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Optimization of Urban Ecological Network Based on MSPA–MCR Model: A Case Study of Jingzhou City

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Abstract As a key carrier supporting urban ecological health and living environment quality, urban ecological network is a key focus of current urban green space research. Jingzhou City of Hubei Province is taken as the research object. Relying on GIS technology platform, MSPA method is used to analyze the landscape pattern of Jingzhou City. On this basis, the landscape connectivity evaluation method is used to accurately identify and extract the source areas with important ecological value in Jingzhou City. Then, the normalization method and weighting method are combined to create a resistance factor evaluation system to construct the resistance surface. Based on the MCR model, the ecological network of Jingzhou City is successfully constructed, and targeted spatial optimization strategies and development suggestions are proposed.

Keywords Ecological network, MSPA, Landscape connectivity evaluation, Normalization method, MCR model, Ecological source area, Jingzhou City
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With the acceleration of urbanization, Jingzhou City is under tremendous pressure of urban development. The continuous expansion of urban space and the large-scale construction of infrastructure undoubtedly pose a potential threat to the ecological environment. How to effectively protect the ecological environment while developing cities has become an important issue that urgently needs to be addressed. Ecological network is an indispensable part of urban ecosystem. It not only provides habitats for numerous organisms and maintains ecological balance, but also significantly improves the quality of urban ecological environment[1]. Therefore, the construction and optimization of urban ecological network is of great significance for improving the quality of urban ecological environment, protecting and restoring biodiversity, and promoting sustainable urban development.

As a complex network structure interwoven between species and their living environment in the urban ecosystem, urban ecological network forms a binary network with ecological source as node and ecological corridor as vein, aiming to maintain the coherence and stability of ecological processes under the influence of human activities[2]. Currently, research on urban ecological network focuses on the selection and layout of ecological source area, planning and design of ecological corridor, construction and optimization of urban ecological network, and comprehensive evaluation of ecological risk[3]. The research methods are becoming increasingly diverse, including remote sensing interpretation, GIS analysis, landscape pattern index method, morphological spatial pattern analysis method, and minimum cumulative resistance model. The minimum cumulative resistance model has shown significant advantages in ecological network research due to its ability to comprehensively consider multiple factors such as terrain, topography, environment, and human interference. By constructing cumulative resistance surfaces, potential ecological corridors are scientifically judged and simulated, providing strong support for the construction and optimization of ecological network. The selection of ecological source areas is a key link in MCR model, and its rationality directly affects the accuracy of the model results. Existing research often tends to focus on forest parks with high ecological service value or directly use nature reserves as ecological source areas, ignoring the connectivity role of patches in the overall landscape[4], which in turn affects the integrity and functionality of ecological network.

In view of this, this paper attempts to use the MSPA method and landscape connectivity evaluation to comprehensively identify ecological sources. Based on the MSPA method, the core area landscape type with the best ecological function in the study area is identified and extracted. Then, the landscape connectivity index is used to quantitatively evaluate the patches in core area and screen out key ecological source areas. On this basis, with the help of the MCR model, ecological corridor is generated through the minimum path method, and a more scientific and practical ecological network is constructed[5]. Taking Jingzhou City as the empirical research object, it not only provides theoretical and practical guidance for the construction and optimization of the ecological network in Jingzhou City, but also provides useful reference and inspiration for the ecological civilization construction of other cities.

1 Study area and data sources

1.1 Study area

Jingzhou City is located in the hinterland of the Jianghan Plain and is the central city of central and southern Hubei, as well as one of the transportation hubs in the middle reaches of the Yangtze River. It is at 111°15'–114°05' E, 29°26'–31°37' N, with a total area of 14,100 km^2, including 8 county-level administrative units and 3 functional zones. The maximum horizontal distance from east to west in the jurisdiction is about 274.8 km, and the maximum vertical distance from north to south is about 130.2 km. It is distributed in a belt shape at the two banks of the Yangtze River and belongs to the northern subtropical monsoon humid climate zone. There are numerous rivers and lakes within the city, with a dense water network. The Yangtze River runs through the city from west to east, with a total length of 483 km. The terrain is slightly higher in the west and lower in the east, gradually transitioning from low mountains and hills to downlands and plains. The transportation within the territory is convenient, with railways and highways crisscrossing.

