Identification and Optimization of Ecological Security Patterns in the Xiangyang Metropolitan Area

Shenglan Wang, Yinzhou Huang, Xiaorong Jiang, Tiantian Wang, and Yinuo Jin

***Abstract*—Robust ecological security patterns (ESPs) serve as the fundamental basis for the entirety of the ecological realm and are the essence of constructing a territorial spatial planning system that promotes development and preservation. However, as urbanization, industrialization, and transportation accelerate, the ecological security of urban agglomerations faces an unprecedented challenge. Nevertheless, judiciously identifying and optimizing ESPs can mitigate this threat. In this study, we constructed a "material-sensitivities-disturbances" framework covering both natural and social indicators and identified ESPs using geo-information system (GIS) spatial analysis, MSPA, minimum cost routes, and gravity models. The identification results reveal that the Xiangyang metropolitan area has 17 248.21 km^2 of ecological source area, 80 possible ecological corridors, 26 ecological hubs, and 4 ecological functional regions. The natural sources are mostly found in Qinba Mountain, Dahong Mountain, Tongbai Mountain, and the woods and rivers around the Han River. We suggested an ecological optimization framework consisting of "one axis, three screens, four belts, and multiple nodes" based on the geographical distribution of ecological safety levels. This study proposes a set of spatial optimization techniques for coordinating urbanization with ecological conservation, which may be utilized as a model for ecological governance and restoration in the Xiangyang metropolitan region and even throughout Central China.**

***Index Terms*—Ecological security patterns (ESP), spatial optimization, the minimum cumulative resistance, Xiangyang metropolitan area.**

I. Introduction

RAPID land urbanization has put the ecosystem under tremendous pressure and degraded the ecological environment to varying degrees [1]. Long-term environmental issues, such as soil contamination, landscape fragmentation, and habitat loss, have been brought on by human activities encroaching on ecological regions [2], [3], which, in the 21st century, is progressively emerging as a new problem for local ecological safety and the development of sustainable socioecological systems [4]. Ecological security patterns (ESPs) are an effective way to support natural urban living systems, maintain ecological security, and achieve smart growth [5], [6]. ESPs emphasize the wholeness and coordination of ecological elements [7]. Ecological security is attained by efficiently and judiciously allocating the region's natural resources and green infrastructure, which enhances the ecosystem's stability and sustainability [8], [9]. After the 18th National Congress of China, ecological security, as an important support and component of national security, was clearly proposed and elevated to a national strategy. As a community, China has proposed an ESP that encompasses mountains, water, woods, fields, lakes, grasses, and sands [10].

LUCC-based ecological safety research has gained popularity recently and mostly focuses on ecological infrastructure construction [11], [12], ecological red line delineation [13], spatial data calculation [14], [15], evolutionary patterns, and optimization from static to dynamic models [16], [17]. Remote sensing images have gradually become an essential data source in ecological research [18]. At present, more and more researchers adopt the combination of "source-corridor-network" to identify and construct ESP [19], [20], [21], and initially form the paradigm of constructing regional ESPs. The development of ESPs can efficiently identify significant regions for ecological restoration in the national space. This will aid in the regulation of human activity, habitat restoration, and the strengthening of key ecological aspects, such as ecological sources, corridors, strategic sites, and overall networks [22], [23].

To establish ecological corridors and networks, it is crucial to accurately identify ecological sources while balancing urban and socioeconomic growth with minimal land preservation [24]. The current evaluation system for ecological source sites lacks a unified standard and is complex. Researchers typically rely on qualitative and quantitative factors, such as ecosystem characteristics, habitat importance, and ecological sensitivity [20], [25], [26]. Some integrate multiple perspectives [27], [28]. However, little attention has been given to strengthening ecological resistance surfaces, which are vital for constructing ecological corridors [2]. These surfaces include internal disruptions of natural ecosystems and external disturbances from social systems [29]. Resistance values are typically calculated based on physical factors, such as land use, DEM, NDVI, and soil erosion index [30]. In rapidly urbanizing areas, anthropogenic activities and socioeconomic disturbances have a greater impact on ecosystems [31], [32]. Therefore, social issues such as traffic, population, and economics should be considered [29], [33]. Ecological corridors

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TABLE I
DESCRIPTION OF THE DATA

Data type	Year	Accuracy	Resoures
Land Use	2020	30m	Globaland 30
NDVI	2020	500m	https://www.resdc.cn/
DEM	2019	30m	https://www.resdc.cn/
NPP	2020	1000m	https://www.resdc.cn/
Soil	2012	1000m	https://www.resdc.cn/
Climate	2019	1000m	http://data.cma.cn/
Road	2021	/	openstreetmap
Population density	2021	100m	https://www.worldpop.org/
Economic density	2020	1000m	http://www.resdc.cn/
Night light	2021	500m	https://www.ngdc.noaa.gov/
Settlement	2021	/	http://www.geodata.cn

are typically established based on minimum cost routes (MCR) between source locations [10]. To identify important corridors, the gravity model, graph theory, and landscape index can be used [20], [34]. An efficient ecological network that connects all ecological sources through corridors improves ecosystem functioning, addresses ecological problems, and protects residents' ecological security and well-being [35].

