Original Research

An Integrated Method to Analyze Forest Ecological Networks for Urban Sustainable Development: A Case Study of Wuhan in Central China

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Abstract

This research takes Wuhan as a case study with a focus on forest ecological network analysis based on an integrated approach. This approach applies the improved least-cost path model and scenario analysis to identify and compare networks with the cost surface setting, including ecological service value and biodiversity index. We proposed cost-based δ index and patch connection index (PCI) to evaluate the whole network structure and ecological source connection, as these two indexes comprehensively consider spatial structure and species migration cost. This study proves that the improved line kernel density method based on species migration cost is an effective tool to identify conservation priority areas and break points. Based on the proposed method, we identify and evaluate four types of urban forest ecological networks from different cost setting. The forest ecological network is uneven in spatial distribution. Overall ecological network structure has poor connection. We illustrate conservation priority areas and divide these priority areas into three categories of ecological security.

Keywords: forest ecological network, improved LCP model, PCI, improved line kernel density model, urban sustainable development

Introduction

Given that urbanization develops at a fast pace, human activities, particularly unlimited sprawl in cities, intensify fragmentation of the urban landscape [1]. Ecological lands in cities, mainly the urban forest, are occupied for other uses. These phenomena result in a significant imbalance between urban ecological protection and urban development [2].

A forest ecological network is a vital way of planning to cope with the fragmentation of the regional ecological landscape and to mitigate the imbalance between urban socioeconomic development and ecological environmental protection [3-6]. Specifically, a forest ecological network mainly contributes to the effective connection of fragmented habitat patches and the improvement of the migration efficiency of species, improvement of ecological system quality, and protection of biodiversity [7].

To identify ecological networks, recent research has proposed numerous techniques and methodologies. Some of these techniques include leverage field observations, which are more practical and definite in approach [8-10]. However, such an approach is difficult to popularize because of the requirement for massive manpower, materials, and funds.

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Therefore, other models based on RS, GIS, physical environment, and anthropic disturbance focused on identifying ecological networks. For instance, a habitat suitability model based on different criteria was used to identify ecological networks [11]. Graph theory and landscape metrics were used to identify and optimize ecological networks from the scope of network spatial structure [12-15]. However, the habitat suitability model and landscape metrics method always fails to correlate with the complicated ecological process. Therefore, the least-cost path (LCP) model was used to identify the ecological network. The LCP model determines optimum paths based on minimal theoretical cumulative-cost that comprehensively considered wildlife behavior and landscape configurations to illustrate connectivity and identify habitat linkages [16-19].

The purpose of this paper is to present an integrated method to analyze forest ecological networks for urban sustainable development of Wuhan City in central China. The aims of this paper are as follows:

(1) to incorporate ecosystem services value, vegetation coverage, biodiversity index to improve the LCP model
(2) to proposed cost-based δ index and patch connection index (PCI) to evaluate the overall network structure and ecological source connection
(3) to improved line Kernel Dentistry Estimate model based on species migration costs, and identify priority conservation areas in Wuhan
(4) to propose a specific forest ecological network planning and urban sustainable strategy for urban constructors and planners.

Materials and Methods

Study Area

As a megacity in central China, Wuhan is situated at the intersection of the Yangtze and Han Rivers. The whole city covers an area of 8,767 km^2. Wuhan boasts rich forest resources, including the Mulan ecotourism area, Jiufeng Mountain, Maan Mountain, Jiangjun Mountain, and other green land patches of various sizes. These areas have important study value because of their significant role in maintaining and developing urban biodiversity and urban ecological environment.

Data Processing

The data used in this study were derived from remotely sensed images of Wuhan City taken by the Landsat 7 ETM+ (retrieved on 10 September 2010). The image was downloaded from the International Scientific Data Service Platform.

The land cover map was interpreted from the remotely sensed image using supervised classification methods in ENVI 4.7 software with references including field surveys and a land-use map (2010 with scale 1/50,000). Based on different landscape functions, these data were classified into seven land-use types: construction land, farmland, water bodies, forestland, grassland, bare land, and wetland.