1.2 Data sources and preprocessing

The research data mainly includes 30 m

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land use data, administrative division data, DEM elevation data, slope data, road network data (railway, national road, provincial road), and NDVI data in Jingzhou City. The land use data is from the National Glacier Frozen Soil Desert Science Data Center; administrative division data and DEM elevation data are derived from geospatial data cloud, while slope data is generated from elevation data; the road network data comes from the OpenStreetMap website; NDVI data comes from the Resource and Environmental Science Data Platform of the Chinese Academy of Sciences.

2 Study methods

2.1 Landscape pattern analysis based on morphological spatial pattern analysis method

MSPA morphological pattern analysis method is a spatial pattern analysis method based on mathematical morphology principle. It is used to describe and identify spatial morphology indicators in raster images, and can identify important patches that play a key role in improving landscape connectivity[6]. Based on the ArcGIS platform, natural elements such as forests, wetlands, and water body are extracted as prospects for MSPA analysis, and other land types are set as background. After obtaining binary raster images through reclassification processing, Guidos Toolbox software is used for deep analysis, and 7 landscape types are identified (Table 1 and Fig.1). Among them, the core area is particularly crucial. It refers to habitat patches with concentrated foreground pixels and a large area, which can provide broad habitats for species[7], and is of great significance for protecting biodiversity. Therefore, the core area is chosen as the ecological source in this paper (Table 2). Due to severe fragmentation of patches in the core area of the study area, the core area with an area greater than 3 km^2 is screened out as the initial ecological source to improve the scientificity of selection and reduce the subjectivity of manual selection.

2.2 Analysis of landscape connectivity index in the study area

The theory of landscape connectivity was proposed by Merriam in 1984 and has gradually been widely applied in the field of landscape ecology. This theory focuses on the degree of connectivity between landscape spatial structural units and is an important indicator reflecting functional characteristics of landscape[8]. It can help optimize the layout of green patches, enhance the stability and sustainability of the ecosystem in the study area by applying this theory. Currently, the integral index of connectivity (*IIC*) and probability of connectivity (*PC*) are widely used in landscape connectivity assessment. These indices help analyze the evolution of landscape structure and ecological processes, providing guidance for optimizing landscape layout and enhancing ecosystem service functions[9]. Based on *PC* and *IIC*, the protection priority of the core source area in the region is calculated and analyzed in depth, and the calculation formula is as follows:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}{A_L^2} \quad (1)$$

where n shows the total number of patches included in the study area; a_i and a_j are the area of patches i and j; p_{ij}^* shows the maximum product of the probabilities of all paths between patches i and j; A_L is total landscape area within the region.

$$dPC = 100 \times \frac{PC - PC_{i\text{-}remove}}{PC} \quad (2)$$

where $PC_{i\text{-}remove}$ refers to the landscape connectivity index of other patches without a certain patch. *dPC* shows the importance of this patch. When the *dPC* is larger, it indicates that the overall change in connectivity index may increase when the patch is missing. It shows that the importance of the patch in landscape connectivity is greater.

Conefor software is used to evaluate the landscape connectivity of core patches in the study area through *IIC*, *PC*, and *dPC*. Moreover, 17 patches of core area with a *dPC* value greater than 1 are used as source areas for the development and reproduction of biological species. Then, river patches are removed, and the remaining 13 patches are used as ecological source areas for constructing the ecological network of Jingzhou City.

2.3 Construction of ecological network based on MCR model

The MCR model is mainly used to describe and predict the path chosen by an object or individual moving in space. The core principle is that when moving objects or individuals move in space, they tend to choose the path with the least resistance[10]. The MCR model in this paper is based on the theory of ecological source and landscape pattern. By considering the resistance coefficients of different landscape types that species migration and energy flow pass through, as well as the spatial distance between the starting source and the target source, the minimum cumulative resistance path of the two is calculated. It comprehensively considers multiple factors such as landscape pattern, resistance coefficient, spatial distance, etc., and can scientifically evaluate the trend of material and energy flow in the ecosystem, avoiding subjective speculation and human influence, and making the construction of ecological corridors more scientific[11]. The selection of ecological source areas and the construction of resistance surfaces are the key to model construction, and the core process is to simulate the competitive diffusion process of ecological source areas under specific resistance, profoundly revealing the interaction mechanism between ecological flow and spatial structure.

