and the ecological corridors produced by the circuit theory.

2.5.1. Resistance Surface

The development of an ecological resistance surface through scientific methods can enhance the delineation of spatial boundaries for biological survival, thereby contributing significantly to the preservation of biodiversity [53]. Combined with the actual situation of Guilin and the study in [54], ten factors, such as landscape type and habitat quality, were selected as resistance factors. Subsequently, the entropy weight method was employed to

determine the weights (Table 3). It consists of three steps: data normalization, information entropy calculation, and weight calculation. The relevant data and weights of different periods were used to construct resistance surfaces in 1990, 2000, 2010, and 2020.

Table 3. Weights and resistance values of the resistance factors.

Resistance Factors and Weights	Classification Criteria	The Value of Resistance Factors	Resistance Factors and Weights	Classification Criteria	The Value of Resistance Factors
Landscape type (0.142)	Core	1	Land use (0.1251)	Forest land	1
	Bridge	2		Water body	3
	Loop	3		Grassland	6
	Branch	4		Cultivated land	8
	Islet	5		Unused land	9
	Edge	7		Construction land	10
	Perforation	9	Distance from rivers (0.0766)	≤100	1
	context	10		100~300	3
Habitat quality (0.169)	0.85~1	1		300~500	5
	0.75~0.85	2		500~1000	7
	0.42~0.75	3		>1000	10
	0.12~0.42	4	Distance from railways (0.0384)	>10	1
	0~0.12	5		5~10	3
Slope (0.0702)	<8	1		3~5	5
	8~18	7		1~3	7
	18~27	8		≤1	10
	27~36	9	Distance from highways (0.0651)	>10	1
	>36	10		5~10	3
NDVI (0.2089)	≥0.8	1		3~5	5
	0.6~0.8	2		1~3	7
	0.4~0.6	6		≤1	10
	0.2~0.4	8	Distance from main roads (0.0567)	>5	1
	<0.2	10		2~5	3
Elevation (0.048)	≤200	1		1~2	5
	200~400	3		0.5~1	7
	400~600	5		≤0.5	10
	600~800	7			
	800~1000	9			
	>1000	10			

2.5.2. MCR Model

The MCR model utilizes the ecological resistance surface to calculate the optimal resistance values between sources, enabling the determination of the most efficient pathway for the migration of ecological material and energy [55]. In comparison to alternative models, MCR offers notable benefits in the simulation and quantification of least-cost routes for the transfer of species, energy, and information between ecological source locations, leading to its widespread adoption. In this study, the MCR model was employed to extract potential ecological corridors. The formula is as follows [56]:

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

In this equation, MCR denotes the minimum cumulative resistance; f_{min} represents an unknown monotonically increasing function; D_{ij} is the distance between ecological sources i and j; R_i is the resistance encountered during migration.

2.5.3. Gravity Model

The gravity model offers a quantitative approach to assessing the level of interaction among distinct ecological patches, serving as a method for evaluating the significance of ecological corridors and identifying redundant pathways between sources. Referring to related studies [57] and combining with the actual situation of Guilin, the gravity model was used to eliminate duplicate paths between ecological sources and identify paths with interacting gravitational values greater than 5000 as important ecological corridors. The formula is as follows [28]:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^m} = \frac{\left[\frac{1}{p} \times ln(S_i)\right]\left[\frac{1}{p} \times ln(S_j)\right]}{\left[\frac{L_{ij}}{L_{max}}\right]^2} = \frac{L_{max}^2 ln(S_i S_j)}{L_{ij}^2 p_i p_j} \quad (5)$$

In this equation, G_{ij} represents the gravitational force value between sources i and j; N_i and N_j denote the weight values; D_{ij} represents the standard value of corridor resistance between sources; p_i and p_j are the average resistance values; S_i and S_j are the source areas; L_{ij} denotes the value of corridor resistance between sources i and j; L_{max} represents the maximum corridor resistance value.

2.5.4. Circuit Theory

Circuit theory draws an analogy between the movement of organisms or gene flow and the flow of electric charge. It utilizes the ecological flow processes within heterogeneous landscapes by utilizing the random wandering properties of electric charge, thereby enabling the effective identification of various ecological elements [58]. In this study, circuit theory was employed to obtain ecological corridors, pinch points, and barriers. We used the Linkage Mapper tool to determine ecological corridors' shape and location by calculating cost-weighted distance (CWD) between multiple pairs of sources. The Pinchpoint Mapper and Barrier Mapper tools in the Circuitscape 4.0.5 software were utilized to extract the ecological pinch points and barriers. By utilizing the metric of cumulative current value as a quantitative measure, the top 20% of cumulative current values were defined as pinch points or barriers.

2.6. Structural Evaluation of Ecological Network

The network analysis method can calculate the degree of connectivity between ecological corridors and connectors to quantitatively evaluate the ecological network structure. This study utilized the network analysis method to calculate network closure (α), line point rate (β), and network connectivity (γ) to evaluate ecological network structure. The calculation formula is presented below [54]:

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

$$\beta = \frac{L}{V} \quad (7)$$

$$\gamma = \frac{L}{3 \times (V - 2)} \quad (8)$$

where L denotes the actual line numbers in the network; V represents the node numbers in the network.

