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Research on Urban Ecological Network Under the Threat of Road Networks—A Case Study of Wuhan

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Abstract: The creation of a road network can lead to the fragmentation and reduction of the connectivity of the ecological habitat. The study of urban ecological networks under threat from rapidly developing road networks is of great significance in understanding the changes in urban ecological processes and in constructing a reasonable ecological network. Spatial syntax is a linear space analysis method based on graph theory. Taking Wuhan city as an example and adopting spatial syntax to quantify road network threat factors, two resistance surfaces are established based on land use type assignment and overlapping road network threat factor assignment. The ecological environment under two scenarios is constructed by combining the MSPA (Morphological Spatial Pattern Analysis) method and MCR (Minimal Cumulative Resistance) model to comprehensively evaluate the network. Results demonstrate that spatial syntax can effectively describe the spatial characteristics of the road network. The average resistance value of the study area increases by 15.94%, the length of corridor increases by 37.9 km, the energy consumption of biological and material exchanges increases, and the resistance increases. To a certain extent, the model reflects the impact of road network threats on ecological processes. The results are useful in identifying the impact of human activities on ecological processes and provide a reference point for the construction of urban ecological security patterns.

Keywords: road networks; spatial syntax; ecological network; MSPA; MCR model

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1. Introduction

The rapid expansion of roads provides a huge economic benefit whilst causing large-scale ecological patches to be eroded, divided and gradually shredded; ecological corridors have been cut off, and connections between ecological patches have gradually been weakened, eventually, forming isolated islands and hindering material and energy flow between them [1,2]. In this context, the concept of "ecological network" has been introduced as a conservation tool for recovery and maintenance of ecological connectivity and environmental continuity [3].

The idea of an ecological network began to appear in the 19th century [4], Olmsted and Vaux designed Central Park in New York in 1858, proposing the protection of natural, historical, cultural and landscape resources with high biological, geological, aesthetic and cultural values, and the establishment of national parks and nature reserves. The park connects Franklin Park, Arnold Botanical Gardens, Jamaica Park and Boston Park. This park system is recognized as the earliest planned ecological network in the United States. After the 1990s, scholars conducted substantial research on how to construct an ecological network and began to use empirical data to simulate potential ecological process diffusion characteristics, thereby determining the ecological network construction mode of "ecological source identification—resistance surface construction—ecological corridor extraction". The model uses cost distances to analyze and simulate potential optimal spatial layouts [5]. In the past, in the research of ecological source identification, scholars selected protected areas such as forests and wetlands as ecological sources. However, this selection is highly subjective and the structure and connectivity of these patches has been neglected. In recent years, the MSPA (Morphological Spatial Pattern Analysis) method focusing on measuring connectivity has been widely adopted [6,7]. In the study of the construction of the resistance surface, the influencing factors include both natural and human factors. Shi et al. consider the elevation and NDVI factors [8], and Wang et al. combine the natural factors such as landslide and environmental factors to correct the land use type assignment [9]. The road network is the concrete embodiment of human disturbance ecology [10,11]. A large number of scholars use the road factor to correct the resistance value. For example, Xu et al. classify the road into one category [12], Jia et al. assign values according to road grades [13], Pan and Liu insist upon a hierarchical assignment based on buffer distance [14], Gurrutxaga et al. classify and assign values based on traffic volume [15]. They all consider the impact of the road itself but ignore the impact of the whole spatial distribution of the road network. Liu et al. used the road network density to characterize the road network, and therefore studied the impact of the road network on the ecological network construction [16]. However, the interpretation of the role of main roads, where road networks are sparse, is insufficient. The spatial syntactic model is based on graph theory to describe the topological connection characteristics and accessibility characteristics of road networks (such as road density, road grade, connection strength, spatial layout) [17]. Using the road factors quantified by spatial syntax to correct the resistance surface and build an ecological network could potentially help researchers to more effectively study the impact of road network threats on ecological networks.

In summary, this paper takes Wuhan city as an example, firstly using the spatial syntax principle to quantify the road network factor; secondly, adopting the MSPA method and the landscape connectivity index to screen the ecological source; then, constructing ecological resistance surfaces in two scenarios based on the minimum cumulative model; simulating ecological corridors under the two scenarios with a comparison and analysis of road network impacts on the ecological process; finally, combing with the gravity model to evaluate and optimize the ecological network incorporating the road factor (Figure 1).

