Proceedings of ICEGEE 2026 Symposium: Sustainable Environment and Ecology: Supporting a Sustainable Environment for Birds
DOI: 10.54254/2753-8818/2026.BH32428

Study on Ecological Security Pattern Construction of the Middle Yangtze River Urban Agglomeration from the Carbon Sequestration Enhancement Perspective

Yihan Mao

School of Design, Huazhong University of Science and Technology, Wuhan, China
1812508733@qq.com

Abstract. Against the background of the "dual carbon" strategy and ecological civilization construction, this study takes the middle reaches of the yangtze river Urban Agglomeration as the research area and uses 2020 multi-source data to construct a carbon sequestration-optimized ecological source system. We comprehensively applied Morphological Spatial Pattern Analysis (MSPA), ecological environment quality assessment and InVEST model-based carbon stock assessment, then formed an optimized resistance surface by superimposing multi-factor resistance surfaces and correcting with carbon sequestration importance. Ecological corridors and pinch points were identified via circuit theory to establish an ecological security pattern from the perspective of carbon sequestration enhancement. The results show that carbon sequestration constraints reduced ecological sources from 1344 to 377, with only a 10.7% drop in total area and more concentrated distribution in high carbon sequestration regions. High-quality ecological areas cluster in mountain forest zones with an obvious ecological gap in the Jianghan Plain, and high-value comprehensive resistance surfaces distribute around provincial capitals. We identified 895 ecological corridors and 60 ecological pinch points . Overall, this study gives a spatial basis for the agglomeration to implement the "one core, two lakes, four rivers, five screens and multiple spots" ecological pattern.

Keywords: Ecological security pattern, Carbon sequestration enhancement, InVEST model, Circuit theory, Urban Agglomeration

1. Introduction

Global climate change has evolved into a systemic crisis threatening human sustainability. In response, China 's strategic commitment to the " dual carbon " goal of peaking carbon emissions by 2030 marks a profound transformation of China 's socio-economic development model [1]. Achieving these targets requires a dual strategy: aggressive reduction of anthropogenic emissions and the substantial enhancement of natural carbon sinks [2]. Terrestrial ecosystems, including forests, wetlands, and grasslands, act as critical carbon reservoirs and are increasingly prioritized as "Nature-based Solutions" (NbS) for climate mitigation [3,4]. Since the 18th National Congress of the China, the integration of ecological protection and territorial space governance has become the key. Specifically, incorporating carbon sequestration capacity into spatial planning is now recognized as a key pathway to achieve the synergistic benefits of pollution reduction and carbon mitigation [5].

The construction of Ecological Security Patterns (ESPs) serves as a fundamental bottom-line approach for maintaining ecosystem integrity and services in territorial planning [6]. The ESP framework typically follows the "source-corridor-node" paradigm to identify critical habitats and maintain landscape connectivity [7]. The concept of " mountain, water, forest, field, lake and grass life community " emphasizes holistic protection [8].existing research on ESPs has predominantly focused on biodiversity conservation or general habitat quality [9]. Few studies have explicitly incorporated carbon sequestration services as a primary objective in the identification of ecological sources [10]. Moreover, in the construction of ecological resistance surfaces, standard methods often rely solely on land cover types, neglecting the spatial heterogeneity of carbon sink functions and the varying resistance of different landscapes to ecological flows [11,12].

The Middle Reaches of the Yangtze River Urban Agglomeration (MRYRUA), spanning Hubei, Hunan, and Jiangxi provinces, represents a crucial strategic region for China's development and ecological security [13]. Covering approximately 349,000 square kilometers, this region hosts a complex network of mountains and water systems, including the pivotal Dongting and Poyang Lakes. However, rapid urbanization since the 1990s has led to the disorderly expansion of impervious surfaces, causing the fragmentation of ecological lands and a significant decline in regional carbon storage capacity [14,15]. The conflict between urban agglomeration expansion and ecological preservation is intensifying [16]. The region's "14th Five-Year Plan" explicitly mandates the restoration of the Yangtze River's ecology and the establishment of a spatial pattern characterized by "one core, two lakes, four rivers, five screens, and multiple spots."