3. Results

3.1. Spatiotemporal Evolution of Ecological Sources

3.1.1. Ecosystem Service Assessment

The InVEST model was employed to quantify the four categories of ecosystem services: water production, soil retention, carbon storage, and habitat quality. Over the period from

1990 to 2020, the spatial distribution pattern of annual water production in Guilin exhibited a relatively consistent trend, characterized by higher water production in the southwest and lower water production in the northeast. The spatial distribution of soil retention exhibited a pattern characterized by elevated values around the periphery and reduced values in the center (Figure 3). Similarly, the spatial distribution of carbon storage demonstrated a pattern of high values at the periphery and low values at the center. The overall spatial configuration of habitat quality mirrored this trend, displaying a distribution pattern of high values in the surrounding areas and low values in the central region. In this study, the importance of ecosystem services was classified into five levels based on natural breakpoints. Notably, higher levels in this classification corresponded to a lower importance of ecosystem services. Over the past 30 years, the proportion of level 1 importance has steadily declined, from 16.13% in 1990 to 13.91% in 2020. The importance of level 2 was predominantly concentrated in the northwest and central eastern regions of the study area. Conversely, the importance of level 3 progressively expanded from the periphery towards the center of the research area, approaching the city center and forming a critical transition zone between important and extremely important regions. The significance of levels 4 and 5 exhibited a general trend of slight increases, predominantly in central urban regions characterized by heightened human activities. This observation indicates that, despite Guilin's rich forest resources, anthropogenic interference continues to inflict a measurable degree of damage (Figure 3).

3.1.2. Classification of Landscape Types

The landscape types in Guilin were categorized into seven types using the MSPA method: core, islet, perforation, edge, loop, bridge, and branch. During the 1990–2020 period, the core area exhibited a continuous decline, decreasing from 14,357.551 km^2 in 1990 to 14,215.337 km^2 in 2020. The bridge area demonstrated a trend of initial decrease followed by an increase, declining from 2078.826 km^2 in 1990 to 2077.835 km^2 in 2000 and subsequently rising to 2123.115 km^2 by 2020. The edge area experienced fluctuations, with areas of 1894.757 km^2, 1888.953 km^2, 21,898.420 km^2, and 1872.244 km^2 in 1990, 2000, 2010, and 2020, respectively. The areas of perforation and islet exhibited a continuous increase, expanding from 1279.746 km^2 and 462.639 km^2 in 1990 to 1309.127 km^2 and 473.504 km^2 in 2020, respectively (Table 4). The areas of branch and loop were only marginally larger than isolated areas and significantly smaller than other landscape types. Despite a relative clustering of patches within this region, there are limited pathways available to mitigate "internal barriers" and enhance connectivity between patches.

3.1.3. Ecological Source Identification

In this study, the core areas exceeding 5 km^2 were identified using the MSPA methodology and subsequently overlaid with patches representing the top 25% of ecosystem service importance values. Then, the patches with a dPC index greater than 0.1 were identified as ecological sources (Figure 4). The number of ecological sources in 1990, 2000, 2010, and 2020 was 23, 13, 15, and 14, respectively. The area of ecological sources decreased by a total of 1570.062 km^2 over 30 years, from 8329.09 km^2 in 1990 to 7515.1845 km^2 in 2000, followed by an increase to 7629.7566 km^2 in 2010 and a rapid decrease to 6759.0322 km^2 in 2020. This trend reflects the intensifying fragmentation of the ecological landscape. The distribution of ecological sources exhibited significant heterogeneity and extensive dispersion, with concentrated patches that fulfill the requirements for species migration and energy exchange. The largest ecological sources were predominantly situated in Longsheng, Ziyuan, Lingchuan, and Xing'an, which collectively constitute a crucial northwestern ecological barrier region in Guilin. In summary, ecological source areas were large and relatively concentrated to meet the needs of species migration and energy exchange.

Table 4. Classification statistics of landscape types.

Landscape Types	Year	Area (km^2)	Proportion of Prospect (%)	Proportion of Total Area (%)
Core	1990	14,357.551	65.75	51.90
	2000	14,335.001	65.73	51.82
	2010	14,310.538	65.64	51.73
	2020	14,215.337	65.34	51.39
Islet	1990	462.639	2.12	1.67
	2000	463.086	2.12	1.67
	2010	472.970	2.17	1.71
	2020	473.504	2.18	1.71
Perforation	1990	1279.746	5.86	4.63
	2000	1281.675	5.88	4.63
	2010	1285.124	5.89	4.65
	2020	1309.127	6.02	4.73
Edge	1990	1894.757	8.68	6.85
	2000	1888.953	8.71	6.86
	2010	1898.420	8.71	6.87
	2020	1872.244	8.73	6.87
Loop	1990	719.025	3.29	2.60
	2000	716.911	3.29	2.59
	2010	682.468	3.13	2.47
	2020	689.836	3.17	2.49
Bridge	1990	2078.826	9.52	7.51
	2000	2077.835	9.53	7.51
	2010	2088.291	9.58	7.55
	2020	2123.115	9.76	7.67
Branch	1990	1044.484	4.78	3.78
	2000	1044.044	4.79	3.78
	2010	1063.268	4.88	3.84
	2020	1073.367	4.93	3.88

3.2. Spatiotemporal Evolution of Ecological Corridors, Pinch Points, and Barriers

3.2.1. Resistance Surface Analysis

The resistance surface was obtained using the Weighted Sum tool in the ArcGIS 10.2 software (Figure 5). The regions with superior resistance values were predominantly concentrated in central urban locales, including districts such as Xiufeng and Diecai. Conversely, regions exhibiting lower resistance values were predominantly located in the hilly terrains surrounding Guilin, including areas such as Yongfu and Guanyang. These regions, characterized by extensive forest cover, provide optimal habitats for a diverse array of flora and fauna, thereby contributing to reduced ecological resistance values. During the period from 1990 to 2020, areas with high resistance values demonstrated a general trend of fluctuating growth, whereas areas with low resistance values continued to diminish in size. This transformation aligns with spatial alterations in land use, particularly in forest land and constructed land.