To identify the ecosystem service value of landscapes with various land use types in the studied area, the ecosystem service value proposed by Costanza was consulted [20]. We also produced digital vegetation coverage and a biodiversity index map by using the same remotely sensed image. The vegetation coverage and biodiversity index of Wuhan was estimated based on the normalized difference vegetation index (NDVI) [21]. We digitized a transportation map of Wuhan City's development master plan (2002-20) to obtain the street map using ArcGIS 10.1.

Selection of forest Ecological Network Sources/Destinations

Birds and small mammals are the main animal species in the rapid urbanization area. Previous studies always selected a number of important habitat patches as the sources of urban forest land ecological network according to the size of habitat. Against this backdrop, in terms of protecting biodiversity, we sorted out all-round ecological nodes by referring to relevant research and combining the local species conditions of Wuhan City. Eventually, 151 forest patches were selected as ecological sources.

Identification of Composite Cost Surface

Landscape cost refers to the difficulty for species to migrate between different landscape units. In this study, we holistically considered all factors affecting species migration. By integrating multiple indicators, we took road grade, ecosystem service value, vegetation coverage, biodiversity index, and land-use type to improve the cost setting of LCP model and set a weight using the entropy evaluation method to obtain the composite cost surface [22] (Tables 1-4). this paper discussed different cost settings with scenario analysis and established four cost planes: cost surface 1, cost surface 2 (about road buffer influences), cost surface 3 (about ecological landscape area variation), and cost surface 4 integrating all landscape costs.

Demarcation of Potential Ecological Network Based on Improved LCP Model

To reflect the LCP between ecological source and target, we used the improved LCP model to identify the potential migration and diffusion path of species. In this study, the cost setting is added ecosystem services value, cost value of vegetation coverage, and biodiversity index to improve LCP model. Meanwhile, the model builder in ArcGIS 10.1 was adopted to build up the improved LCP model with circulatory function. The working flow is in Fig. 1.

Evaluation of Overall Ecological Networks

We use the new cost-based δ index that I proposed and network structure analysis index to evaluate the structure of forest patch connectivity. The formula is given as follows:

Table 1. Ecosystem services value of landscape types in Wuhan.

Landscape type	ESV (RMB/hm^2)	Cost	Landscape type	ESV (RMB/hm^2)	Cost
Wetland	55,489	1	Grassland	6,407	88
River	40,676	27	Construction	0	100
Farmland	4,341	92	Road	0	100
Forest	19,334	65	Bare land	0	100

Table 2. Cost value of vegetation coverage and biodiversity index.

Factor	Classification	Cost	Factor	Classification	Cost
Vegetation coverage	> 0.35	1	Biodiversity index	0-0.21	100
	0.25-0.35	30		0.21-0.33	60
	0.15-0.25	50		0.33-0.44	40
	< 0.15	70		0.44-0.54	20
	0	90		0.54-1	1

$$\begin{aligned} \alpha &= \frac{L - V + 1}{2V - 5} \\ \beta &= \frac{L}{V} \\ \gamma &= \frac{L}{L_{max}} = \frac{L}{3(V-2)} \\ \delta &= \frac{L_i}{L} \end{aligned} \tag{1}$$

...where L is the number of corridors, V is the number of nodes, and L_i is the total cost of networks. The α index ranges from 0 to 1. When β is smaller than 1, it means that the network takes on a dendroid pattern. When β is equal to 1, it means that there is single loop in the network. When β is bigger than 1, it means that there is more complex connectivity in the network. The γ index varies from 0, indicating that none of the nodes is linked, to 1.0, where every node is linked to every other possible node. The δ index represents the average cost of ecological networks. When the δ index is bigger, the more effective is species migration.

Evaluation of Ecological Source Connection

In this study, the evaluation of ecological sources connection was based on patch connection index (PCI) that I proposed. PCI was represented by the average distance cost confronted by species in migration between different patches. Based on the LCP model, the cost path matrix between various forest ecological patches in Wuhan was obtained. On this basis, we used the OD Metrics in ArcGIS 10.1 Network Analyst module to calculate the actual distance of corridor between different ecological sources. The formula is given as follows:

$$\mathrm{PCI} = \frac{C_i}{D_i} = \frac{f_{min} \sum R_{ij}}{\sum P_{ij}} \qquad (i = 1,2,3 \cdots, \mathrm{m}; \mathrm{j} = 1,2,3, \cdots, \mathrm{n}) \tag{2}$$

...where P_{ij} is the real distance from ecological source *i* to another ecological source j across the landscape cost plane; R_{ij} is cost encountered by the ecological source *i*; C_i is cumulative cost for the ecological source *i* to connect with other ecological sources; and D_i is sum of distances from the ecological source *i* to other ecological sources.