This study aims to construct a carbon-sequestration-optimized ecological security pattern. Using multi-source data from 2020, we adopt a coupled methodology integrating Morphological Spatial Pattern Analysis (MSPA) to identify landscape structural elements [17] and the InVEST model to quantify habitat quality and carbon stocks [18]. Crucially, we introduce a carbon sequestration importance correction mechanism to optimize the ecological resistance surface, a methodological improvement over traditional approaches [19]. Finally, Circuit Theory is applied to identify key ecological corridors and pinch points [20]. This research provides a scientific, spatial basis for the MRYRUA to implement its ecological goals and offers a technical reference for integrating carbon targets into regional territorial planning.

2. Study area overview and data sources

The MRYRUA consists of mountains, hills and plains in terms of landform, with extensive mountain distribution, as shown in Figure 1.The Mufu Mountains and Luoxiao Mountains, as representative mountains, form an important ecological framework at the junction of the three provinces, while the Daba Mountain area lies in the west, the Dabie Mountain area in the north, the Huaiyu Mountains and Wuyi Mountains influence the southeast, and the Xuefeng Mountains are associated with the southwest. The water system takes the Yangtze River as the main trunk, with the Han , Xiang and Gan River as important tributaries, and the Dongting, Poyang Lake form a key lake wetland system. Its annual average runoff reaches 450 billion cubic meters, accounting for 47% of the Yangtze River basin. In terms of data, the study mainly uses land use data, elevation data, NDVI, GDP and population raster data, traffic data from the OpenStreetMap platform, socio-economic statistics and energy consumption data, with specific data sources shown in Table 1. All indicators are processed with 0–1 standardization to eliminate dimensional influence.

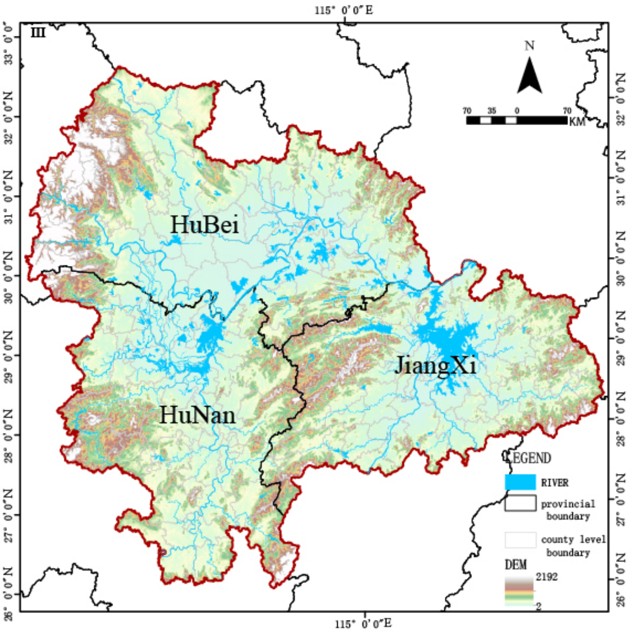

Figure 1. Study area

Table 1. Data source

Data	Spatial resolution	Year	Data source
DEM	1km	2015	Geospatial Data Cloud (http://www.gscloud.com)
Population, GDP	1km	2020	Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
Socio-economic statistics	-	2020	Statistical Yearbooks of Hubei, Hunan and Jiangxi Provinces, annual socio-economic statistical yearbooks of various cities, the 6th and 7th population census data of various cities
Land use	30m	2020	GlobeLand30: Global Geographical Information Public Product (http://www.globallandcover.com/)
NDVI	1km	2020	Resource and Environmental Science Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
Energy consumption data	-	2020	Annual socio-economic statistical yearbooks of various cities
Traffic	-	2020	OpenStreetMap platform (https://openmaptiles.org/)