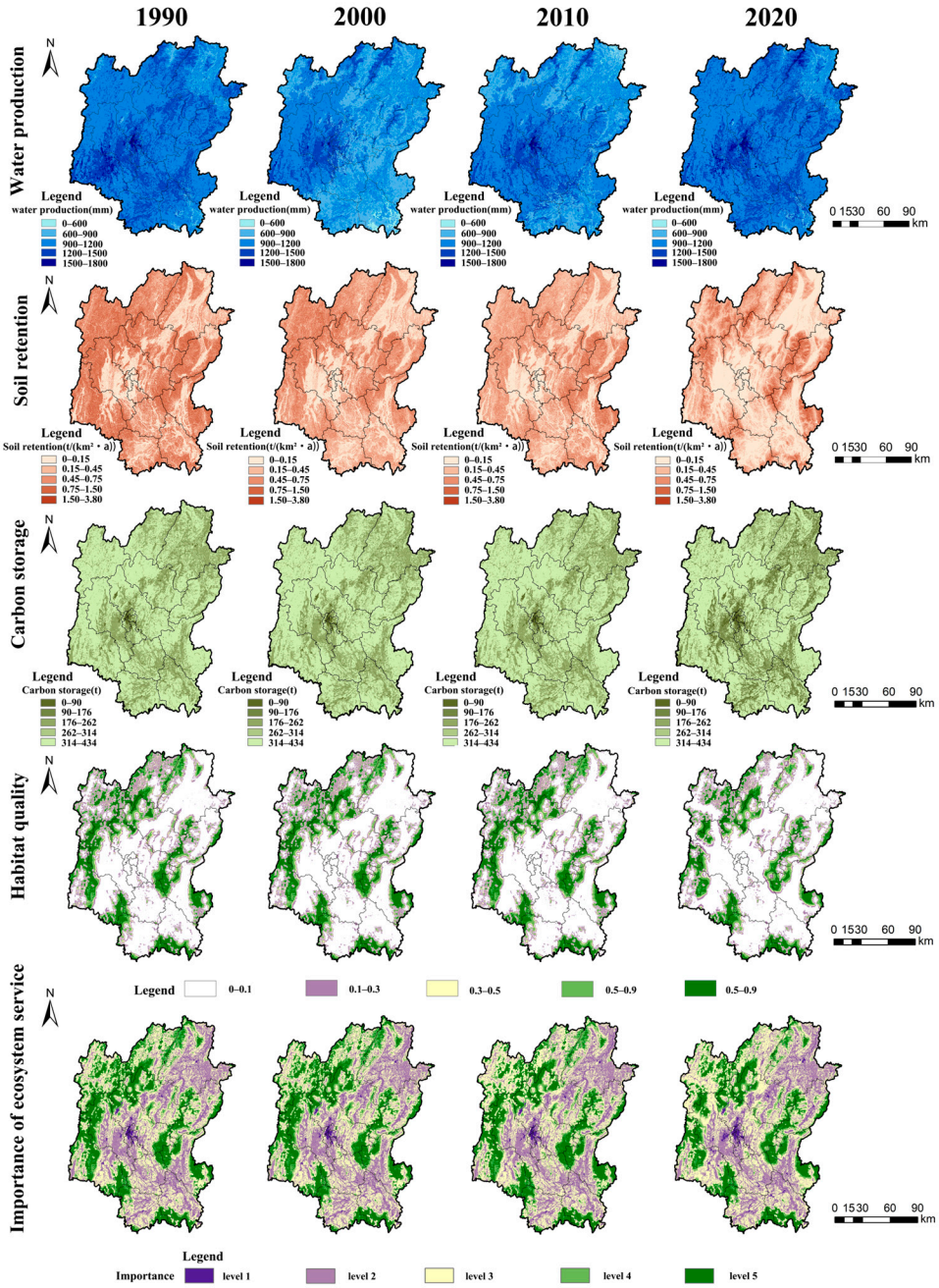


Figure 3. Spatial distribution of ecosystem services in 1990, 2000, 2010, and 2020.

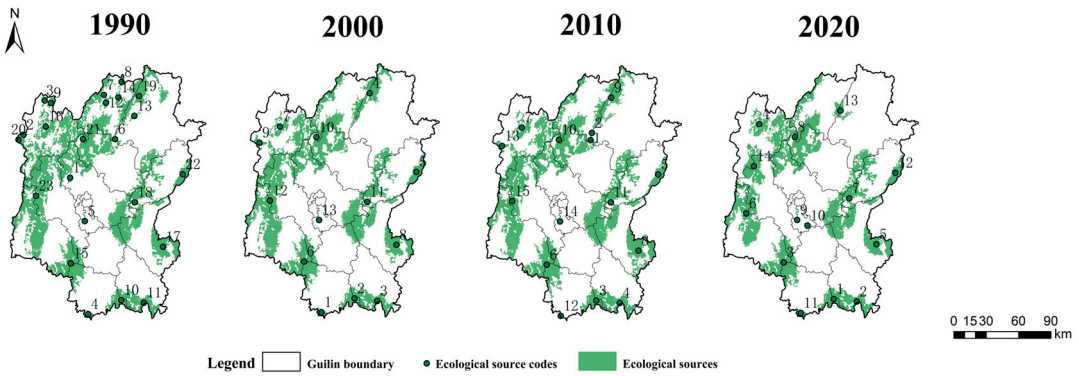


Figure 4. Spatial distribution of ecological sources in 1990, 2000, 2010, and 2020.