In conclusion, prior methods have emphasized the functional characteristics of ecological land patches while disregarding the spatial structural significance of such patches in the overall matrix landscape and their connection to the environment [36], [37]. This implies that the precision of ecological source identification must be enhanced. MSPA assists in focusing on structural correlations with measurable ecological sources, highlighting structural linkages [38]. For areas undergoing accelerated urbanization, socioeconomic factors need to be included in the system of indicators affecting ecological resistance, such as traffic projects (high-speed railroads, highways, etc.), population distribution, economic activities, and other phenomena that interfere with the native ecological land. Meanwhile, compared with the simple analysis of ecological source points and corridors, the ecological network emphasizes the integrity of the ecosystem, which helps to propose more precise strategies for ESP optimizing [39].

As one of the three main biodiversity centers in China, the Xiangyang metropolitan area protects the most intact mid-latitude forest environment in the world [40]. Rapid socioeconomic growth has had a substantial influence on the structure and function of ecosystems, resulting in several ecological challenges, such as ecological land loss and landscape fragmentation. In terms of physical geography, the region represents an ecological entity that is intricately linked through the Han River Basin as its central axis. Simultaneously, it serves as a conceptual framework for administrative division adjustments. With the objective of constructing a protective ecological barrier in the northern part of Hubei Province and safeguarding the South-to-North Water Diversion Project (SNWD), Hubei Province is committed to achieving ecological cogovernance within this region, thereby facilitating its holistic ecological integration and green development. Consequently, this region surpasses the spatial scale of cities or river basins, encompassing a comprehensive dimension influenced by both natural and administrative factors. Thus, the establishment of an indicator system that comprehensively assesses the ecological impact of this region becomes imperative, considering the amalgamated influence of nature and society. To discover ESPs using GIS spatial analysis, MSPA, MCR, and gravity models, we provide a novel "importance-sensitivity-disturbance" research paradigm. The study's main goals are to

1) combine landscape connectivity with the sensitivity and significance of ecosystems to identify ecological sources;
2) establish an ecological resistance surface that emphasizes the significant upsetting influence of socioeconomic factors;
3) extrapolate significant ecological corridors using MCR and gravity models to form ecological networks;
4) identify alert areas for protecting green space and provide guidance for regulating ecological restoration in national land space.

II. Materials and Methods

A. Study Area

Xiangyang metropolitan area (109°29′–113°46′E, 31°15′–33°16′N) is located in northwestern Hubei Province, China, with an area of 56 300 km^2, and includes four cities: Xiangyang, Shiyan, Suizhou, and Shennongjia Forestry District (see Fig. 1). The Danjiangkou Reservoir in the area serves as the water intake point for the middle route of SNWD. As the central axis of the city group, Han River, together with Qinba Mountain in the southwest, Dahong Mountain in the southeast, and Tongbai Mountain in the northeast, forms the ecological barrier of northwest Hubei, forming a complex and diverse ecological function area of biodiversity and water and soil conservation. Therefore, this place is also called the "ecological regulator" in Central China. The study area is distinguished by nearby mountains and bodies of water and strong cultural ties between various cities, connecting the Central Plains, Guanzhong Plain, and middle reaches of the Yangtze River city clusters, and supporting the high-quality growth of Hubei Province in the northern array. As a result, the Xiangyang metropolitan area has clear geographic advantages and serves as a key transportation hub that connects the east, west, north, and south, which is crucial for advancing the "Belt and Road Initiative" and the growth of the Yangtze River Economic Belt.

The Xiangyang metropolitan area had 11.37 million residents as of the end of 2020, with an urbanization rate of 67.83%. The GDP was over 10 000 billion Yuan, with the main industries being tourism, modern agriculture, and automotive manufacture. Significant changes in land use brought about by population and economic expansion have resulted in environmental issues including landscape fragmentation and biodiversity loss. Therefore, for sustainable regional development, it is crucial to identify significant ecological source sites, corridors, and ecological restoration regions.

B. Data Sources and Processing

The data presented in this study include information on land use, net primary production (NPP), soil, NDVI, VIIRS/DNB night light information, climate, and socioeconomic information including population and economy. The data sources, timing, accuracy units, and utilization are listed in Table I. To facilitate spatial calculations, all raster data were uniformly resampled to a spatial resolution of 1000 m $\times$ 1000 m.