Based on MSPA and landscape connectivity analysis, 13 ecological source areas are selected according to the *dPC* value of patches in core areas. Moreover, resistance factors such as elevation, slope, land type, NDVI, and road distance are selected, and a comprehensive

Table 1 Landscape types and ecological implications of MSPA

Landscape type	Ecological implications
Core area	It can serve as a “source” for various ecological processes, is mostly forest parks and large forest farms with large patch areas, and is of great significance for species reproduction and the protection of biodiversity
Connecting bridge	Narrow and elongated areas connecting different core patches, with the characteristics of ecological corridors. It is mostly belt shaped green belts, and facilitates species migration and connecting function of landscape within the area
Marginal zone	Located at the edge of the core area, the transitional area between core area and peripheral non green landscape areas. It can reduce the impact of external environment and human interference, and is usually the peripheral forest belts of forest parks, large forest farms, etc.
Branch line	The area with only one end connected to the main patch. It is mainly an extension area of green space, which is a channel for species diffusion and energy exchange with the peripheral landscape
Roundabout	The internal channel for material and energy exchange within the same core area patch and a shortcut for material and energy exchange within the core area
Isolated island	Small patches located independently and with low connectivity. It has a lower likelihood of material and energy exchange with other patches, and is mostly small green spaces in urban or rural areas
Pore	As a transitional region, it also has edge effects, existing between the core patch and its non green interior space

resistance surface is constructed through normalization and weighting methods (Fig.2).

3 Results and analysis

3.1 Identification of ecological source areas

As the core land for maintaining regional ecosystem stability, ecological source area is a key cornerstone for building an urban green space ecological network, covering various ecological functional land such as forests, wetlands, and lakes[12]. Based on the MSPA method, a total area of 2,156.03 km^2 was identified for 7 landscape types within Jingzhou City, accounting for 15.3% of the total urban area, with a relatively small proportion (Table 3).

Because Jingzhou City is located in the central area of the Jianghan Plain, cultivated land has become the largest land type in the area. When conducting prospect analysis, natural landscapes with good ecological functions and less human influence are selected mostly. Cultivated land is greatly affected by human activities and is generally not considered[13]. Among the identified landscape types, the core area serves as a high-quality alternative ecological source area, with an area of 1,434.66 km^2, occupying 66.54% of all landscape types. These core areas are mainly distributed in the western and northeastern parts of the city, as well as within the Yangtze River basin, forming a clustered and belt shaped spatial distribution pattern. Among them, the Baling Mountains in the western part of Jingzhou, as well as important lake systems such as Honghu Lake in the eastern part and Changhu Lake in the northern part, are the main components of the core area. However, the distribution of the core area in the southern part of the city shows a point like feature, with severe fragmentation, and the northern part of the city lacks core area patches, resulting in poorer landscape ecology in the area. This spatial distribution pattern affects the connectivity of the eastern and western landscapes, restricting the diffusion and exchange of organisms and matter.

Overall, the ecological resources of Jingzhou City are relatively abundant, providing a large area of ecological habitat and a good ecological environment for the circulation and exchange of material and energy. Among them, island patches can serve as temporary resting places and stepping stones for biological migration and diffusion, with an area of 138.82 km², with significant strategic value that cannot be ignored for the optimization of future ecological networks. In addition, the connecting bridge has an area of approximately 54.5 km², with great significance for the exchange of material and energy between core patches in the study area. It is a key node in material circulation and energy flow within the ecosystem, and is crucial for maintaining ecological balance and biodiversity. Therefore, it should be fully protected and reasonably expanded. Although the core area of Jingzhou City is large, from the perspective of spatial layout, its patch distribution is relatively scattered, resulting in insufficient overall connectivity. These core patches are mainly distributed in the east and west, with a high degree of fragmentation, which affects the overall stability and service function of the ecosystem to some extent. In summary, the distribution of ecological source areas in Jingzhou City has its unique characteristics and complexity. It not only has core areas with prominent ecological service functions, but also faces challenges of fragmentation and poor connectivity. In future urban planning and ecological protection work, these characteristics should be fully considered. Effective measures should be taken to strengthen the protection and management of ecological source areas, and enhance the ecosystem service functions of the region.