Identification of Priority Conservation and Break Point

The improved line kernel density model weighted by the unit corridor cost used to identify the network priority and break point. The unit corridor cost can be calculated by the improved LCP model. Then add every unit cost to the attribute table of the network corridors as the weight of the improved line kernel density model. The improved formula is given as follows:

$$\lambda_\tau(s) = \sum_{i=1}^{n} \frac{1}{\tau^2} k\left(\frac{l \times c + l_i \times c_i}{\tau}\right) \tag{3}$$

...where τ is the area of the circle that is a smoothing parameter, τ>0, k(•) is the kernel function – a symmetric but not necessarily positive function that integrates to one; *l* is the length of a corridor; *c* is the corridor cost.

Table 3. Cost value of land use classification.

Landscape type	Subclass	Cost surface 1	Cost surface 2	Cost surface 3	Cost surface 4
Wetland		10	10		
	area>100 hm^2			5	5
	50 hm^2< area<100 hm^2			7	7
	area < 50 hm^2			10	10
Water		600	600		
	main river			800	800
	main lake			600	600
	pond			400	400
Farmland		100	100	100	100
Forest		1	1		
	area>100 hm^2			1	1
	50 hm^2< area<100 hm^2			3	3
	area<50 hm^2			5	5
Grassland		30	30	30	30
Construction area		1000	1000	1000	1000
Road	trunk road	500	500	500	500
	150 m buffer zone		300		300
	300 m buffer zone		150		150
	secondary road	300	300	300	300
	150 m buffer zone		200		200
	railway	900	900	900	900
	150 m buffer zone		800		800
	300 m buffer zone		700		700
	expressway	700	700	700	700
	150 m buffer zone		550		550
	300 m buffer zone		400		400
Bare land		100	100	100	100

Results and Discussion

Multi-Scenario Ecological Network Identification

Based on the composite cost surface of forest ecological network, the improved LCP was used to identify forest ecological networks in Wuhan, as shown in Fig. 2.

According to the urban forest ecological networks in Wuhan based on four different cost surfaces, the number of ecological corridors in the network gradually increases from downtown to suburb, such that the ecological network gradually becomes complicated in structure and is distributed more intensively.

Overall Evaluation of Ecological Network Structure

The evaluation results of four urban forest ecological network structures, which are identified on the basis of four cost planes, are listed in Table 5.

The lowest value of α on cost surface 2 is 0.26. It reaches the peak on cost surface 3, equaling 0.61. The index of α is used to describe the number of loops existing in ecological networks. The higher as is, the more available migration paths for species to cross over ecological networks. The results show roads and road buffers have a significant effect in blocking migration path and might sharply reduce available loops.

Table 4. Weights assigned for different landscape cost surfaces entropy method.

Cost surface type	Cost surface 1	Cost surface 2	Cost surface 3	Cost surface 4
Land use type	0.2892	0.2686	0.2941	0.2919
Ecosystem services value	0.0282	0.0290	0.0280	0.0281
Vegetation coverage	0.5880	0.6051	0.5840	0.5858
Biodiversity index	0.0946	0.0973	0.0939	0.0942

Table 5. Structure evaluation of the overall ecological network.

Ecological Networks	α	β	γ	δ
Cost surface 1	0.56	2.11	0.71	0.60
Cost surface 2	0.26	2.08	0.69	0.63
Cost surface 3	0.61	2.21	0.74	0.53
Cost surface 4	0.31	1.61	0.54	0.79

β and γ indicate connectivity of ecological networks. They both achieve the highest value on cost surface 3, respectively 2.08 and 0.74, and touch the bottom on cost surface 4 at 1.61 and 0.54. The higher β and γ are, the more complicated the ecological network is.

δ is used to quantify the validity of species migration in ecological network. The average cost of corridor reaches the highest value is 0.79 on cost surface 4. The lowest value is 0.53 on cost surface 3. It shows that roads and surrounding buffers increase average corridor cost in ecological network and decrease validity of species migration.