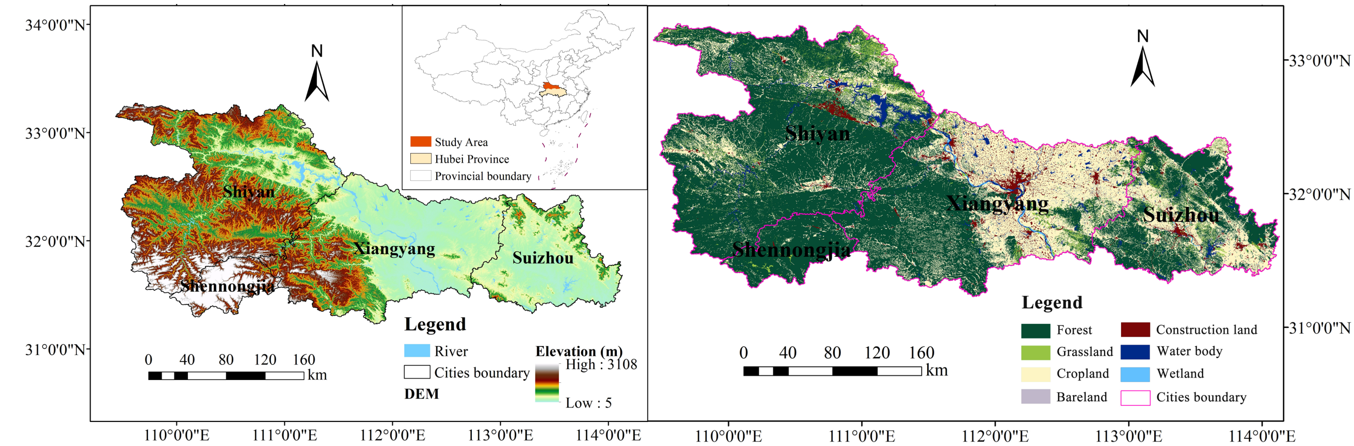


Fig. 1. Location and environment of the Xiangyang metropolitan area.

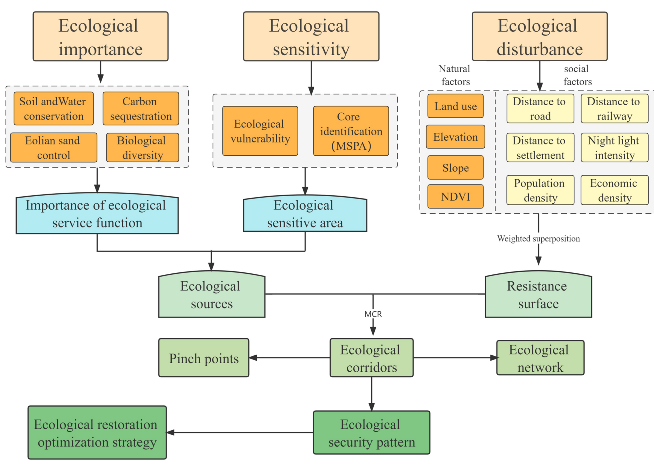


Fig. 2. Research framework.

C. Methods

The current paradigm for developing regional ESPs is the study framework of "identifying ecological sources, building resistance surfaces, and extracting corridors" [4], [41]. With reference to earlier techniques, this study created a brand-new framework called "importance-sensitivity-disturbance" to construct ESPs (see Fig. 2). It emphasizes the disruptive influence of natural and socioeconomic factors together to suggest the best ways to effectively balance conservation and development.

1) Identification of Ecological Sources: Two crucial factors for choosing an ecological source location are high ecosystem service quality and strong landscape connectivity [42]. The following processes are required for ecological source identification.

Step 1: Evaluation of the value of ecosystem services. Considering the abundance of forest resources and biodiversity in the Xiangyang metropolitan area, which is located in the Qinba mountains' eastern part, biodiversity and carbon sequestration are two important considerations to take into account. Given that recent widespread rainfall might raise the risk of erosion in mountainous areas, soil and water conservation is another crucial aspect to take into account. Eolian sand control also warrants consideration since there are vast tracts of deserted hills, bleak beaches, and sandy arable land north of the Han River. The InVEST model was used to compute four ecological services: biodiversity, carbon sequestration, soil and water conservation, and wind and sand management. Based on the biological features of the research region, the need for ecosystem services, and the availability of data, these services were chosen. Analyzing normalization and superposition data allowed for the evaluation of the integrated ecosystem service function. Table II displays the precise assessment techniques and calculating procedure.

Step 2: MSPA can establish the spatial link between target image sets and structural features and categorize target image sets into seven categories: core, patch, pore, edge, bridge, loop, and branch, which is often used in ESPs identification and ESPs network study. In this study's MSPA analysis, forest land and water area were used as the foreground and background land categories, respectively, and their core regions were identified as probable ecological source areas utilizing the Guidos Toolbox software platform.

Step 3: Considering the ecological sensitivity encompasses the vulnerability and susceptibility to disturbance of ecosystems [43]. This is of utmost importance for the Xiangyang metropolitan area, which encompasses the Shennongjia National Park and the SNWD reservoir area. Five sensitive factors, slope, slope direction, elevation, NDVI, and distance to water (see Table III), were graded and given values corresponding to 1–5, and the AHP approach was used to calculate the weights of the indicators [21], [43].

2) Construction of Ecological Resistance Surface: Typically, both human actions and environmental factors have an impact on the degree of ecological resilience. Along with natural indicators, such as land use, elevation, slope, and NDVI, we also selected certain variables that are directly connected to human activity, such as economic density, population density, distance to communities, and distance to roadways (railways and highways). Ten indicators were selected, as indicated in Table IV; with reference to pertinent research [44], [45], [46], ten indicators were identified, as shown in Table IV. The resistance values range from 5 to 300. Each indicator's weights were calculated using the AHP approach. All parameters are weighted and overlaid in ArcGIS to get the final ecological resistance surface raster data.