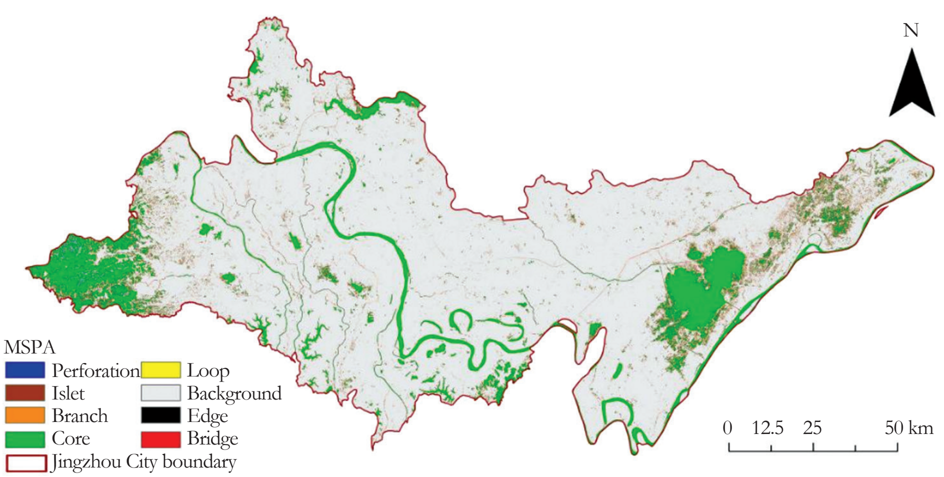

Fig.1 Classification of landscape elements in Jingzhou City based on MSPA

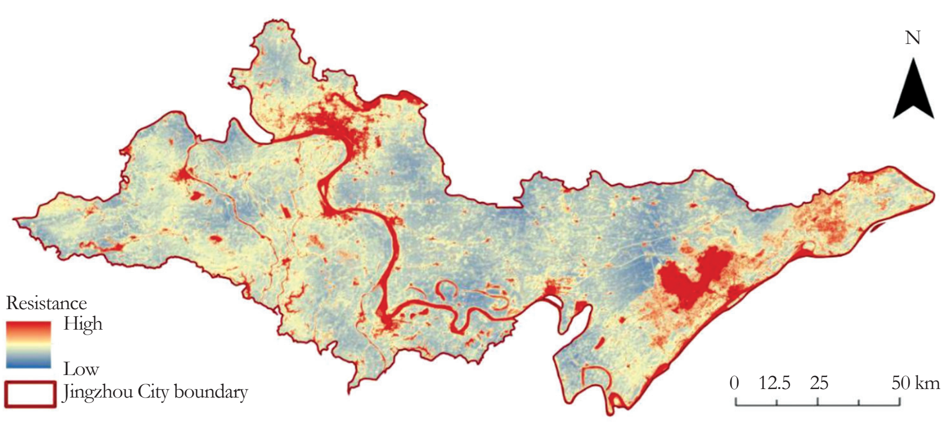

Fig.2 Comprehensive ecological resistance surface of Jingzhou City

3.2 Evaluation of ecological source areas

To further improve the accuracy of identifying core ecological source areas, based on research experience, the core area patches larger than 3 km^2 are selected. Referring to relevant research and the specific situation in Jingzhou City, the distance threshold is set to 5 km, and the probability of connectivity is set to 0.5[14]. Then, Conefor 2.6 software is used for calculation and analysis. Its *PC* is evaluated. Based on the connectivity evaluation results of the patches, the core areas are divided into first-level core area ($1 \leqslant dPC$), second-level core area ($0.5 < dPC < 1$), and three-level core area ($0 < dPC \leqslant 0.5$) (Fig.3). There are a total of 17 first-level core areas, with a total area of 1,275.51 km². It accounts for 37.78% of the total number of patches in the core area, and 88.91% of the total area of the core area, mainly including the Baling Mountains, the Yangtze River basin, Changhu Lake, and Honghu Lake. They are of high importance and should be given priority protection. Among them, the main land use types of core area patches are mostly large water bodies and wetlands. In order to reduce the obstruction of water bodies to animal migration, artificial afforestation can be carried out around the water bodies to expand the patch area, improve landscape connectivity, provide temporary habitats for animal migration, and promote migration and exchange of regional species.