3. Research methods

3.1. Ecological identification

Ecological source identification adopts a three-step method combining Morphological Spatial Pattern Analysis with the coupling of ecological quality and carbon sequestration. First, the MSPA method is adopted, Among them, forests and grasslands are used as foreground elements, and other land types are used as background. The edge width is set to 1 and the transition parameter to 0 in GuidosToolbox, and the eight-neighborhood rule is applied to identify landscape types such as core areas, isolated patches, edge areas and bridge areas, among which core areas correspond to large natural patches and important habitats and serve as the basic candidates for ecological sources. Secondly, the.acHabitat InVEST model was used to evaluate the ecological environment quality. The quality index in the range of 0–1 is output by synthesizing the weights of threat factors, influence distances and habitat sensitivity parameters, Threatened factors include arable land, urban land, rural settlements, other construction land and unused land. At the same time, the Carbon Storage module was used to counting the carbon storage based on the four carbon pools of aboveground biomass carbon, underground biomass carbon, soil organic carbon and litter carbon. Based on precipitation and temperature, the carbon density parameters are corrected to form a localized database. in which the aboveground carbon density of forest vegetation is 58.4 Mg/hm², the underground carbon density is 14.5 Mg/hm² and the soil carbon density is 18.3 Mg/hm², the highest among all land types. Finally, the core areas from MSPA are superimposed with high-value areas of ecological environment quality and carbon stock. Patches with an area of more than 10 km² are selected as main ecological sources, and Poyang Lake, Dongting Lake and Honghu Lake are taken as supplementary ecological sources, which results in 1344 morphological ecological sources. On this basis, high carbon sequestration areas are superimposed as constraints to accurately identify carbon sequestration-optimized ecological sources, as shown in Figure 2.

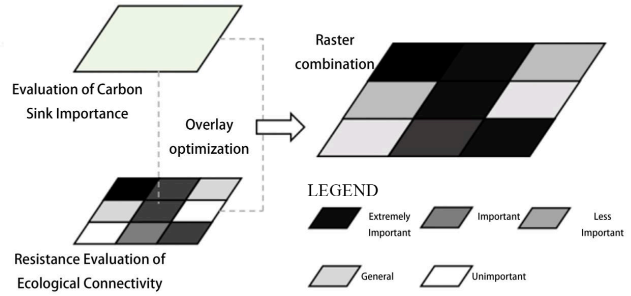

Figure 2. Calculation of ecological sources

3.2. Ecological resistance surface construction

The resistance surface is constructed from three dimensions: natural environmental conditions, accessibility level and economic development level, with a total of 11 resistance factors set. Specifically, natural environmental conditions include slope, vegetation coverage and topographic elevation; accessibility is classified based on the distance to national highways, provincial highways, railways, waterways and expressways; economic development level incorporates the spatial distribution of population and GDP as well as landuse types. The weights of factors are determined by the combination of mean information content weight method and analytic hierarchy process, and the basic resistance surface is formed by weighted superposition in ArcGIS. To reflect the carbon sequestration orientation, this study constructs a regional carbon sequestration importance evaluation index system, which includes carbon sequestration resistance factors and carbon sequestration enhancement factors (carbon sequestration density, forest coverage rate, total forest land and forest land reduction rate). The graded results of carbon sequestration importance are then superimposed with the raster of the basic resistance surface, and the resistance values of regions at different grades are adjusted: the resistance value of the most important region is increased by 1, that of the more important region by 0.75, that of the general region by 0.5, that of the less important region by 0.25, and that of the least important region remains unchanged, thus generating the carbon sequestration-optimized resistance surface, as shown in Figure 3.

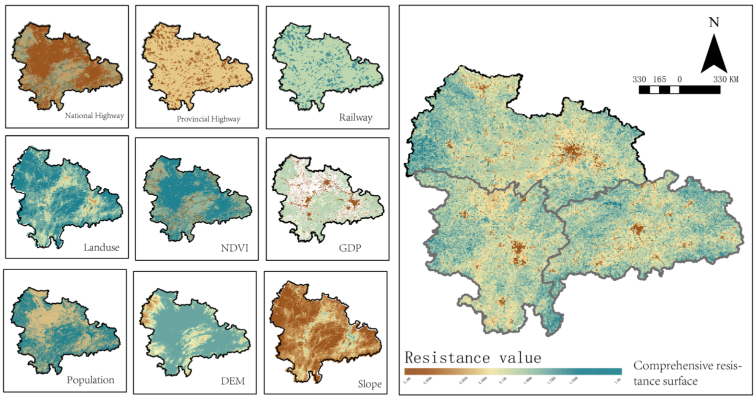

Figure 3. Calculation of ecological resistance surface

3.3. Identification of ecological corridors and pinch points

Using the Linkage Mappe to analogy the corridor, the landscape is abstracted as a conductive surface based on the circuit theory, and the resistance is used to characterize the hindrance of different land cover types to the ecological flow. The current density in this theory reflects the concentrated area of potential ecological flow. Based on the ecological source vector optimized by carbon sink and the resistance surface grid optimized by five carbon sinks, the minimum cost path between ecological sources is calculated to form an ecological corridor, and the corridor is further classified according to the relative resistance. In addition, the ecological pinch is identified by calculating the current density between the ecological sources at 7 o 'clock.