TABLE II
ECOLOGICAL IMPORTANCE ASSESSMENT METHOD

Type of assessment	Formula	Parameter meanings
Biodiversity	$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt})$	S_{bio} measures a service's capacity to provide upkeep, NPP_{mean} is the average annual net primary production of plants, F_{pre} is the mean annual precipitation, F_{tem} is the mean annual temperature, F_{alt} is the altitude factor.
Carbon sequestration	$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$	C_{total} is the total carbon stock of the watershed, C_{above} is the carbon stock of the above-ground part, C_{below} is the carbon stock of the below-ground part, C_{soil} is the carbon stock of the soil; C_{dead} is the dead organic carbon stock.
Soil and water conservation	$S_{pro} = NPP_{mean} \times (1-k) \times (1 - F_{slo})$	NPP_{mean} is the mean annual net primary productivity of vegetation, F_{slo} is the slope factor. k is the soil erodibility.
Eolian sand control	$S_{ws} = NPP_{mean} \times k \times F_q \times D$	F_q is the multi-year average climate erosion force, D is the surface roughness factor

The calculation of the above four indicators is mainly based on the InVest model and ArcGIS analysis.

TABLE III
FACTORS OF ECOLOGICAL SENSITIVITY

Ecological factor	Classification	Degree of sensitivity	Value	Weight
Slope(°)	0-10	Insensitive	1	0.15
	10-25	Low Sensitive	2	
	25-45	Medium Sensitive	3	
	45-60	High Sensitive	4	
	>60	Extremely High Sensitive	5	
Elevation(m)	<50	Insensitive	1	0.25
	50-200	Low Sensitive	2	
	200-500	Medium Sensitive	3	
	500-1500	High sensitive	4	
	>1500	Extremely High Sensitive	5	
Slope orientation	Flat、South	Insensitive	1	0.15
	South West、South East	Low Sensitive	2	
	East、West	Medium Sensitive	3	
	North East、North West	High Sensitive	4	
	North	Extremely High Sensitive	5	
NDVI	0-0.3	Insensitive	1	0.25
	0.3-0.5	Low sensitive	2	
	≤0	High sensitive	4	
	≥0.5	Extremely High Sensitive	5	
Distance to water (m)	Other regions	Low Sensitive	2	0.20
	300-800	Medium Sensitive	3	
	<300	High Sensitive	4	
	Water body	Extremely High	5	

TABLE IV
CLASSIFICATION AND WEIGHT OF RESISTANCE FACTORS

Type	Code	Weight	Resistance value				
			300	100	50	10	5
nature	a	0.25	construction land	cropland	grassland	water	forest
	b	0.10	<50	50-200	200-500	500-1500	>1500
	c	0.05	<10	10-20	20-30	30-40	>40
	d	0.10	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	>0.8
Socio-economic	e	0.10	<1	1-3	3-5	5-10	>10
	f	0.05	<1	1-3	3-5	5-10	>10
	g	0.05	<0.5	0.5-1	1-1.5	1.5-2	>2
	h	0.10	>20	10-20	5-10	1-5	<1
	i	0.10	>5000	1000-5000	500-1000	100-500	<100
	j	0.10	>5000	2000-5000	1000-2000	500-1000	<500

a refers to land use type; b refers to elevation (m); c refers to slop (°); d refers to NDVI; e refers to distance to main road (1 km); f refers to distance to railroad (1 km); g refers to distance to settlement (1 km); h refers to night light intensity; i refers to population density (person/km_2); j refers to economic density (yuan/km_2).

3) Extraction of Ecological Corridors and Hub Nodes: Important elements of ESPs are ecological hubs and corridors. Ecological corridors play a crucial role in the flow of materials and energy between ecological sources and serve as important passageways for migrating species [47]. With reference to transportation network theory [48], An ecological hub node, which we describe as the junction of many ecological corridors, is crucial to the connection and stability of ESPs and must be preserved and repaired. Using earlier findings [2], [28], [41], to extract ecological corridors and nodes, the MCR model and complex network theory are employed. The following is the calculating formula:

$$\text{MCR} = f_{\min} \sum_{i=1}^{k} D_{ij} \times R_i \tag{1}$$

where D_{ij} indicates the physical separation between sources i and j, f stand for the minimal positive correlation between MCR and ecological process, and R_i denotes the resistance coefficient of i. This study uses a GIS distance model to identify biological corridors.

To assess the relative significance of prospective ecological corridors in the area, gravity models may assess the strength of linkages among different source patches. A higher level of corridor importance is indicated by stronger contact forces [18]. The calculating formula is shown as follows:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{L_{max}^2 \ln(S_i) \ln(S_j)}{L_{ij}^2 P_i P_j} \tag{2}$$

where G_{ij} is the interaction force between patches i, j; N_i, N_j are the weight values of patches i, j. D_{ij} is the resistance value of potential corridors between patches i, j; P_i and P_j are the resistance values of patches i and j; and S_i and S_j are the areas of patches i and j; Between patches i and j, there may be potential resistance values for corridors, and these values are cumulatively expressed as L_{ij} and maximally expressed as $L_{\max}$, respectively.