Generally speaking, roads exert a great impact on the structure of the ecological network. In the urban forest ecological network in Wuhan, there are only a few migration paths available for species; the ecological networks are less complicated, integral, and connected.

Evaluation of Ecological Sources

Based on the ArcGIS spatial model builder, PCIs of ecological sources are worked out using Formula 2 and classified into five classes by using the natural break method. The higher the class, the lower the connectivity.

As shown in Fig. 3, the connectivity of ecological sources increases progressively from downtown to suburb. Patches with Class 5 connectivity are mainly distributed in

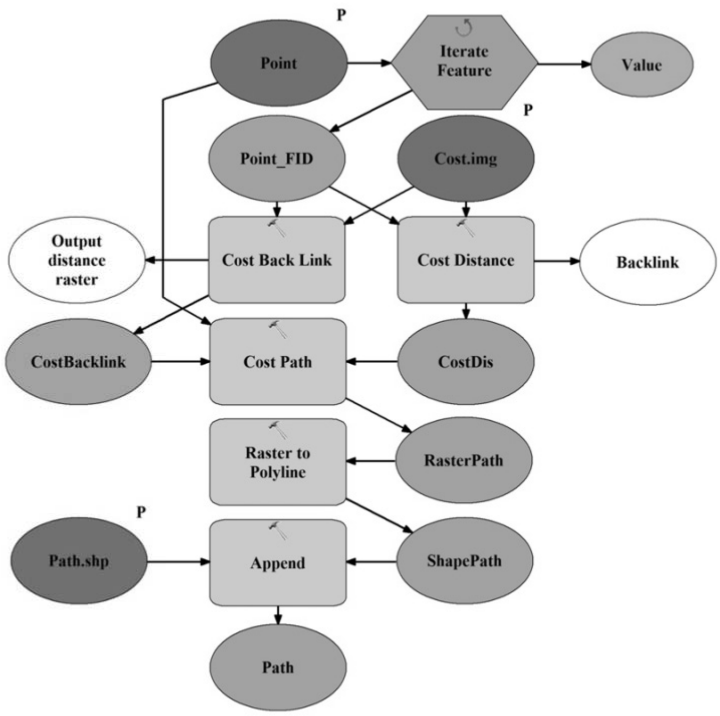

Fig. 1. Working flow of the improved LCP model.

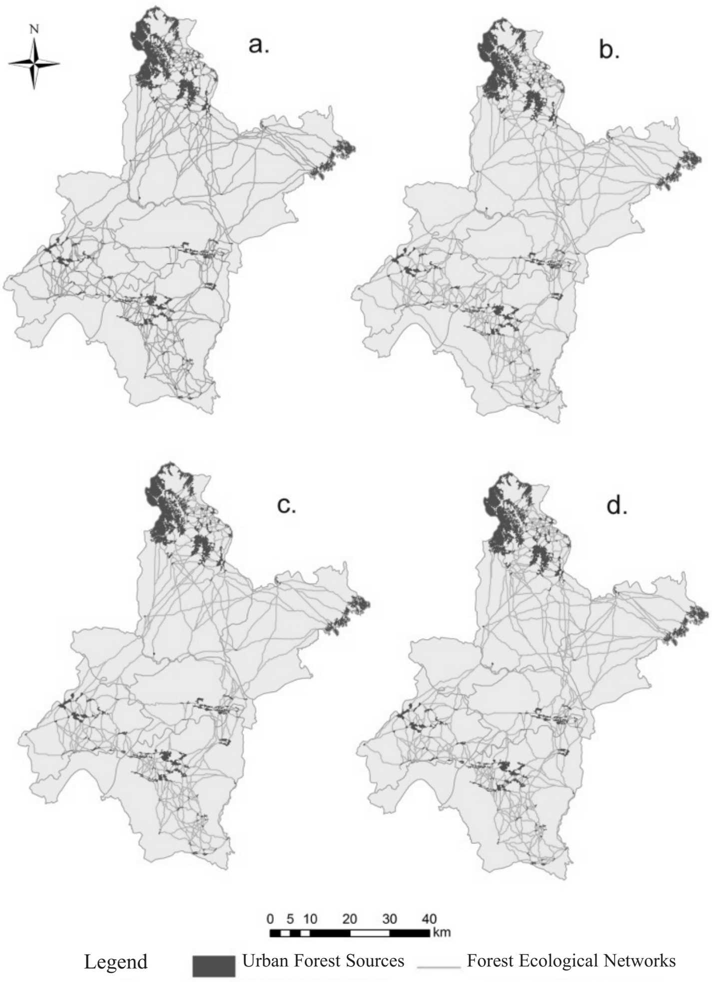

Fig. 2. The map of Forest Ecological Network in Wuhan.