The line landscape takes the weighted distance of 20 km as the corridor width. The natural breakpoint classification method is used to divide the cumulative current into five grades, and the highest grade area is selected as the pinch point.

4. Results and analysis

4.1. Spatial pattern of ecological sources

The results of MSPA show that the core areas present a "2+3" distribution pattern, mainly concentrated in the central Mufu Mountains-Luoxiao Mountains and the western Daba Mountains, and also distributed in the eastern Dabie Mountains, Wuyi Mountains and the southwestern Xuefeng Mountains. The areas of core areas in the three provinces are 53902.0 km² in Hubei, 56995.2 km² in Hunan and 62197.1 km² in Jiangxi respectively, with Jiangxi accounting for the highest proportion and concentrated in the Mufu Mountains-Luoxiao Mountains area. In contrast, the core areas in Hubei are scattered, and an obvious source discontinuity exists in the Jianghan Plain. Furthermore, the core areas in the Mufu Mountains-Luoxiao Mountains area at the junction of the three provinces account for nearly half of the total core area, and the surrounding bridge areas and perforation areas account for 53% of the total area, showing the most significant connectivity effect.The comprehensive results of ecological source identification are shown in Figure 4.

In terms of ecological environment quality, the high-quality areas in the three provinces are 51766.6 km², 60543.15 km² and 65392.6 km² respectively, all concentrated in mountain forest zones; the low-quality area in Hubei reaches 81039.7 km², about twice that of Hunan and Jiangxi, which reflects the significant impact of urbanization on ecological quality in the Jianghan Plain. In terms of carbon stock, the high carbon sequestration areas in the three provinces are 50720 km², 58168 km² and 57110 km² respectively, with high-value areas concentrated in the mountain belts of the Daba Mountains, Mufu Mountains-Luoxiao Mountains and Huaiyu Mountains-Wuyi Mountains. Carbon sequestration constraints optimize the number of ecological sources from 1344 to 377, with the total area adjusted from 105865 km² to 94501 km², a reduction of only 10.7%. Specifically, the number of ecological sources in Hubei decreases from 483 to 140, in Hunan from 462 to 146, and in Jiangxi from 399 to 91. After optimization, the ecological sources show four concentrated distribution areas, corresponding to the Daba Mountains, Xuefeng Mountains, Dabie Mountains-Huaiyu Mountains-Wuyi Mountains, and the Mufu Mountains-Luoxiao Mountains and the two lakes area respectively. As a result, their carbon storage capacity becomes more concentrated, and the spatial distribution is more focused on the overlapping areas of high carbon sequestration and high ecological quality.