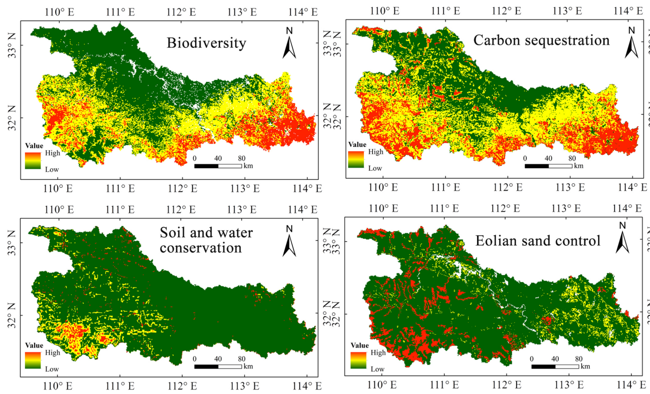
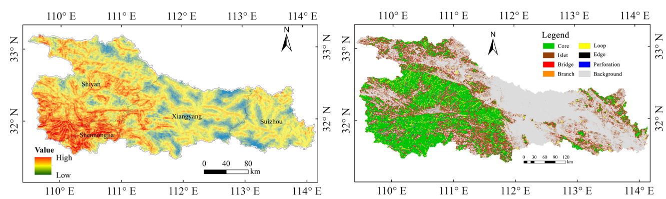


Fig. 3. Evaluation of ecosystem services.



(a) (b)

Fig. 4. Spatial pattern of ecological sensitivity and MSPA landscape. (a) Ecological sensitivity. (b) MSPA landscape pattern.

III. Results

A. Spatial Variation in Ecological Sources

1) Ecosystem Service Importance Assessment: According to Fig. 3, when considering the evaluation of four different types of ecosystem services, large ecological patches, such as in Shennongjia Forestry District and Jing Mountain in the study area's south-west and Dahong Mountain and Tongbai Mountain in the study area's south-east, offer the Xiangyang metropolitan area a wealth of ecological benefits. In contrast, the central plains of the research area and the northern half of the Gangetic region have insufficient levels of ecosystem services.

2) Ecological Sensitivity Assessment: Ecological sensitivity refers to an ecosystem's susceptibility to human behavior disruption, which raises the risk of ecological imbalance and ecological environmental issues. Ecological sensitivity varies significantly across the Xiangyang urban region [see Fig. 4(a)]. The very high sensitive area covers the entire Shennongjia Forestry District in Shiyan City's south-west and covers an area of about 2026.43 km^2, or 3.61% of the study area's total area. The high sensitive area is located on the periphery of the sensitive area and covers an area of about 11 248.75 km^2, or 20.12% of the total area. The plain area, which makes up around 24 543 km^2 or 43.82% of the entire area, dominates the medium-sensitive area. The low sensitive area, covering an area of approximately 15 679 km^2, or 27.91% of the total area, is located in Xiangyang City and portions of Suizhou and Shiyan Cities. The nonsensitive zones are generally located in the plains and low, gentle hills along the Han River, particularly in the south of Xiangyang City, Suizhou City, and the north of Shiyan City, and cover around 2573 km^2 (4.65% of the total area).

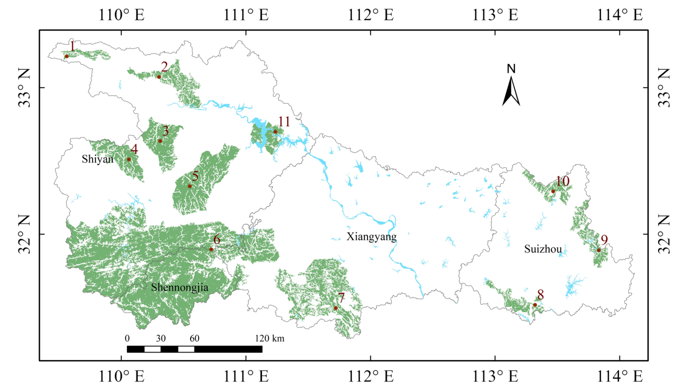


Fig. 5. Distribution of ecological sources. 1: Daliangshan forest area in the northwest of Yunxi County. 2: Huling Yumai mountain in the central and eastern Yunxi County. 3: Canglang Mountain Yunyang. 4: The wild mountain in the north of Zhushan County. 5: Wudang Mountain. 6: Shennongjia Forest area. 7: Jingshan Mountain in the south of Nanzhang County. 8: Dahongshan forest area in southern Suizhou. 9: Tongbai Mountain area in the north of Sui County. 10: Tongbai Mountain area to the east of Guangshui. 11: Danjiangkou Reservoir and surrounding woodlands.