forest areas in Mt. Mo, Mt. Yujia, and Mt. Maan. This phenomenon is largely distributed because of the short distance to downtown and intensive human activities. By contrast, the patch with Class 1 connectivity is the forest zone in Mt. Mulan in the north. This forest zone covers a large area, and offers a good precondition for biodiversity.

Identification of the Conservation Priority Areas

Identification of preferential protective zones in the ecological network and optimization of overall network structure can make the protection of forest ecological network in Wuhan more targeted and feasible. In this study, the improved line kernel density is used to analyze the line kernel density of potential ecological corridors and classified using the natural break method. The zones with high density are those given priority in protection and recovery.

According to the analysis results (Fig. 4), the conservation priority areas with high density are primarily distributed in the forest zone in Mt. Mulan in the northern part of Wuhan and peripheral areas around downtown. Specifically, these areas include the forest zone from East Lake to Mt. Jiufeng, the part from Lu Lake to Mt. Qinglong, and the forest zone from Houguan Lake and Mt. Jiuzhen to Chenhu Lake wetland.

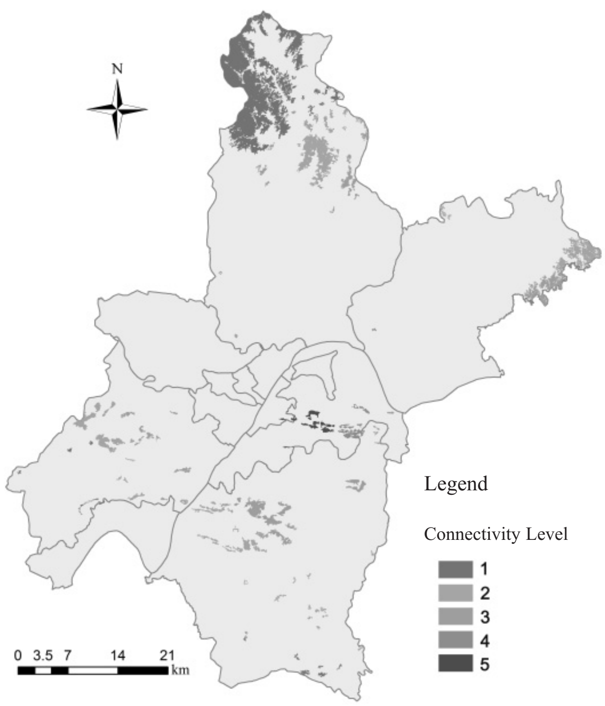

Fig. 3. Level of patch connection index (PCI) in Wuhan.

Identification of the Break Points

In the course of ecological network optimization, road landscape, especially high-level road networks, has a blocking effect that cannot be ignored on green corridors. This paper discusses the Wuhan transportation network system by railway, expressway, and trunk road, identified intersections between road networks of all levels with ecological networks, and analyzed spatial distribution and density using line kernel density.

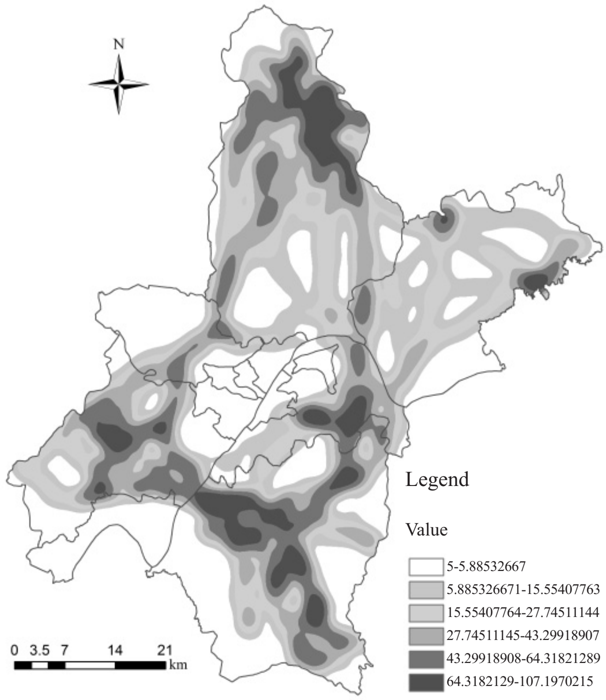

Fig. 4. The line kernel density map of conservation priority areas in Wuhan.