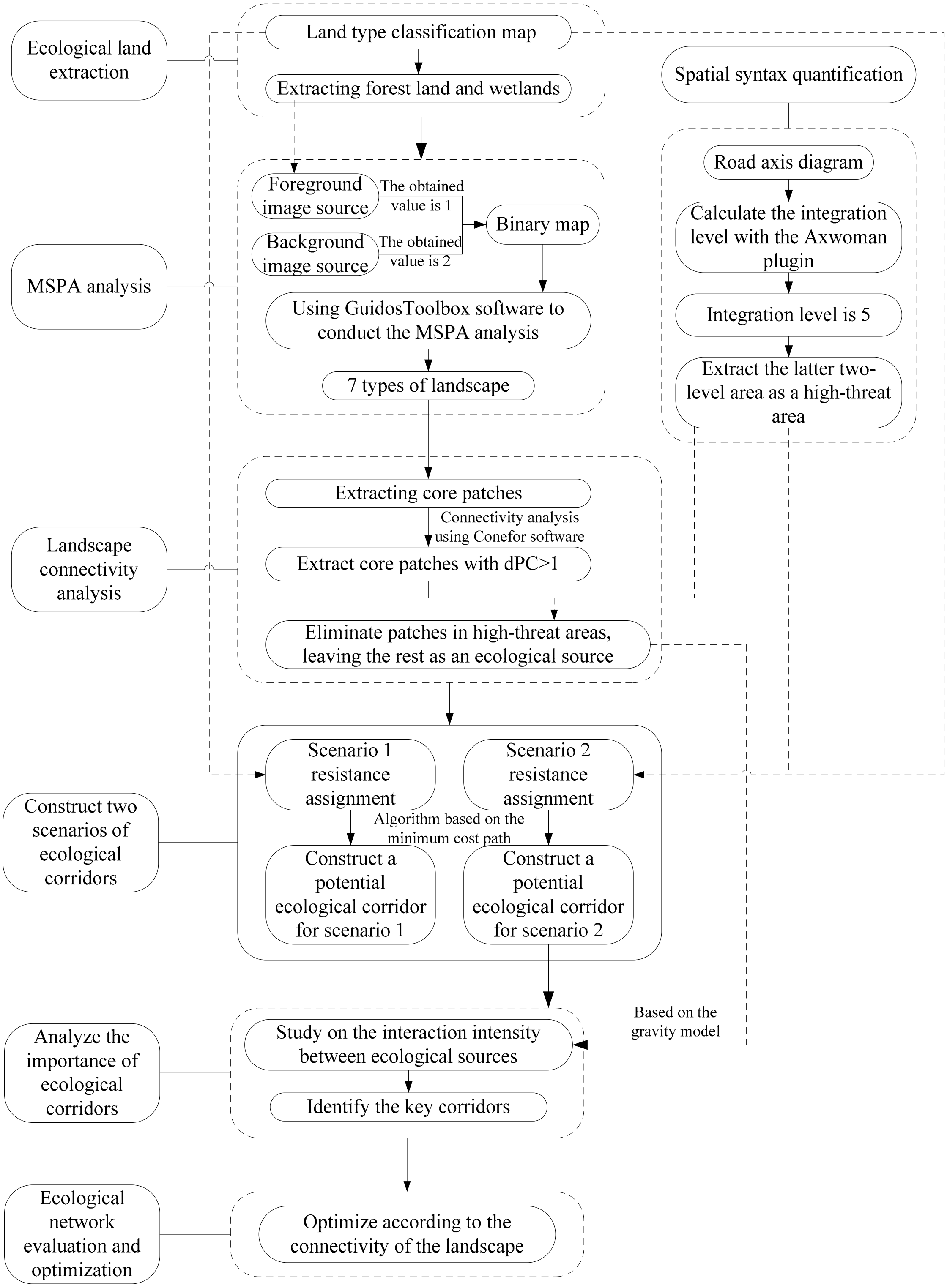


Figure 1. Methodology roadmap.

2. Research Theories and Methods

2.1. Space Syntax

From the perspective of road topological relations, spatial syntax is adopted to study the relationship between spatial organization and human activities [18]. The theory holds that the characteristics of spatial organization structure are the sum of the topological relationships of all spatial nodes in the system, and the characteristics of one spatial node are determined by its relationship with all other spatial nodes. This spatial structure relationship is the main factor determining the type and number of "natural travel" in space. The main parameters of the method are connection degree, depth value and integration (Table 1). Amongst these factors, integration is the core parameter of the space syntax, reflecting the importance of a certain road in its road network, road grades and densely populated areas to a certain extent (the greater the integration, the more people in the area, the more frequent human activities).Therefore, integration is used to quantify the road factor. In this paper, roads are first converted to an axis diagram, then further converted to a dual diagram, that is, the axis is converted into node elements with node connection lines representing the connection relationship between the axes (Figure 2).

Table 1. Space syntax parameters.

Parameter	Formula	Significance
Connection degree (C_i)	$C_i = k$	k represents the number of nodes directly connected to the i-th node.
Depth value (Di)	$D_i = d_i$	d_i represents the sum of the shortest distance between the i-th node and all the remaining nodes (the minimum number of steps, and the distance between two adjacent nodes is 1 step).
Integration (RAi)	$RA_i = \frac{2\left(\frac{\sum_{i=1}^{n} d_i}{n-1} - 1\right)}{n-2}$	n represents the number of nodes.

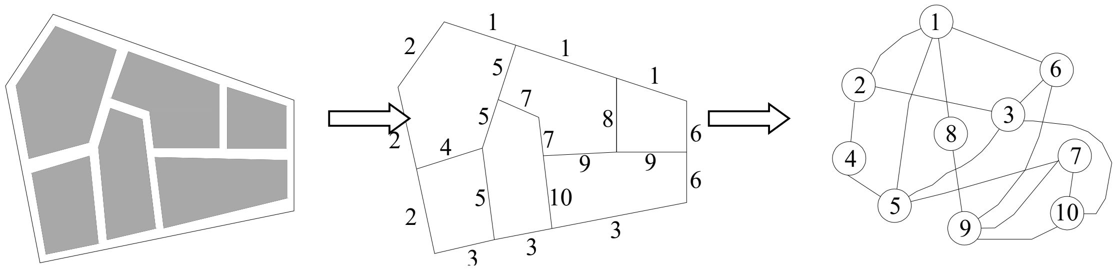


Figure 2. Illustration of the road Network, axis map and dual graph.

2.2. MSPA Method

The MSPA method is a new method based on the pixel level to identify and classify the grid space structure. It is proposed by Soille and Vogt based on the mathematical morphology of corrosion, expansion, opening and closing operations [19,20]. The method classifies land with a high ecological effect as the foreground and sets other land as the background by utilizing the land use data after interpretation and classification, then conducts binary reclassification (foreground assignment is 1, background is assigned to 0).After a series of graphics, the treatment method is divided into 7 types of landscapes with different functions (Core, Islet, Perforation, Edge, Loop, Bridge, Branch) (Table 2).

Table 2. Types and Ecological Implications of MSPA.