3) Connectivity of Ecological Patches: The connection of ecological patches should be taken into account while choosing ecological sources, in addition to the value of ecological services. The scientific rigor of identifying ecological source sites is increased by MSPA's ability to identify habitat patches that are significant in the landscape connectivity in the research region [49]. The Guidos Toolbox program was used to get the MSPA classification findings for landscape features [see Fig. 4(b)], where the core region, with a total area of 28.67%, was mostly dispersed in Shennongjia, Daba Mountain, Wudang Mountain, and Dahong Mountain in the east.

4) Thorough Analysis to Locate Ecological Sources: Considering ecological sensitivity, patch connectivity, and ecosystem service functions are important, we found 11 ecological source sites with an area of more than 10 km^2 (see Fig. 5). It can be clearly found that the ecological source areas are mainly contiguous large areas of woodlands and waters, mainly because they are considered as priority areas for conservation due to their high biodiversity and ecosystem functions, and are located relatively remote from human activity., which reduces the impact of human disturbance. The 11 biological source sites' combined area was 17 248.21 km^2, accounting for 22.03% of the study area. The majority of the ecological sources in the Xiangyang metropolitan area are located in the south-west. Large nature reserves, mountainous forests, and the Han River Danjiangkou Reservoir Area make up the majority of these resources. They are crucial for supporting the region's population and ecosystem overall and preserving its ecological functions and fostering sustainable regional development.

B. Ecological Resistance Surface

A weighted overlay calculation of 10 criteria based on both environmental and socioeconomic factors (see Fig. 6) finally led to the determination of the least cumulative resistance surface of the Xiangyang metropolitan area (see Fig. 7). The mean, lowest, and maximum integrated resistance values are 24.73, 5, and 250, respectively, making the total ecological resistance values

TABLE V
INTERACTION MATRIX BETWEEN PATCHES OF ECOLOGICAL SOURCE

Patches No.	1	2	3	4	5	6	7	8	9	10	11
1	0	**9.324**	1.719	0.535	0.709	2.282	1.499	0.205	0.348	0.218	2.267
2		0	**23.565**	**10.822**	2.335	1.477	0.762	0.889	0.107	1.051	**20.891**
3			0	**33.21**	**6.044**	4.103	1.239	0.852	0.947	1.626	**17.112**
4				0	**16.236**	**5.558**	3.519	1.628	0.707	0.291	3.265
5					0	**87.085**	2.035	**8.603**	1.024	0.763	4.802
6						0	**6.787**	3.182	**8.993**	2.573	2.051
7							0	**10.266**	2.404	1.819	0.634
8								0	3.488	1.075	0.426
9									0	**17.528**	0.778
10										0	0.245
11											0

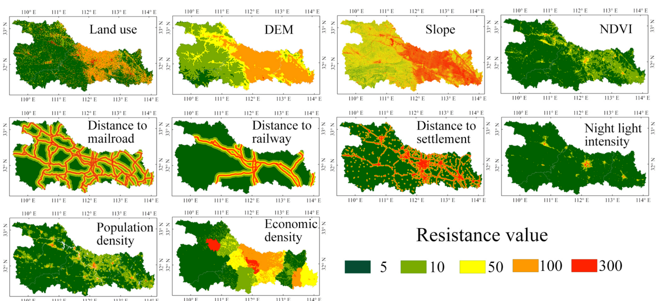


Fig. 6. Natural and socioeconomic aspects disturbance.

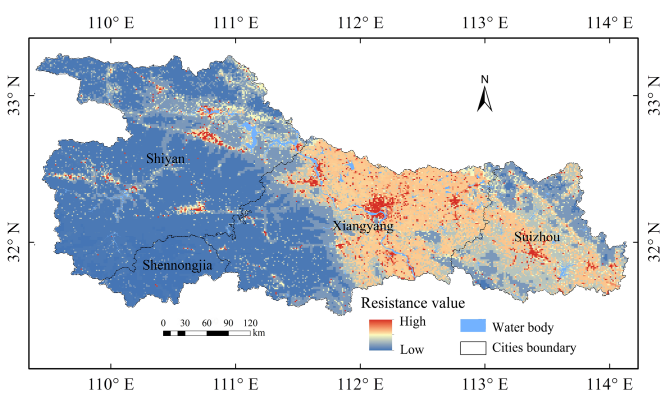


Fig. 7. Distribution of ecological resistance surface.

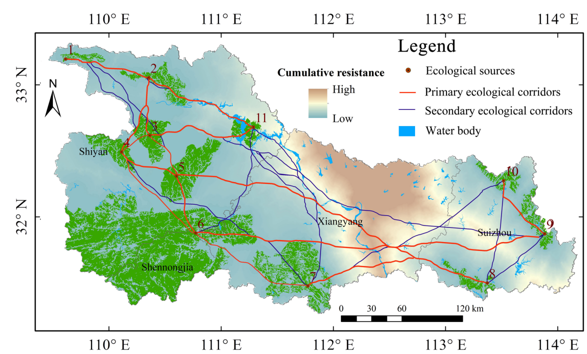


Fig. 8. Distribution of ecological corridors.

comparatively low. High values in the east and low values in the west make up the overall geographical pattern. The middle and eastern plains have a distribution of high-value locations that are heavily impacted by human activities, where the average resistance values are approximately the same in Xiangyang and Suizhou (35.77 and 35.67). On the other hand, the low-value areas are distributed in the western mountainous and upper Han River areas, among which Shiyan City and Shennongjia Forestry District have average resistance values of 13.68 and 6.22.