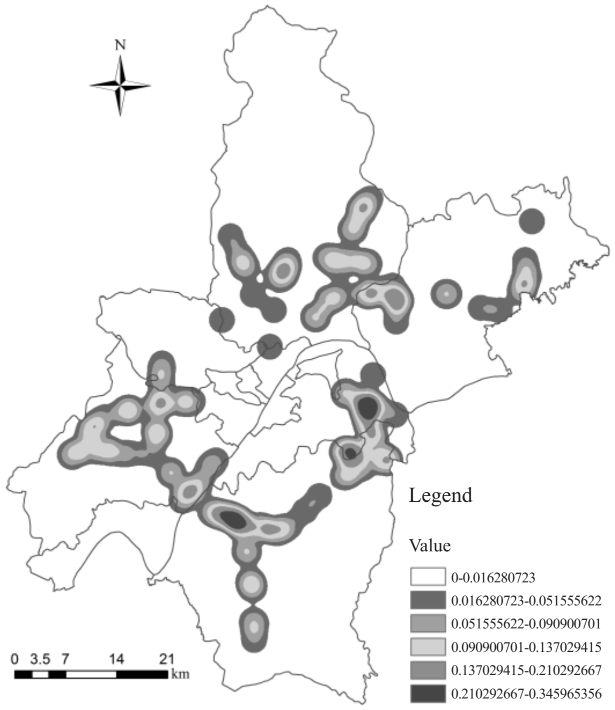

Fig. 6. The line kernel density map of expressway break points.

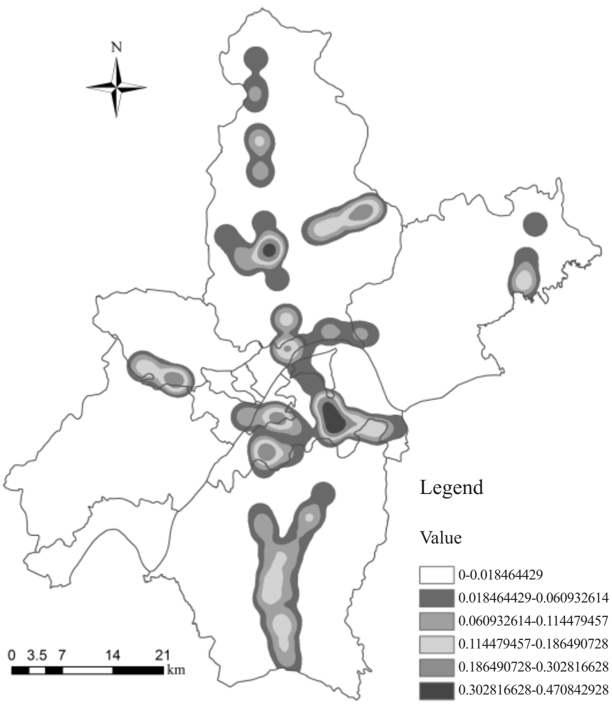

Fig. 5. The line kernel density map of railway break points.

As shown in Fig. 5, railway break points are mainly distributed near places where Beijing-Guangzhou Railway and Beijing-Kowloon Railway cross Wuhan and Huhanrong. The Passenger Dedicated Line crosses Wuhan and various railway intersections, especially the place where Huhanrong Passenger Dedicated Line, Beijing-Kowloon Railway, Beijing-Guangzhou Railway, and Beijing-Guangzhou Passenger Dedicated Line.

The expressways in Wuhan are distributed in a radial manner around the ring expressway. Therefore, the distribution of expressway break points in an ecological network follows this feature. These break points (Fig. 6) are mainly distributed on two sides of the ring expressway.