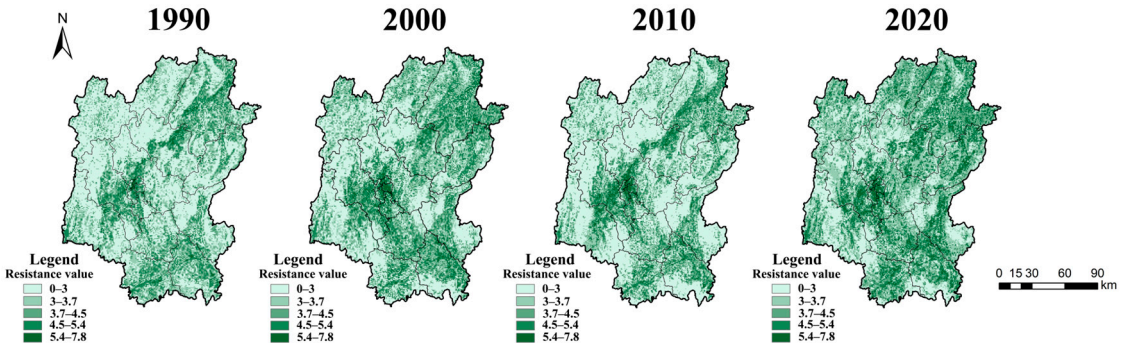


Figure 5. The resistance surface in 1990, 2000, 2010, and 2020.

3.2.2. Spatiotemporal Evolution of Ecological Corridors

The final ecological corridors were extracted using a multi-model overlay of the MCR model, gravity model, and circuit theory, as depicted in Figure 6. According to the potential corridors during each period, the gravity model was employed to compute the interaction force matrix between ecological sources, and an interaction force greater than 5000 was used as the reference threshold to extract the important ecological corridors. Subsequently, these important ecological corridors were overlaid with those generated by circuit theory. The overlapping segments were designated as the primary ecological corridors, while the non-overlapping segments were classified as the secondary ecological corridors.

The final ecological corridor numbers in 1990, 2000, 2010, and 2020 were 58, 29, 35, and 30, respectively. The alterations in the number of ecological corridors were congruent with the trend of changes in the number of ecological sources, which was primarily attributable to the substantial modifications in the ecological source areas instigated by the escalating fragmentation of the landscape. The distribution of ecological corridors exhibited a pattern of sparsity in the northeastern region and density in the southwestern region, with a more intensive intersection phenomenon observed in the southwest. This pattern suggests a stronger internal connectivity within the southwestern region. Conversely, the northeastern region displayed a lower number of ecological corridors, exhibiting poor connectivity that does not favor organism migration. The primary ecological corridors predominantly followed a ring-like distribution, mainly concentrated within Ziyuan, Longsheng, Yongfu, Lipu, Pingle County, and Guanyang. The regions were primarily characterized by mountainous and hilly terrains, which exhibit superior patch connectivity, increased corridor correlation, and diminished resistance to species migration. Consequently, these areas warrant prioritization in conservation efforts. Since 1990, substantial changes have been observed in the principal ecological corridors of Longsheng and Ziyuan, predominantly due to the decline in ecological sources.

3.2.3. Spatiotemporal Evolution of Ecological Pinch Points and Barriers

This study recognized 52, 50, 60, and 42 ecological pinch points in 1990, 2000, 2010, and 2020, respectively, predominantly located in the southwestern and east-central regions (Figure 7). Forest land and cultivated land constituted a significant proportion of these ecological pinch points, serving as critical areas for species movement. Additionally, the number of ecological barriers identified in the years 1990, 2000, 2010, and 2020 was 41, 60, 68, and 66, respectively, indicating a continuous increasing trend in area over the examined period. The majority of ecological barriers were distributed in the central and southern regions of the city. The predominant land uses within these barriers comprised cultivated land, forest land, and construction land. Between 1990 and 2020, ecological barriers in the northern region of Guilin experienced a gradual decline, whereas those in the southern and central hinterlands exhibited a trend of gradual aggregation. This change pattern is attributable to anthropogenic activities, including deforestation and road construction, which disrupted the original ecological land. Consequently, these activities diminished landscape connectivity and led to a decline in biodiversity.