C. Potential Ecological Corridors and the ESPs

A matrix of interactions between ecological sources was derived based on (2). The strength of the connection between patches of ecological source increases with higher values, resulting in a greater ecological impact. The interactions between patches >5 were classified as primary ecological corridors, totaling 14 (see bolded entities in Table V); interactions ≤5 were classified as secondary ecological corridors, totaling 66 (see Table V). A total of 80 prospective ecological corridors were found (see Fig. 8), totaling 4855.34 km in length. The average path length is 60.69 km, the largest path length is 305.04 km, and the lowest path length is 0.62 km. Pathways smaller than 10 km in length account for 52.50% of all pathways. The crucial corridor is mostly found in the southern half of the research area, where ecological paths have a big area, significant ecological service relevance, and ecological sensitivity. The ecological corridor, which stretches along the Han River and its tributaries, has significant amounts of forest, shrubland, and grassland. On the whole, the horizontal and vertical distribution of ecological corridors is obvious, showing a distribution pattern of "three horizontal and four vertical."

Using the key mountain ranges and water systems in the research region as a natural backdrop, we superimposed the identified biological source locations, ecological nodes, and ecological corridors. Based on this, we propose an optimization strategy for the ESPs of the Xiangyang metropolitan area, which is "one axis, three screens, four zones, and multiple nodes" (see Fig. 9). "Han-Shi High-Speed Railway," which serves as an axis connecting numerous towns within the Xiangyang urban area, effectively enhances economic interconnections and communication within the region. The Qinba Mountains, the Tongbai Mountains, and the Dahong Mountains are the three ecological barriers. The

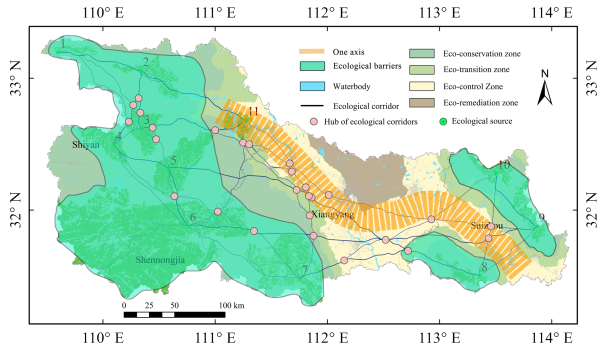


Fig. 9. ESPs of the Xiangyang metropolitan area.

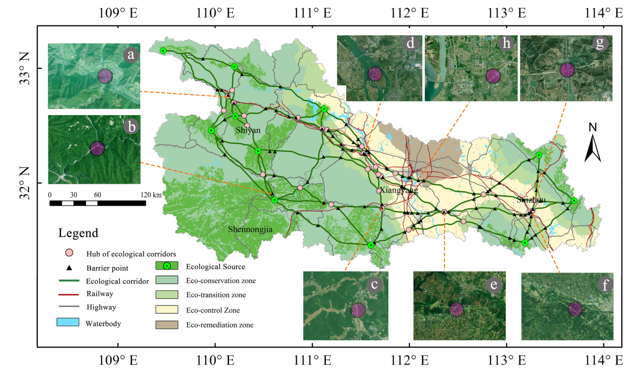


Fig. 10. Typical ecological restoration area. (a) and (b) Typical barrier points in ecological conservation zone. (c) and (d) Typical barrier points in the ecological transition zone. (e)–(g) Typical barrier points in ecological control zone. (h) Typical barrier points in ecological remediation zone.

entire region is split into four ecological zones—ecological conservation zone, ecological transition zone, ecological control zone, and ecological remediation zone—based on the level of ecological importance, connectivity, and sensitivity to develop distinct national land space management policies.

In addition, the long distance of the ecological corridor poses a threat of fragmentation, particularly in its cross-sectional regions. These intersections, 26 in all, akin to transportation network hub sites, serve as crucial "stepping stones" for the maintenance of ecological security and are thus targeted areas for repair. These intersections play a pivotal role in ecosystems as they link diverse habitats and biomes, serving as vital connectivity corridors and holding significant importance in ecological restoration efforts.

IV. Discussion

A. Ecological Protection, Restoration, and Spatial Optimization

The key objective of ecological space conservation is to preserve the authenticity and wholesomeness of natural ecosystems [17]. However, this poses a significant challenge for China, which is undergoing a rapid process of urbanization. Maintaining the crucial ecological impacts of existing nature reserves is crucial, but it is equally important to continuously monitor and address the threats posed by human activities that may interfere with these ecosystems. For instance, the continual expansion of construction and agricultural land will result in the fragmentation of ecological spaces, whereas the construction of traffic arterials will disrupt the connectivity of ecological source sites and migration corridors. Thus, it is imperative to undertake effective measures to mitigate the adverse effects of these human activities and ensure the long-term sustainability of the ecosystems.