Landscape type	Ecological Implications
Core	A habitat patch with a large pixel. It can provide a spacious habitat for organisms and therefore is important for species reproduction and biodiversity conservation. It is the ecological source of ecological networks.
Islet	A small, isolated, fragmented patch with a low connectivity to other patches and less possibility of material and energy exchange.
Perforation	The transition zone between the core patch and its interior non-green space, i.e. the edge interior patch (Edge Effect).
Edge	The transition zone between the edge of the core area and the surrounding non-green landscape area. It can reduce the impact of external environment and human interference.
Loop	The internal channel connecting the same core area, which is a shortcut for the exchange of material and energy within the core area.
Bridge	The long and narrow area connected with the core area. It has the characteristics of ecological corridor, which is conducive to species migration and the connection of landscapes within the country.
Branch	An area with only one end connected to an edge, a bridge, an island or a pore, mainly an extension of green space, and a channel for species diffusion and energy exchange with the surrounding landscape.

2.3. Landscape Connectivity

Measuring the landscape connectivity is a common method for quantitatively evaluating whether a patch is suitable for biological communication and migration. Indicators often include IIC (integral index of connectivity), PC (probability of connectivity), and dPC (patch importance) (Table 3). This research used the dPC indicator to measure the importance of patches. The dPC thus represents the relative decrease (in percentage) of PC following the removal of patch i. The greater the value of dPC is, the more important patch i is.

Table 3. Connectivity index.

Landscape Connectivity Index	Formula	Significance
IIC	$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i.a_j}{1+nl_{ij}}}{\mathrm{A_L}^2}$	n represents the total number of patches in the landscape; a_i and a_j represent the area of patch i and patch j; nl_{ij} represents topological distance between patch i and j (minimum number of links that have to be passed to move from i to j); A_L is the total area of the landscape; d_{ij} is the Euclidean distance between patch i and $j k$ is a constant; PC_{remove} is the connectivity index value of the landscape after the patch i is removed from the landscape.
PC	$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}a_i.a_j.p_{ij}^{*}}{\mathrm{A_L}^2}$ $p_{ij}^{*} = e^{-kd_{ij}}$	
dPC	$dPC = \frac{PC - PC_{remove}}{PC} \times 100\%$	

2.4. Minimum Cumulative Resistance Model

The minimum cumulative resistance model (MCR) was further modified by Knaapen and other researchers on Knaapen (Formula (1)) [21,22]. The model plans the path by calculating the amount of resistance that is accumulated from the source patch to the target patch, to determine the trend and likelihood of biological and material energy flowing between the patches [23].

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

In the formula: MCR refers to the minimum cumulative resistance value; D_{ij} represents the Euclidean distance from source j to spatial unit i; R_i refers to the degree of difficulty of organisms passing through unit i (The greater the resistance value, the more difficult it is for organisms to pass through this type of area.); $\sum$ refers to the accumulation of the product of the distance of all units passing from source j to unit I and resistance; f_{min} refers to the minimum cumulative resistance value of unit i to different source units [24].

2.5. Gravity Model and Network Connectivity Index

The gravity model is used to measure the interaction force between the ecological sources and evaluate the interaction intensity between sources to determine the relative importance of the ecological corridor. The formula is as follows:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left[\frac{1}{P_i} \times \ln(S_i)\right]\left[\frac{1}{P_j} \times \ln\left(S_j\right)\right]}{\left(\frac{L_{ij}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln S_i \ln S_j}{L_{ij}^2 P_i P_j} \tag{2}$$

In the formula: G_{ij} refers to the interaction force between patch i and j, N_i and N_j are the weight values of the two patches respectively, D_{ij} is the normalized value of the potential corridor resistance between the i and j patches, and P_i is the resistance of the patch i value, S_i is the area of the patch i, L_{ij} is the cumulative resistance value of the corridor between the patch i and j, and L_{max} is the maximum value of the resistance of each corridor [25].

The α index (Network circuitry), the β index (Line point rate), and the γ index (Network connectivity) are used to evaluate the degree of perfection of the ecological network. The greater the value, the better the network connectivity. The formula is as follows:

$$\alpha = \frac{L - V + 1}{2V - 5} \tag{3}$$

$$\beta = \frac{L}{V} \tag{4}$$

$$\gamma = \frac{L}{3(V - 2)} \tag{5}$$

In the formula: L is the number of corridors; V is the number of patches in the source. α is used to describe the degree of loops in the network, that is, the ratio of the actual number of loops to the maximum number of possible loops in the network; β is the average number of links per node in the network; and γ is used to describe the degree to which all nodes in the network are connected, that is, the ratio of the number of connecting corridors to the maximum number of possible connecting corridors in a network.

3. Case Study

3.1. Data Source

Wuhan is located in the eastern part of Hubei Province, at the junction of the Yangtze River and Han River with a total area of about 8559.52 km^2. It belongs to the north subtropical monsoon region and has abundant rainfall with four distinct seasons. The terrain is mainly flat with minimal variation. Wuhan is known as the "City of hundred lakes", where freshwater resources rank first among Chinese major cities; its wetland resources rank third among the inland cities of the country and form an important part of Wuhan's ecological area. However, due to urban development and human disturbance, the wetland resources have been occupied and transformed, resulting in changes in the landscape structure of the wetlands, which has affected the exchange of biological resources.

The data in this paper is mainly divided into two parts: First, the land use information from the geospatial data cloud (http://www.gscloud.cn/) of Wuhan 2016 Landsat8 30 × 30m remote sensing data. After data interpretation combined with Google Maps and the secondary Wuhan land survey data, we divide Wuhan land types into forest land, wetland (mainly natural lakes), other waters (the Yangtze River and artificial reservoirs, etc.), cultivated land, construction land and other land types (Figure 3);

second, the road network data is derived from the Wuhan City Road Network data of Open Street Map (http://download.geofabrik.de/) (Figure 4).