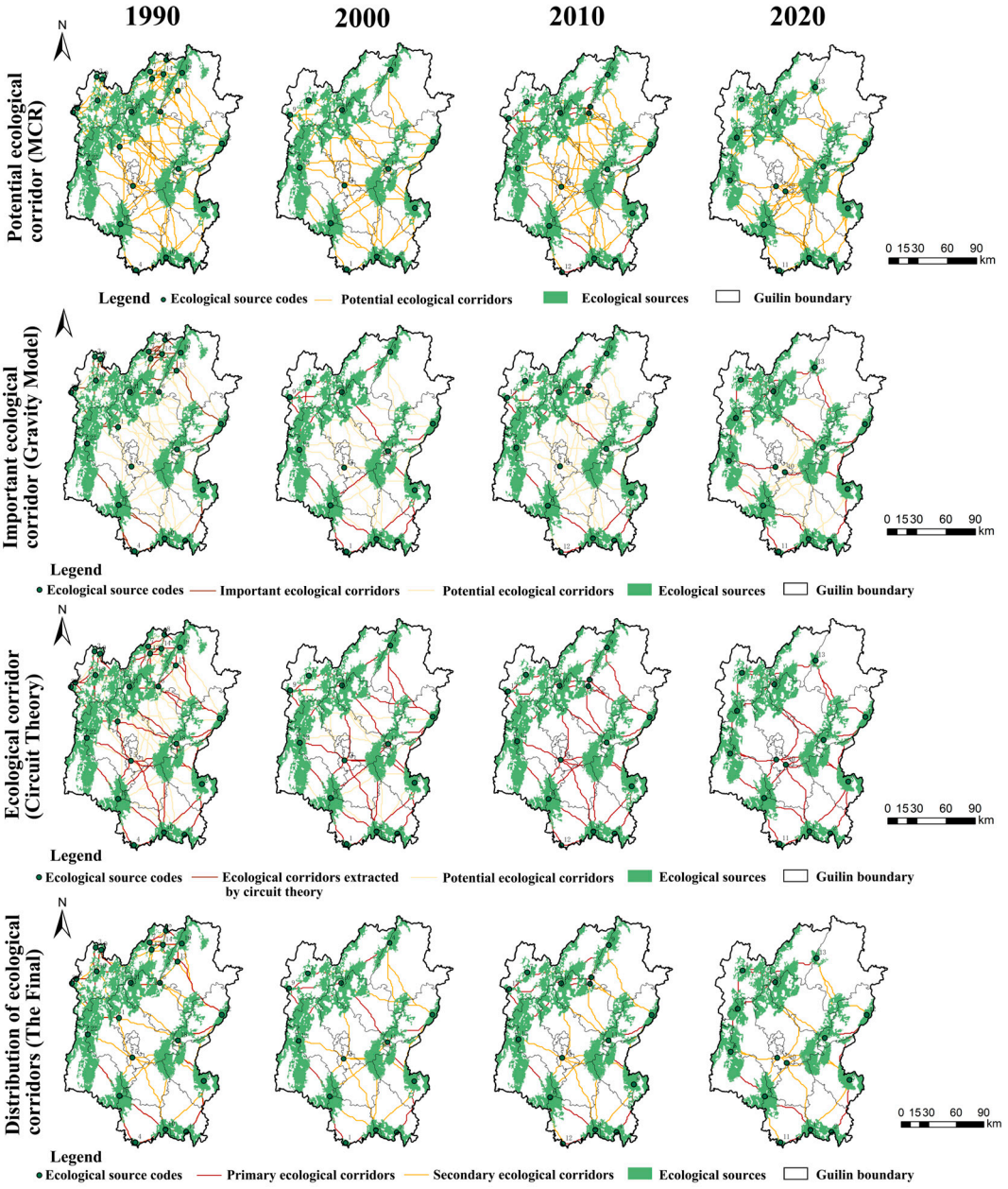


Figure 6. The ecological corridors in 1990, 2000, 2010, and 2020.

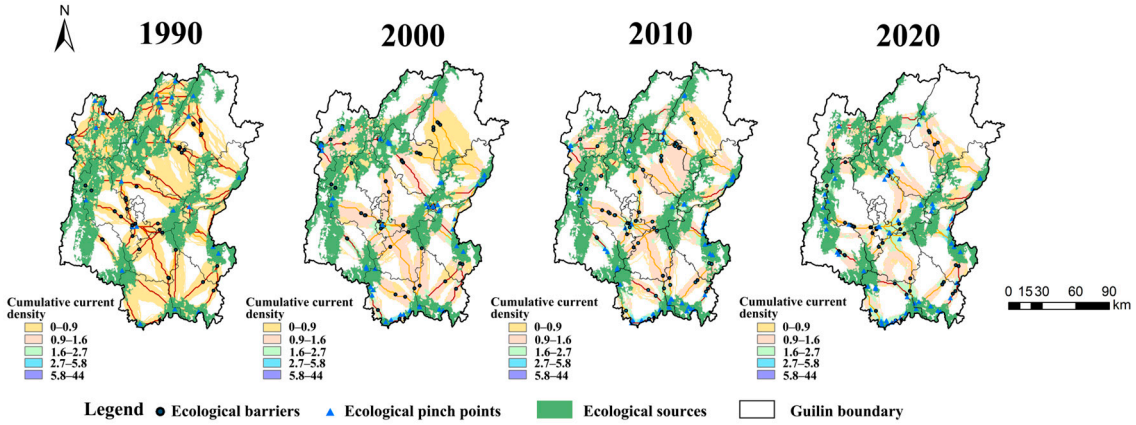


Figure 7. The ecological pinch points and barriers in 1990, 2000, 2010, and 2020.