Identification of priority areas for ecological conservation and restoration is the key to maximizing ecological space [50]. The obstruction of natural corridors by high-traffic highways is the subject of this research's identification of ecological barrier zones that need to be restored. Landscape fragmentation is exacerbated by intersecting transportation facilities, which cut off landscape connectedness directly or partially at the intersection with the corridors (see Fig. 10). It is essential to form significant nodes while also taking the presence of ecological fracture sites into account while building and optimizing ecological networks. Our study analyzed the superimposition of road networks and potential corridors and identified 216 ecological fracture points in the study area. These fracture points were classified as 87 intersections with railroads, 35 intersections with highways, and 94 intersections with national roads.

As seen in Fig. 10, a significant number of these ecological barrier points (72.68%) are located in areas with high agricultural and industrial development, as well as dense populations. Moreover, some of the roads were found to directly cross ecological sources, with the most prominent instances observed in the Shennongjia Forest Area and Dahongshan. 35 (16.21%) of the total fracture spots were found within designated ecological protection zones.

Mitigating ecological barriers necessitates a holistic approach that embraces a range of measures. These encompass the establishment of wildlife corridors, mitigation of road impacts, ecological restoration and habitat enhancement, restriction of human disturbances, collaborative efforts across sectors, policy support, and rigorous monitoring and assessment. The integrated application of these measures effectively ameliorates ecological barriers, bolsters ecological connectivity, and safeguards biodiversity.

Measures for ecological control optimization are applied differently according to the location of ecological nodes and barrier points, as well as the zoning of ecological functions and the land use type of the patch. For instance, in the ecological conservation zone, characterized by primarily forested lands, the construction of traffic infrastructure should be minimized and road routes should be chosen in such a way as to avoid key ecological zones and special areas designated for plant and animal protection, thereby preserving the ecological protection baseline. In the ecological transition zone, primarily comprised of farmland and sparse forest lands, a gradual shift towards reforestation and grassland restoration is necessary to protect low hills and gentle slopes and prevent human activities from encroaching on natural spaces. Ecological conservation and economic growth must be coordinated in the ecological control zone, which is mostly located along the Hanshi High-Speed Railway's development axis. The ecological remediation zone, primarily located in the downtown area of Xiangyang city and the northern cultivated region, must be coupled with the control of urban development boundary lines to prevent the unchecked expansion of urban spaces.

B. Limitations and Future Research

The current research increases the understanding of environmental benefits and ecological vulnerability by including landscape connectivity in a comprehensive methodology. This methodology offers a more comprehensive and systematic method for identifying ecological source sites compared to previous studies that relied solely on single indicators. Despite recent advances, it is critical to recognize that more research is required to precisely identify and define the boundaries of these ecological sources.

In China, spatial planning is still in its early stages, and the optimization of the ESPs is affected by policies from various departments, complicated by the conflict between environmental preservation and economic growth. Given the intricacy of optimizing the ESP, future studies should explore how it can align with the objectives of local spatial planning. For example, the width of the ecological corridor is particularly crucial for regional ecological restoration. Efforts should be made in the future to determine the corridor width of the ESPs.

V. Conclusion

This study shows how intricately human actions interact with natural systems, underscoring the need for a more comprehensive strategy to comprehend and manage ecological security issues. Our findings underscore the necessity for policies and management approaches that strike a balance between societal requirements and ecological sustainability and underline the need to take into account both biophysical and socioeconomic elements when assessing the vulnerability and resilience of ecosystems. The research's findings contribute to the growing body of knowledge on the relationships between ecological security and human-caused environmental change, and they have important implications for the creation of sustainable development policies that ensure the long-term stability and health of both natural and social systems.

The analysis of ecological source sites in the Xiangyang metropolitan area has revealed a spatial extent of 17 248.21 km^2, representing a substantial proportion of 22.03% of the total study area. These critical ecological sources are situated in the southwestern Qinba Mountains, the SNWD region and its contiguous mountain ranges, as well as the eastern portions of the Dahong and Tongbai Mountains. The presence of these ecological source sites and the surrounding conservation areas augurs well for the future ecological safety of the region, serving as an important barrier to degradation and destruction. Our study has identified 80 potential corridors, displaying a general spatial distribution pattern of "three horizontal and four vertical." By taking into account the potential impacts of both natural and anthropogenic disturbances, the protection of these ecological sources and the establishment of green infrastructure could mitigate the tension between urban expansion and ecological preservation. In light of these findings, we suggest an improved model made up of "one axis, three screens, four zones, and multiple nodes" for the preservation of the Xiangyang metropolitan area's ecological safety. The findings of our study advance our understanding of the ecological characteristics of this area and offer a set of spatial optimization strategies for balancing urbanization and ecological protection. These strategies can be used as a useful guide for ecological governance and restoration in the Xiangyang metropolitan area and even throughout Central China.

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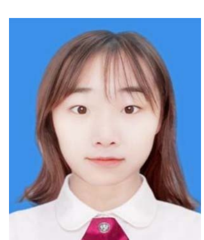

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