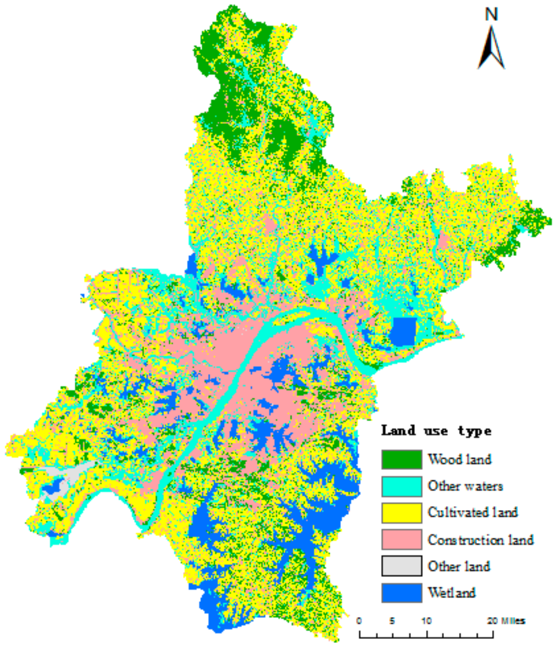


Figure 3. Land use types in Wuhan.

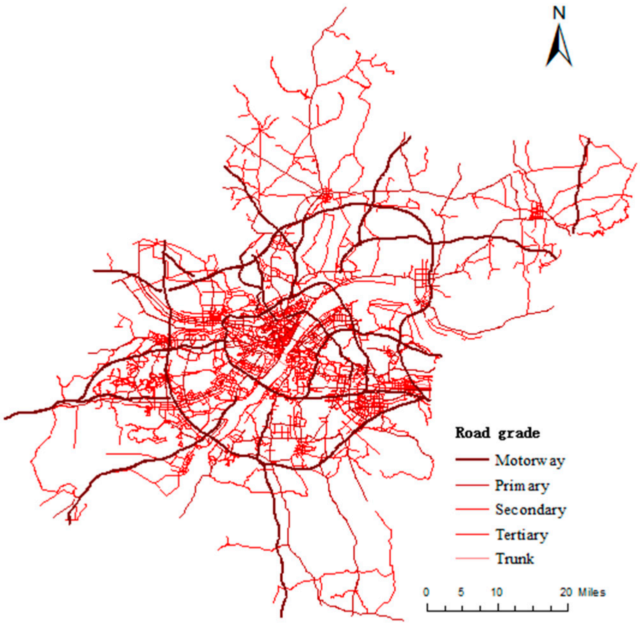


Figure 4. Wuhan road network.

3.2. Experimental Results and Analysis

3.2.1. Source Selection Results and Analysis

This research quantifies road data based on spatial syntax and applies the spatial analysis module of ArcGIS and Axwoman plug-in (Bin Jiang, University of Gävle) to calculate the integration level parameter. We also use the inverse distance weight interpolation method and the natural breakpoint method to divide the area into 5 levels (Figure 5: the higher the level number, the greater the threat). Thus, it takes level 4 and 5 as the high-risk area for the road network (man-made interference area).

Figure 5 shows that the high threat zone of the road network is mainly distributed in the central urban area, with the important roads distributed in a ring shape in the center, and vertically distributed in the north and south.

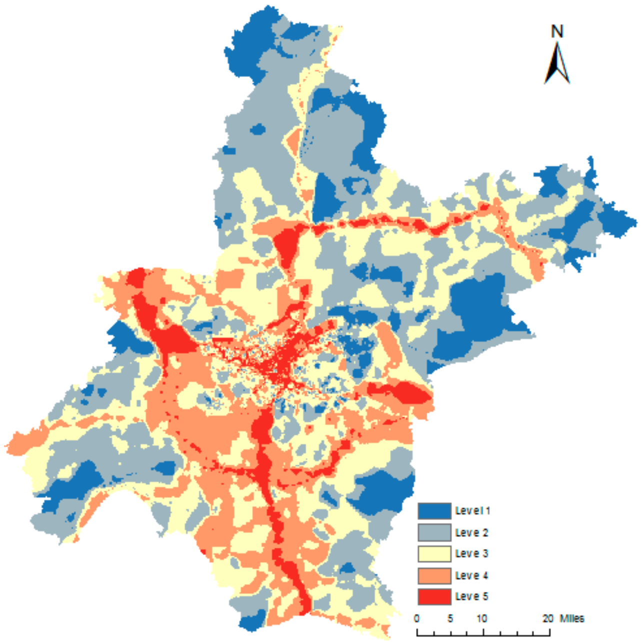


Figure 5. Integration level distribution map.

As Table 4 explained, the core is the large area which provides a spacious habitat for organisms, permitting the flow of materials and energy and is therefore important for species reproduction and biodiversity conservation. Firstly, a binary reclassification was conducted for the land use raster data (we assign a value of 1 to the forest land and wetland and assign other land types a value of 0). Secondly, we adopted the Guidos Toolbox software to conduct MSPA analysis and obtained 7 types of landscapes (Figure 6). Then, we statistically analyzed the results of the analysis (Table 4). If too many ecological sources are chosen however, there will be too many overlaps in the subsequent ecological corridors, leading to a redundancy of corridors, increasing the cost of construction and management and causing excessive calculation in subsequent experiments. Therefore, referring to the research of Chen et al. [26], combined with the regional scale, the area threshold is set at 0.1 km^2. Patches with a landscape area greater than 0.1 km^2 in the core were extracted as alternative patches for the ecological source.

Table 4. Statistics table of MSPA.