3.3. Spatiotemporal Evolution of Ecological Network Structure

Currently, ecological networks typically follow a fundamental research paradigm that involves identifying ecological sources, extracting ecological corridors, and recognizing ecological pinch points and barriers. Ecological source numbers were recorded as 23, 13, 15, and 14 in 1990, 2000, 2010, and 2020, respectively. Concurrently, the number of ecological corridors was 58, 29, 35, and 30, while the number of ecological pinch points was 52, 50, 60, and 42, and the count of ecological barriers was 41, 60, 68, and 66, respectively (Figure 8). The spatiotemporal evolution of ecological networks showed that ecological sources and corridors were generally decreasing in both number and areas (length), coupled with a notable increase in the number of ecological pinch points and barriers over the 30-year period. A qualitative analysis based on the Statistical Communiqué of Guilin on the National Economic and Social Development (https://tjj.guilin.gov.cn/tjsj/tjgb/, accessed on 18 December 2022) and land use data (http://www.resdc.cn, accessed on 18 December 2022) during 1990–2020 was conducted to investigate the factors influencing ecological network changes. The findings indicated that alterations in the ecological network were closely associated with national policy orientations, the process of urbanization, and the development of tourist attractions. Taking the changes in ecological corridors as an example, the reduction in ecological corridors between 1990 and 2000 can be primarily ascribed to the advancement of urbanization and the transportation network, coupled with the development and construction of tourist attractions. The expansion of ecological corridors between 2000 and 2010 can be primarily attributed to the significant ecological outcomes realized by a series of ecological protection and restoration initiatives. Between 2010 and 2020, ecological corridors experienced a significant reduction. This decline was concomitant with the accelerated pace of economic development and industrialization.

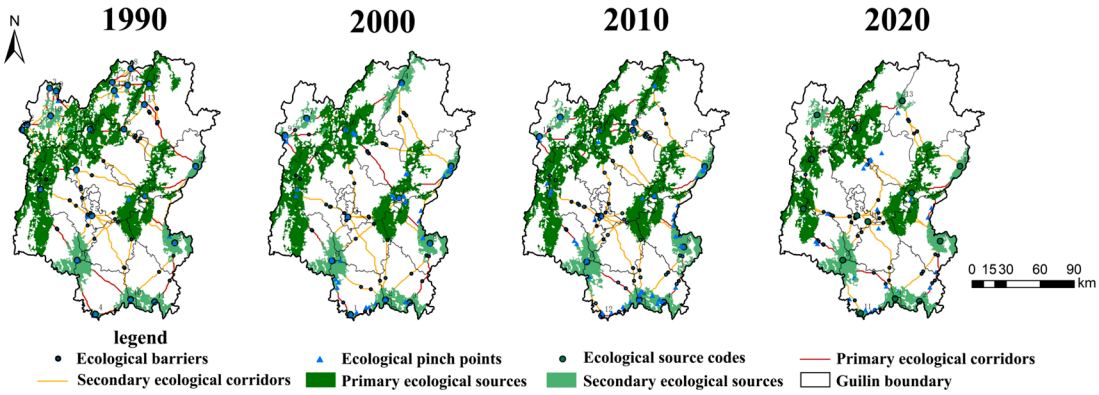


Figure 8. The ecological networks in 1990, 2000, 2010, and 2020.

According to the principle of graph theory, this study defined ecological sources as nodes and ecological corridors as edges so as to carry out the calculation of the index related to the ecological network structure. Table 5 reveals that the α values consistently exceeded 0.7, suggesting that the devised ecological network structure of Guilin boasts superior connectivity and an abundance of routes for species migration and dispersal. The β values, all surpassing 2 (>1), implied a relatively complex level of connectivity within the ecological network. Additionally, the γ values, all exceeding 0.8, denoted that the ecological nodes within the network possess superior connectivity. In summary, the ecological network's structural nodes and edges exhibit a high degree of completeness, resulting in an elevated overall structural connectivity. Structural evaluation of the ecological networks revealed that during 1990~2020, the value of α exceeded 0.7, the value of β surpassed 2, and the value of γ was greater than 0.8, indicating robust overall connectivity within the ecological networks. Nonetheless, the observed decline in these three indicators over time suggests diminishing connectivity and available dispersal paths for species across the ecological network, underscoring the necessity for protective measures and optimization strategies.

Moreover, these changes have led to a simplification of linkages and networks between habitats, which can affect species migration and ecosystem stability.

Table 5. Evaluation indicators for ecological network structure.

Years	Evaluation Indicators for Ecological Network Structure		
	α	β	γ
1990	0.878	2.25	0.92
2000	0.809	2.23	0.878
2010	0.8	2.26	0.87
2020	0.739	2.14	0.833

4. Discussion

4.1. Reflections on the Identification of Ecological Sources

The identification of ecological sources constitutes a critical phase in the development of ecological networks, with numerous methodologies and considerations available for this purpose. In most studies, large nature reserves or forest parks are used as ecological sources. However, this method is too subjective and lacks valid data [35,36]. Several studies also employ MSPA methods or a target species-oriented identification of ecological sources [25,37]. Nonetheless, these methodologies often overlook ecological service value or use a single method that is not sufficient to address the challenges associated with implementing ecological networks in urban areas, particularly the fragmentation and isolation of natural habitats resulting from high-intensity land use.