Compared with the other two kinds of break points, trunk road break points (Fig. 7) are distributed more broadly, mainly at the intersection where Wuluo Road, Luoyu Road, and Luoshi North Road cross and where Xiongchu Avenue and Luoshi South Road cross in downtown, as well as the intersection where Luoyu East Road, Wuhuang Road, Hi-tech Avenue, and Huashan Avenue cross the Mt. Jiufeng area where Wuhan East Lake High-tech Zone is located. The phenomenon fully suggests that unlimited urban sprawl exerts a serious impact on animal migration.

Protection Strategy of Ecological Network and Break Points

In this study, the forest zone in Mt. Mulan in the northern part and the forest zone from Lu Lake wetland to Mt. Qinglong in the south-central part are the places where eco-

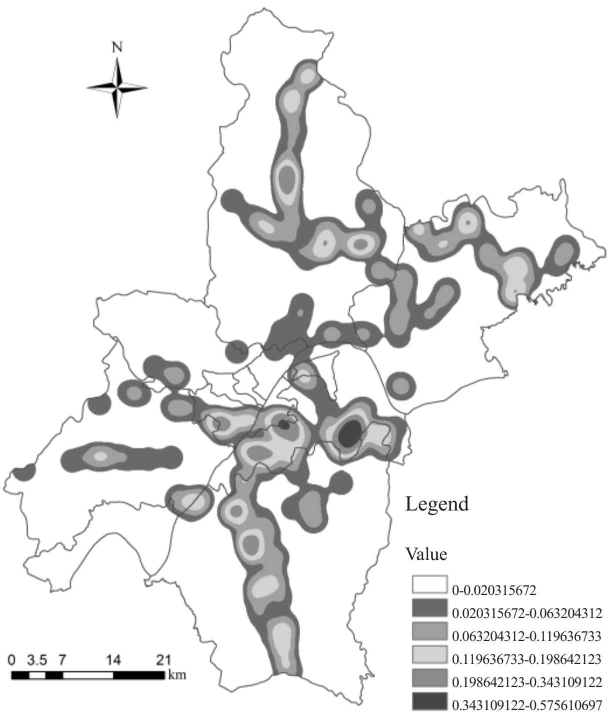

Fig. 7. The line kernel density map of trunk road break points.

logical sources are distributed with high forest coverage. These two forest zones are two core ecological sources in the study area, especially the forest zone in Mt. Mulan, which is the southern branch of the Ta-pieh Mountain Range. This area is not only a core ecological source, but an important source for substance and energy exchange with external ecological systems. On this basis, protection of the forest zone in Mt. Jiufeng southeast of downtown must be intensified. These three forest zones will constitute three essential ecological sources and the main framework of forest systems across Wuhan.

The major break point region lies mostly in the south and southeast of main urban areas, which is a typical demonstration of how immoderate transport system expansion affects ecological networks. To limit the disturbance to species migration in the process of city development, appropriate biological channels must be built in forms such as underground passages, tunnels, and over bridges in the break point region based on the landform and economic development level at various break points to accelerate the progress of restoration at the ecological break points.

Conclusions

In this study, we demonstrated the effectiveness of an integrated method to analyze forest ecological networks for urban sustainable development of Wuhan in central China. To identify forest ecological networks for multiple purposes and integrate them into an urban sustainable development system, this innovative integrated approach combined the improved LCP model, network analysis, new δ and PCI index, and improved line kernel density model.

The forest ecological network in Wuhan is identified using the improved LCP mode and issues in the more realistic forest ecological networks in Wuhan, which exhibits uneven spatial distribution, are revealed. After comparison of the 4 different cost surfaces in Wuhan forest ecosystem networks, we concluded that the δ index is an effective cost-based index for evaluating the networks and urban transportation system has a huge impact on the ecosystem networks. The patch connectivity index based on migration cost that proposed in this study to quantify the connectivity level of ecological network sources in Wuhan forest ecological networks, which is characterized by lower connectivity level when nearer the main urban area.

Forest ecological conservation priority areas and ecological break points are identified using the improved line kernel density model weighted unit corridor cost. The protection work for ecological networks will be better targeted to avoid an unrealistic conservation plan. This study will provide a good reference for a sustainable ecological environment in urban development systems and transportation planning systems.

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