Landscape Type	Area/km^2	Percentage of Total Area of Ecological Land/%
Core	1257.15	66.23
Islet	102.83	5.42
Perforation	11.14	0.61
Edge	373.63	19.68
Loop	11.14	0.57
Bridge	23.14	1.24
Branch	119.12	6.25
Total	1898.15	100

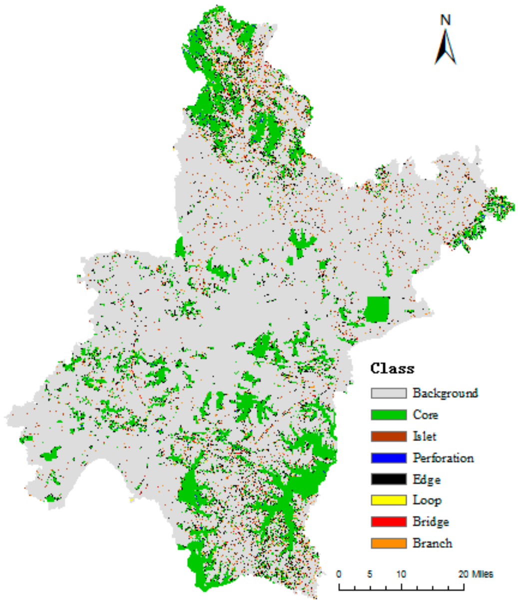


Figure 6. Landscape type analysis map based on MSPA.

We used the Conefor Sensinode software, in line with previous studies [27,28], set the patch connection distance threshold to 5000 m, and the connectivity probability to 0.5 to calculate dPC, and extracted patches with dPC>1 as a preliminary screening.

Given the high-threat area is a serious area of human disturbance and is not conducive to biological migration, we eliminated patches in the high-threat area and finally 24 source areas were obtained. Then, we ranked the area statistics and landscape connectivity (Table 5).

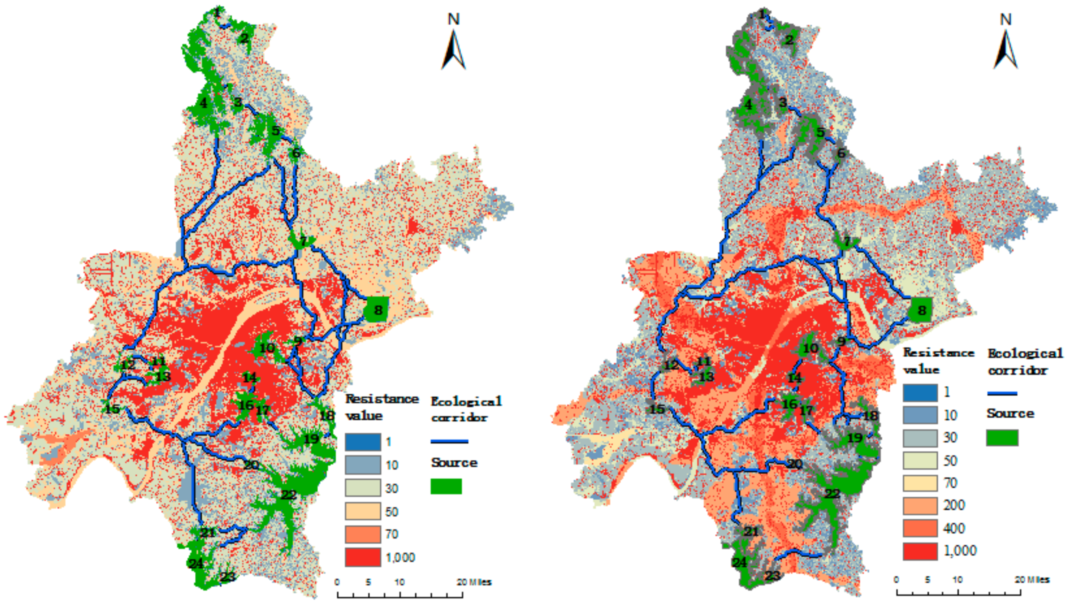
Table 5. The importance of source landscape connectivity index.

Sort	Source Number	Area/km^2	dPC
1	22	154.16	38.30
2	4	132.63	17.43
3	19	51.32	15.91
4	24	63.18	12.14
5	5	51.97	8.39
6	16	24.59	7.45
7	10	29.36	5.81
8	18	18.77	5.33
9	21	10.98	4.65
10	17	11.85	4.31
11	2	26.09	3.53
12	3	12.43	3.48
13	8	38.06	3.06
14	14	6.77	2.73
15	13	13.25	2.14
16	1	6.74	1.93
17	7	17.66	1.72
18	20	2.09	1.55
19	23	7.21	1.54
20	6	11.18	1.46
21	12	7.99	1.40
22	11	5.09	1.28
23	9	6.53	1.23
24	15	7.67	1.06

From Figures 4 and 5 we find that the high-threat area is mainly concentrated in the central city with the most complete road network; the ring high-threat area and the high-threat area of the north-south trend that extends to the periphery are caused by national highways such as G107 and G318 (G107 and G318 are the names of national highways.), which are important parts of the Wuhan road network and have a greater impact on the migration of living things. We took the high-threat area as the region where the ecological network is affected by the road network. It was also used as the resistance value correction area in the second scenario.

From Figure 6 and Table 4, we find that the core area is around 1257.15 km^2, which accounts for 66.23% of the total area of ecological land. The core area is mainly distributed in the northwest and southeast of the study area with small patches scattered in the central and southwest and the northeast area relatively isolated. This results in poor connectivity between other parts of the study area and the northeastern part. This is not conducive to biological and material circulation between the patches.

From Figure 7 and Table 5, we find that the ecological source extends from the north to the southeast, with a total area of 717.56 km^2, accounting for 37.8% of the total area of ecological land.