We endeavored to identify ecological sources via a quantitative assessment of the importance of ecosystem services, landscape types, and landscape connectivity. This approach helps to improve the precision and multi-method fusion of ecological source identification. Ecosystem services not only supply humans with food and various raw materials essential for production and daily living but also establish and sustain the foundational support systems for life, thereby creating the environmental conditions requisite for human survival. In this study, we quantified water production, soil retention, carbon storage, and habitat quality and utilized their importance as a criterion for ecological source identification. MSPA is an advanced image processing technique utilized to segment spatial elements within raster images. This method is based on mathematical morphological principles, including operations such as erosion and expansion, which help to enable the precise delineation of landscape types and structures [37]. Landscape connectivity serves as a crucial framework for examining the reciprocal feedback relationship between landscape structure and landscape function. The identification of ecological sources commonly employs a combination of landscape type and connectivity, but the outcomes are contingent upon the specific patches and metrics utilized. The ecological resources identified in Guilin encompass extensive areas and exhibit concentrated distribution patterns, thereby adequately supporting species migration and energy exchange requirements.

4.2. Analysis of Factors Influencing the Changes in Ecological Networks

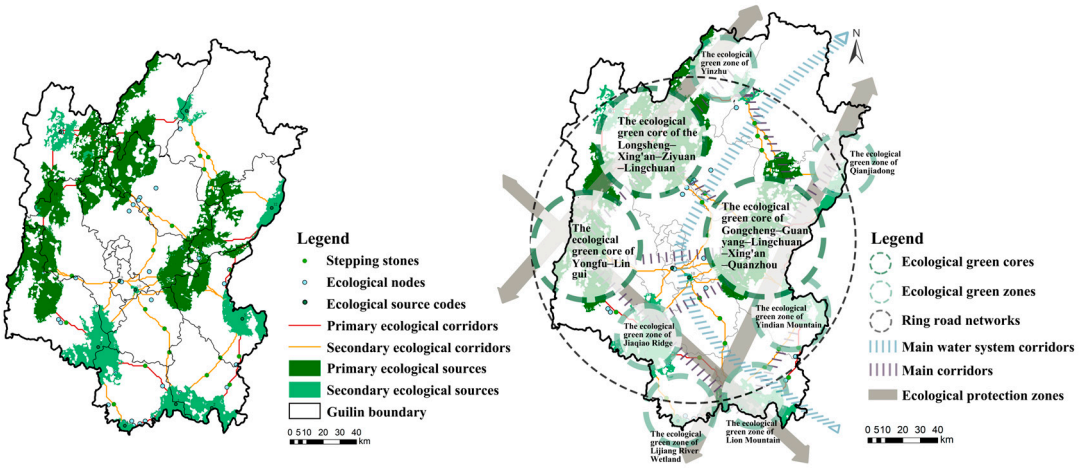
Revealing the factors influencing the changes in ecological networks is essential for effective regional ecosystem management. Between 1990 and 2020, there was a general decline in both the number and extent (length) of ecological sources and corridors. The area of ecological resources in Guilin diminished by a total of 1570.062 km^2, indicating an intensifying fragmentation of the ecological landscape. However, the period from 2000 to 2010 saw an increase in the area of ecological sources, primarily attributable to a series of ecological protection and restoration initiatives. These initiatives included wetland conservation, water environment management, and significant ecological achievements from major projects such as the conversion of farmland to forests and grasslands. Between 2010 and 2020, the ecological environment experienced notable degradation due to continuous economic development, resulting in a reduction in ecological sources. Concurrently,

the consolidation of fragmented patches during comprehensive land space improvement efforts further diminished the number of ecological sources, indicating a declining trend. This phenomenon underscores the impact of anthropogenic activities on the natural environment and highlights the intricate relationship between ecological conservation and economic growth.

The reduction in ecological corridors between 1990 and 2000 can be primarily ascribed to two key factors. Firstly, the advancement of urbanization has resulted in the expansion of construction land, thereby diminishing the area of ecological sources and consequently reducing the corridors that connect these ecological nodes. Secondly, the transportation network, coupled with the development and construction of tourist attractions, has exerted a detrimental impact on ecological corridors. The expansion of ecological corridors between 2000 and 2010 can be primarily attributed to the significant ecological outcomes realized by a series of ecological protection and restoration initiatives. These initiatives include wetland conservation, water environment management, and major projects such as the conversion of farmland to forests and grasslands. Between 2010 and 2020, ecological corridors experienced significant reduction. This decline was concomitant with the accelerated pace of economic development and industrialization, which included rapid urbanization, industrialization, and agricultural intensification. Additionally, from 2000 to 2020, there was an observable increase in ecological pinch points. This phenomenon is primarily attributable to the substantial ecological outcomes achieved through various ecological protection and restoration initiatives, including water ecology protection and major projects such as the conversion of farmland to forest and grassland. The impact factors of the ecological network changes have undergone temporal variations, indicating that ecosystem management policies must be promptly adjusted to accommodate evolving environmental conditions.

4.3. Strategies for Enhancing Ecological Space Management

The rapid advancement of urbanization and the burgeoning tourism industry have contributed to a continuous reduction in ecological space within tourist cities. According to the aforementioned analysis and findings, this study recommends improving the management of ecological spaces in Guilin through the conservation of ecological networks and the development of ecological patterns (Figure 9a). For the ecological sources, a hierarchical approach and the establishment of buffer zones were the main means of protecting them. The primary ecological sources were designated as areas of ecological priority conservation, whereas the secondary ecological sources were classified as areas of sub-priority conservation. The land-use types within the primary and secondary ecological corridors were predominantly characterized by forested areas and grasslands, which hold significant ecological protection value. Consequently, it is imperative that policies stringently regulate the conversion of these land-use types. Additionally, there should be a strong emphasis on implementing engineering measures such as reforestation, the conversion of farmland to grasslands, ecological re-greening, and the establishment of plant and animal corridors. Based on the characteristics of ecological sources and network intersections, new ecological steppingstones were introduced to reduce the distance between ecological sources and enhance the connectivity of corridors. Ecological nodes include both ecological pinch points and barriers. Priority will be given to the protection of ecological pinch points. Additionally, the development of ecological facilities and industries, such as natural parks in select suburban areas, will be considered to increase the number of high-quality habitat patches and provide recreational and educational venues for local residents. Concurrently, efforts are being directed towards the restoration of ecological barriers, with particular emphasis on the ecological protection and landscape restoration of forested land, cultivated land, and construction land.