At the same time, it is necessary to clarify the functions and positioning of different levels of ecological source areas, explore differentiated protection and utilization models, and more accurately formulate targeted protection measures and development and utilization strategies. The first-level ecological source areas of Jingzhou City are mainly distributed in the eastern and western parts of the city, such as the Honghu Lake Ecological Tourism Scenic Area and the Baling Mountain National Forest Park. These areas have high forest and grass coverage and excellent ecological quality. Priority should be given to strengthening their existing ecological leisure functions, while strictly prohibiting high-intensity and large-scale development and construction activities to maintain their ecological integrity and stability. For the existing industrial, mining, and construction land, an exit strategy should be gradually implemented, and they could be adjusted to ecological land to optimize the land use structure and enhance the overall ecological value. In contrast, the third-level ecological source areas are mostly scattered in the western part of the city. For these areas, more attention should be paid to the connectivity between patches, and their impact on the overall landscape connectivity should be reduced through scientific and reasonable planning and layout. This can not only enhance the overall functional benefits of ecological source areas, but also help promote the realization of biodiversity and ecological balance.

3.3 Construction of ecological network pattern

By integrating geographical elements such as land use type data, normalized vegetation index data, road distance information, elevation, and slope of Jingzhou City, a model surface that can comprehensively reflect the ecological resistance of Jingzhou City is constructed[15]. After in-depth analysis, the ecological resistance values in Jingzhou City exhibit distinct regional characteristics in spatial distribution: the resistance values in the northwest and eastern regions are relatively high and gradually decreasing towards the surrounding areas. The differences in ecological functions among different regions of Jingzhou City have been revealed, especially in key areas such as the Yangtze River basin, Honghu wetland area, and Jingzhou urban area, where resistance values are particularly significant. Based on the minimum cumulative resistance model, the minimum cost distance from each ecological source area to all other source areas is calculated, and the optimal path for ecological flow is identified, thus constructing an ecological network closely connected by the source areas and corridors (Fig.4). This ecological network fully considers the ecological background of Jingzhou City and the impact of human activities. Through the organic connection between the source area and the corridor, it achieves the efficiency and sustainability of ecological flow.

From Fig.4, it can be seen that the ecological security pattern of Jingzhou City is centered around the Honghu Lake and the Baling Mountain. Together with other ecological source areas, a green spatial system with multiple patches and corridors has been constructed. Based on the construction of the ecological network in Jingzhou City, a future ecological network optimization strategy is proposed: firstly, the key to the optimization work is accurately identifying the ecological source area. Not only should it strengthen the protection of large-scale green spaces and water spaces, but it should also pay special attention to the protection of corridors between ecological patches. Secondly, considering the distance between patch 5 and patch 11, the possibility of ecological exchange between the two patches is relatively small, reflecting the weak connection between the eastern and western regions of Jingzhou City. It is urgent to build a bridge for material and energy exchange to enhance the landscape connectivity of the entire region. Therefore, it is necessary to strengthen the construction of corridors between the two to promote species migration and enhance landscape connectivity between the eastern and western regions of the study area, which has profound significance for the construction of the overall ecological network of Jingzhou City. In addition, the central area of Jingzhou lacks a functional ecological source area, so more green patches need to be introduced as stepping stones[16], especially in mountainous areas, forest farms and forest parks, such as Mount Huangshantou Forest Park, Xingdao Ecological Tourism Scenic Spot and Baling Mountain Forest Farm. By optimizing the ecological structure of these areas, the integrity and functionality of the ecological network in Jingzhou City can be further enhanced.