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

Figure 7. Network maps under different situations. (**a**) Scenario 1 Corridor Network; (**b**) Scenario 2 Corridor Network.

3.2.2. Simulation Results and Analysis of Different Landscape Corridors

This paper reveals the ecological network changes under threat from the road network by comparing the simulation of ecological corridors under two scenarios. Scenario 1: Resistance surface without road network threat; Scenario 2: Resistance surface with road network threat. In this paper, the resistance factors are assigned according to the statistical analysis of previous studies (Table 6) [12–16]. Also, an ArcGIS cost distance module was adopted to obtain the minimum cumulative cost resistance surface, and the cost path module was used to simulate the corridor, deleting the overlapping corridors, and obtaining the potential ecological corridor network map based on the two-two connection principle.

Table 6. Assignment of different situational resistance factors.

Resistance Factor	Situation 1	Situation 2
Source region	1	1
Forest land	10	10
Wetland	10	10
Cultivated land	30	30
Other water are	50	50
Construction land	1000	1000
Other land	70	70
Road factor Grade 4	/	200
Road factor Grade 5	/	400

From the perspective of the spatial layout of the ecological network, as shown in Figure 7, the ecological network of the study area is mainly distributed in the center of the central city and presented as a circular distribution. This is because the central city is the most complete area of the road network with the largest human disturbance and the highest resistance value, which hinders the circulation of organisms and materials. Compared with scenario 1, the ecological network in scenario 2 shows a trend of expansion towards the surrounding area. This is mainly due to the increase in the landscape resistance value partially caused by the road network. The average resistance of the study area increased by 15.94%, and the length of the corridor increased from 586.87 km to 624.77 km, indicating that the threat of the road network hindered the circulation of organisms and materials, and changed its movement path, resulting in a change in the spatial layout of the ecological network.

From the connection of individual ecological corridors, the corridors extending to the south from the sources 4, 5, and 6 tend to merge and extend to the south due to the increase in resistance; the source sites 7 and 8 directly connected to the source 18 are revised to 7, 8-9-18 connection modes; the path direction between the source areas 11, 12, 13 is changed from the original 12-13-11 to 12-13-11; the directly connected paths of the source 13 and the source 15 are changed into indirect connection through connecting with the source 12; the source grounds 21, 24 to the source ground 22 are changed from the many-to-one directly connected to the 21-24-23-22 connected mode.

3.2.3. Ecological Network Evaluation and Optimization Analysis

The greater the value of G_{ij}, the stronger the interaction between patch *i* and patch *j*, and the more important the corridor between patch *i* and *j* is. According to previous studies [25], we selected the corridors between patches with $G_{ij} > 100$ as important corridors. From Table 7 and Figure 8, we find that the important corridors identified by the gravity model should be protected from damage due to urban expansion. Although the source 15 and the source 21 are weak in connection, they should also be protected as important corridors because they serve as a bridge between the southwest region and other regions and play a key role in the overall connectivity of the study area. From Table 7, we find that the average connection strength between the source and the ground is gradually weakened from the periphery to the center, the source of the northern region (source 4) and the southeast region (source 22) is strong, and the source of the central region (source 13 and source14) is the weakest.

Table 7. Interaction matrix between source patches based on gravity model.

7	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0																							
2	79,933	0																						
3	68,898	32,396	0																					
4	178,560	72,762	652,933	0																				
5	14,704	14,114	47,848	55,541	0																			
6	4109	4672	9533	13,574	63,840	0																		
7	448	670	690	1234	1420	953	0																	
8	141	225	201	375	357	227	844	0																
9	46	75	65	122	112	71	191	637	0															
10	75	122	105	198	181	114	292	882	29,504	0														
11	5	8	6	12	9	5	6	6	3	5	0													
12	10	16	13	26	20	12	13	12	6	11	94	0												
13	7	12	10	19	15	9	10	10	5	9	21,150	153	0											
14	6	10	8	15	13	8	12	19	14	27	4	7	6	0										
15	9	14	11	22	17	10	12	11	6	11	65	3167	105	8	0									
16	9	15	12	24	20	12	18	28	21	39	9	18	15	417	20	0								
17	7	12	10	19	16	10	15	23	17	31	7	14	11	273	16	72,620	0							
18	13	22	18	34	29	18	29	47	29	76	11	29	18	66	34	322	282	0						
19	18	29	24	46	39	24	39	63	53	101	16	40	25	92	47	463	407	315,875	0					
20-	3	5	4	8	7	4	7	11	9	18	3	8	5	16	9	78	68	8993	32,320	0				
21	6	10	8	16	13	8	12	18	13	25	13	40	21	19	49	55	45	151	215	40	0			
22	22	37	30	58	50	31	49	80	67	128	20	52	32	116	61	575	505	204,362	3,253,449	73,681	282	0		
23	5	8	7	12	11	6	10	14	10	19	9	24	14	14	29	40	33	103	146	27	1342	191	0	
24	11	18	14	28	23	14	21	32	23	43	23	69	37	33	84	96	78	267	379	70	2,597,833	497	2484	0

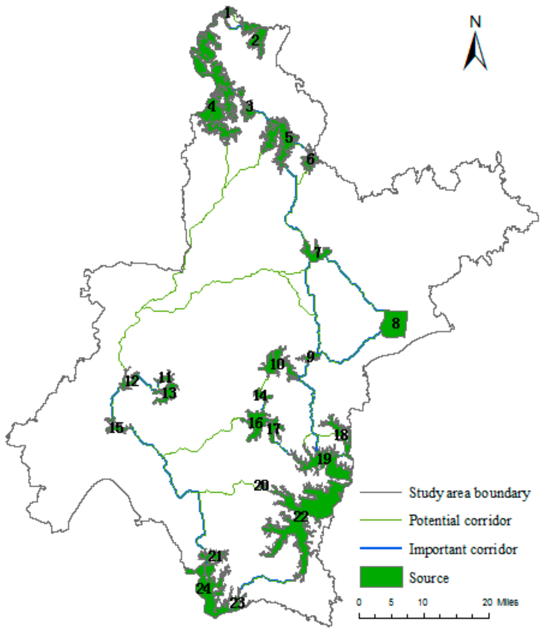


Figure 8. Potential corridor map of the study area.