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

Figure 9. (**a**) Guilin's ecological network in 2020; (**b**) construction of ecological network patterns in Guilin.

In alignment with the Guilin Territorial Spatial Master Plan (2021–2035) and analysis of ecological networks, this study developed an ecological network pattern characterized by "three cores, six zones, three belts, and multiple corridors" to enhance the ecological spatial management of Guilin (Figure 9b). The "three cores" refer to the ecological green cores of Longsheng–Xing'an–Ziyuan–Lingchuan, Yongfu–Lingui, and Gongcheng–Guanyang–Lingchuan–Xing'an–Quanzhou County in east-central Guilin. The landscape is predominantly characterized by forested areas and high biodiversity, functioning as the principal ecological source region in the northwestern and east-central zones. Based on identified sources and the natural elements of Guilin, six ecological green zones have been established: Jiaqiao Ridge, Lijiang River wetland, Lion Mountain, Yindian Mountain, Yinzhu Mountain, and Qianjiadong. The "three belts and multiple corridors" constitute the foundational structure of Guilin's ecological network. The term "three belts" denotes the ecological belts of Ziyuan–Longsheng, Yongfu–Lipu, and Guanyang–Pingle. In the interim, the term "multiple corridors" denotes the ecological pathways that interlink the east–west and north–south axes, thereby establishing an integrated network characterized by "three verticals and three horizontals". This network is underpinned by Guilin's principal Lijiang River water system and its natural woodlands.

4.4. Contributions and Limitations

Recent discussions in urban planning literature acknowledge the enhanced effectiveness of ecological networks in improving patch connectivity and maximizing ecological space [59–61]. However, the implementation of ecological networks frequently suffers from inadequacies due to geographical disparities and a lack of historical continuity. To address this gap, this study proposed a comprehensive framework for the spatiotemporal evolution of ecological networks, facilitating a multidimensional analysis of their dynamic development. Methodologically, we endeavored to identify ecological sources via a quantitative assessment of the importance of ecosystem services, landscape types, and landscape connectivity. This approach helps to improve the precision and multi-method fusion of ecological source identification. Furthermore, dynamic changes in ecological networks over four time periods were analyzed in this research across various scenarios, encompassing ecological sources, corridors, pinch points, and barriers transformed in time and space. This research offers new insights into the spatiotemporal evolution analysis of ecological networks and could provide scientific references for regional ecological management and policy formulation. The findings offer potential solutions for addressing habitat fragmenta-

tion and promoting ecological restoration in Guilin, while also facilitating the coordination of ecological protection and urban development in future land-use planning.

In the context of accelerated urbanization, elucidating the spatiotemporal evolution of ecological networks represents a critical research trajectory that warrants attention both currently and in the future. This study introduces a comprehensive framework for the construction and spatiotemporal evolution of ecological networks, enabling a multidimensional analysis of their dynamic development. Nevertheless, the study acknowledges certain limitations and highlights areas for future improvement. First, in the application of the MCR model to identify potential ecological corridors, this study did not account for the extensive effects of habitat and the distribution of various species on the construction of resistance surfaces, owing to limited access to detailed research data. Consequently, the scientific selection of resistance factors remains a subject necessitating further in-depth investigation. Additionally, the analysis of factors influencing changes in ecological networks was dominated by qualitative studies. In the future, quantitative means such as the geographical detector can be considered for complementary analyses.

5. Conclusions

This study analyzed the spatiotemporal evolution of ecological networks from 1990 to 2020 and proposed strategies for improving territorial space management. The findings revealed a general decline in both the number and extent (length) of ecological sources and corridors, accompanied by a significant increase in the number of ecological pinch points and barriers over the 30-year period. Network structure analysis revealed that the value of α exceeded 0.7, the value of β surpassed 2, and the value of γ was greater than 0.8 during 1990–2020, indicating robust overall connectivity within the ecological network. Nonetheless, the observed decline in these three indicators over time suggests a diminishing connectivity and available dispersal paths for species across the ecological network, underscoring the necessity for protective measures and optimization strategies. The results provide valuable scientific references for regional ecological management and policy formulation. Specifically, the findings present potential solutions for addressing habitat fragmentation and promoting ecological restoration in Guilin while also aiding in the coordination of ecological protection and urban development in future land use planning.

Furthermore, this study offers new perspectives and methodologies for spatiotemporal changes in ecological networks and enhancing territorial space management in tourist cities. Methodologically, we endeavored to identify ecological sources via a quantitative assessment of the importance of ecosystem services, landscape types, and landscape connectivity. This approach helps to improve the precision and multi-method fusion of ecological source identification. Although existing research on ecological network construction is relatively mature, the network structure of ecological space is rarely analyzed because of the complexity of ecological networks. This study addresses a critical knowledge gap in the dynamics of ecological networks and offers valuable insights for mitigating habitat fragmentation and enhancing ecological space management in tourist cities.

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