Table 2 Importance ranking of core areas based on landscape connectivity

No.	Serial number	*dPC*	*dIIC*
1	11	49.75	46.93
2	5	22.46	23.05
3	6	6.82	5.00
4	3	6.54	3.05
5	13	3.21	2.02
6	1	3.01	0.66
7	12	2.12	2.08
8	2	2.03	0.08
9	7	1.84	1.56
10	4	1.55	1.01
11	9	1.21	0.90
12	8	1.13	0.86
13	10	1.02	0.83

Table 3 Area and proportion of different landscape elements

Landscape type	Area//km^2	Proportion in natural element types//%
Core area	1,434.66	66.54
Island patch	138.82	6.40
Bridging zone	54.50	2.53
Pore zone	42.77	1.98
Marginal zone	349.57	16.21
Ring road	23.88	1.11
Branch	111.82	5.19

4 Conclusions

Based on the MSPA method and landscape connectivity analysis method, the ecological source areas of Jingzhou City are comprehensively identified, and an ecological corridor is constructed using the minimum resistance model. Finally, an urban ecological network system

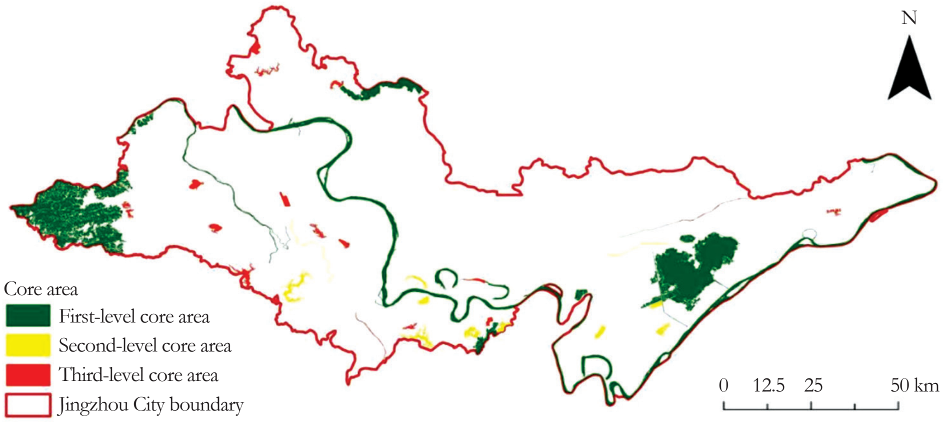

Fig.3 Core area classification based on connectivity index

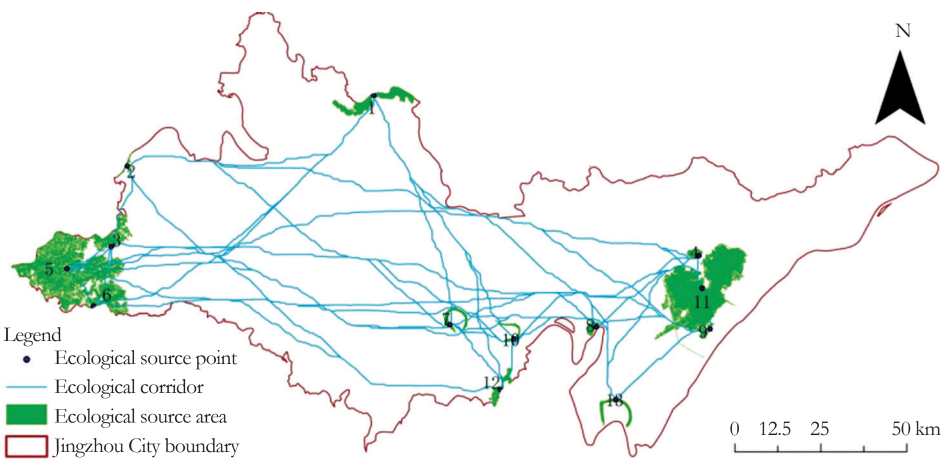

Fig.4 Ecological network layout in Jingzhou City

closely connected by the "source area–corridor" is constructed[17]. Taking into account the integrity of ecological functions and the rationality of ecological structures, the quantitative analysis method also ensures the objectivity and accuracy of the research, and this method is efficient and convenient. A preliminary urban ecological network system is formed, providing a high-quality ecological corridor for species migration and diffusion. Specific protection and optimization measures have been proposed for the existing ecological network in Jingzhou City, providing strong support for the sustainable development of the urban ecological network. Therefore, this paper believes that the organic combination of landscape connectivity evaluation with MSPA and MCR models provides a scientific basis for the construction of ecological security patterns, and has important theoretical significance and practical value for the construction of current ecological security patterns in national land space.

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