From Figure 7b, we find that the study area lacks a connection with the northeast and southwest. Therefore, in the core area obtained by MSPA analysis, we have considered the importance of patch and selected 3 nodes in the Ministry with larger dPC values in order to cover the northeast and southwest and therefore ensure the overall connectivity of the research area. The planning results are shown in Figure 9, adding nine corridors and calculating the α, β and γ indexes before and after the planning. The pre-planning indexes were 0.18, 1.29 and 0.47 respectively, whilst the post-planning index increased to 0.29, 1.48 and 0.53 respectively, indicating that the ecological network after planning would be enhanced and the connectivity of the study area would effectively be improved.

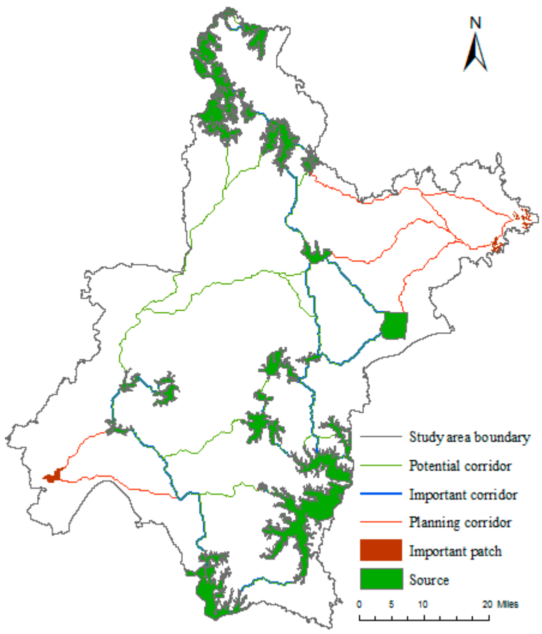


Figure 9. Planning corridor map of the study area.

4. Conclusions and Prospects

Construction of an ecological network can improve the connectivity of ecological landscape fragmentation caused by road construction and has a practical significance for the protection of ecosystems. Spatial syntax quantifying road factors can effectively characterize road network attributes and characteristics (road density, road grade, connection strength, spatial layout, etc.). Taking Wuhan as an example, this research quantifies road factors through the use of spatial syntactic principles, completes ecological source screening, resistance assignment and ecological network construction and optimizes the area under threat from the road network. It potentially helps to identify the impact of human activities on ecological processes and provides objective and effective support for the construction of an urban ecological security pattern. The research can be concluded as follows:

(1) Space syntax can effectively describe the characteristics and distribution of road networks (including road density, road grade, connection strength, spatial layout, etc.).
(2) Under the road network threat scenario, the average resistance of the study area was increased by 15.94%, and the length of the corridor increased by 37.9 km, indicating that a road network can increase the energy consumption of biological migration, change the biological migration path, and affect the spatial pattern of ecological processes.
(3) According to the spatial distribution and connectivity of ecological patches in the study area, three important patches were added, which improved the overall connectivity of the study area and augmented the ecological network of the study area. In future urban construction, attention should be paid to protecting and conserving the existing ecological land, maintaining the sustainable development of the urban ecosystem, whilst avoiding greater ecological security problems.

In the process of constructing ecological networks, the construction of resistance surface is very important. For different types of landscape patches, different resistance values are assigned, but there is no uniform standard for the resistance evaluation of patches. Considerable research has been undertaken on the selection of suitable resistance factors. Chen et al. considered the influence of elevation according to the topography of the study area [7]; Wang et al. considered the influence of landslide sensitive factors on biological migration and communication according to the frequency of geological hazards in the area [9]. The study area, Wuhan, is located in the plain area, so the influence of topographic factors is not obvious, but it belongs to an area where rapid urbanization has significantly affected habitats. As the main driving factor of the urbanization process, road networks are also the concrete embodiment of human disturbance to the ecology. Therefore, this paper chooses the road network factor as the factor of optimizing resistance surface. In future research, the selection of resistance factors should be further discussed, and the appropriate resistance factors should be formulated in combination with the selected research areas. In addition, different organisms have differing needs for corridor width in the process of migration, which is also a concern of many scholars. Due to the lack of detailed ecological data for the study area, when simulating the corridors, this paper focuses on consideration of the length of the corridor, and does not specify its width, instead making it the same as that of the grid. Establishing the corridor width is a suitable question for future research.

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References

1. Montis, A.D.; Caschili, S.; Mulas, M.; Modica, G.; Ganciu, A.; Bardi, A.; Ledda, A.; Dessena, L.; Laudari, L.; Fichera, C.R. Urban–rural ecological networks for landscape planning. *Land Use Policy* **2016**, *50*, 312–327. [CrossRef]
2. Vimal, R.; Mathevet, R.; Thompson, J.D. The changing landscape of ecological networks. *J. Nat. Conserv. (Jena)* **2012**, *20*, 49–55. [CrossRef]
3. Fichera, C.R.; Laudari, L.; Modica, G. Application, validation and comparison in different geographical contexts of an integrated model for the design of ecological networks. *J. Agric. Eng.* **2015**, *46*, 52–61. [CrossRef]
4. Shi, H. Research on Urban Green Space Ecological Network Construction Technology Based on RS and GIS. Master's Thesis, Nanjing Forestry University, Nanjing, China, 2010.
5. Beier, P.; Spencer, W.; Baldwin, R.F.; McRae, B. Toward Best Practices for Developing Regional Connectivity Maps. *Conserv. Biol.* **2011**, *25*, 879–892. [CrossRef] [PubMed]
6. Saura, S.; Vogt, P.; Velázquez, J.; Hernando, A.; Tejera, R. Key structural forest connectors can be identified by combining landscape spatial pattern and network analyses. *For. Ecol. Manag.* **2011**, *262*, 150–160. [CrossRef]
7. Chen, Z.; Kuang, D.; Wei, X.J.; Zhang, L.T. Construction of Yujiang County Ecological Network Based on MSPA and MCR Models. *Resour. Environ. Yangtze Basin* **2017**, *26*, 92–100.
8. Shi, N.N.; Han, Y.; Wang, Q.; Quan, Z.J.; Luo, Z.L.; Ge, J.S.; Han, R.Y.; Xiao, N.W. Construction and optimization of protected area ecological network in Qinghai Province. *Chin. J. Ecol.* **2018**, *37*, 1910–1916.
9. Wang, Z.H.; Wang, D.C.; Hu, B.X.; Guo, Q.Z.; Xiu, L.N.; Zhao, H.T. Construction of ecological network in Yinzhou District of Tianjin considering landslide sensitivity. *Acta Ecol. Sin.* **2017**, *38*, 4351–4362.
10. Benítez-López, A.; Alkemade, R.; Verweij, P.A. The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. *Biol. Conserv.* **2010**, *143*, 1307–1316. [CrossRef]
11. Coffin, A.W. From roadkill to road ecology: A review of the ecological effects of roads. *J. Transp. Geogr.* **2007**, *15*, 396–406. [CrossRef]
12. Xu, F.; Yin, H.W.; Kong, F.H.; Xu, J.G. Construction of the ecological network of the western central city of Bazhong based on MSPA and minimum path method. *Acta Ecol. Sin.* **2015**, *35*, 6425–6434.
13. Jia, Z.Y.; Chen, C.D.; Tong, X.X.; Wu, S.J.; Zhou, W.Z. Construction and Optimization of Ecological Network in the Three Gorges Reservoir Towns—Taking Kaizhou New City in Chongqing as an Example. *Chin. J. Ecol.* **2017**, *36*, 782–791.
14. Pan, J.H.; Liu, X. Ecological security assessment and pattern optimization of inland river landscape based on spatial principal component and minimum cumulative resistance model: A case study of Ganzhou District, Zhangye City. *Chin. J. Appl. Ecol.* **2015**, *26*, 3126–3136.
15. Gurrutxaga, M.; Lozano, P.J.; Barrio, G.D. GIS-based approach for incorporating the connectivity of ecological networks into regional planning. *J. Nat. Conserv.* **2010**, *18*, 318–326. [CrossRef]
16. Liu, R.C.; Shen, C.Z.; Jia, Z.Y.; Wang, J.X.; Lu, C.F.; Zhou, S.L. Construction and optimization of ecological network along beaches under road landscape stress: Taking Dafeng District of Yancheng City as an example. *Chin. J. Ecol.* **2019**, *38*, 828–837.
17. Jiang, B.; Claramunt, C. Integration of Space Syntax into GIS: New Perspectives for Urban Morphology. *Trans. GIS* **2002**, *6*, 295–309. [CrossRef]
18. Hiller, B. *Space is the Machine*; Cambridge University Press: Cambridge, UK, 2007.
19. Soille, P.; Vogt, P. Morphological segmentation of binary patterns. *Pattern Recognit. Lett.* **2009**, *30*, 456–459. [CrossRef]
20. Qiu, Y.; Chang, Q.; Wang, J. Urban Green Infrastructure Network Planning Based on MSPA—Taking Shenzhen City as an Example. *Chin. Landsc. Archit.* **2013**, *5*, 104–108.
21. Yu, K.J. Landscape ecological security pattern of biological protection. *Acta Ecol. Sin.* **1997**, *19*, 10–17.
22. Knaapen, J.P.; Scheffer, M.; Harms, B. Estimating habitat isolation in landscape planning. *Landsc. Urban Plan.* **1992**, *23*, 1–16. [CrossRef]
23. Yang, Y.Q.; Ren, P.; Hong, B.T. Development and Utilization of Low Slope Landslide in the Hinterland of the Three Gorges Reservoir Area Based on Ecological Security Pattern. *Res. Soil Water Conserv.* **2019**, *26*, 305–310.
24. Liu, X.F.; Shu, Y.M.; Zhang, L.B. Application of Minimum Cumulative Resistance Model in Urban Land Ecological Suitability Evaluation—Taking Xiamen as an Example. *Acta Ecol. Sin.* **2010**, *30*, 421–428.

25. Kong, F.H.; Yin, H.W. Construction of urban green space ecological network in Jinan. *Acta Ecol. Sin.* **2008**, *28*, 1711–1719.
26. Chen, C.D.; Jia, Z.Y.; Wu, S.J.; Tong, X.X.; Zhou, W.Z.; Chen, R.Y.; Zhang, C.L. A bibliometric review of Chinese studies on the application of landscape connectivity. *Acta Ecol. Sin.* **2017**, *37*, 3243–3255.
27. Liu, C.F.; Zhou, B.; He, X.Y.; Chen, W. Selection of distance threshold for urban forest landscape connectivity in Shenyang. *Chin. J. Appl. Ecol.* **2010**, *21*, 2508–2516.
28. Yu, Y.P.; Yin, H.W.; Kong, F.H.; Wang, J.J.; Xu, W.B. Scale effect of network structure and connectivity analysis of green infrastructure in Nanjing. *Chin. J. Appl. Ecol.* **2016**, *27*, 2119–2127.