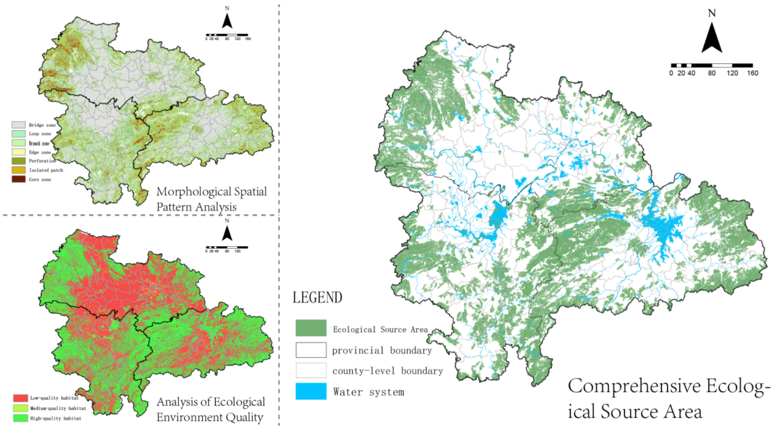

Figure 4. Ecological source identification results

4.2. Ecological resistance surface pattern

The basic resistance surface presents a spatial pattern of high values around provincial capitals and low values in mountainous and water areas.The basic ecological resistance surface of the study area is shown in Figure 5, and the carbon sequestration-optimized ecological resistance surface is presented in Figure 6.The areas of low resistance zones in the three provinces are 25770 km², 38920 km² and 31250 km² respectively; the areas of medium resistance zones are 79050 km², 64440 km² and 63430 km² respectively; the areas of high resistance zones are 16635.5 km², 15180 km² and 15130 km² respectively. Hubei has the widest distribution of high resistance zones, which reflects the urbanization barrier effect in the Jianghan Plain.

After correction based on carbon sequestration importance, the area of low resistance zones decreases by 12.4%, the area of medium resistance zones increases by 16.27%, while the area of high resistance zones changes slightly. After optimization, high resistance zones account for 15.3% of the research area, medium resistance zones for 61.1%, and low resistance zones for 23.6%. The regions with the highest carbon sequestration resistance importance are located in the core of the three metropolitan circles of Wuhan, Changsha and Nanchang, and the regions with the strongest carbon sequestration enhancement capacity are concentrated in the western Xuefeng Mountains-

Daba Mountains and the central Mufu Mountains-Luoxiao Mountains areas. The county-level regions with the strongest carbon sequestration importance include Zigui, Changyang, Wufeng, Taoyuan, Anhua, Pingjiang, Tonggu, Fuliang, Wuyuan, Guangxin, Guangfeng and Yanshan, which are mainly situate in mountainous areas and areas at administrative borders.

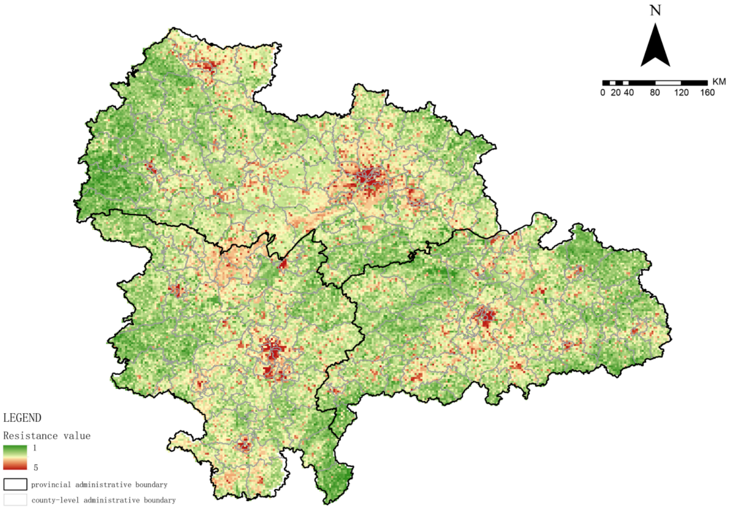

Figure 5. Ecological resistance surface

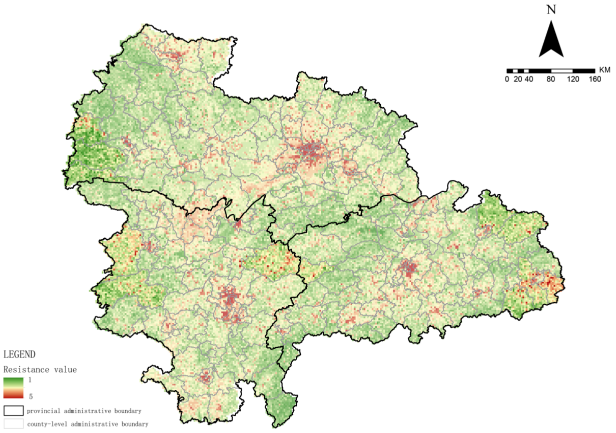

Figure 6. Ecological resistance surface under carbon sink optimization

4.3. Ecological corridors and pinch points

A total of 895 ecological corridors are identified in this study, with their spatial distribution shown in Figure 7. Sixty ecological pinch points are identified with severe fragmentation, and their specific distribution is presented in Figure 8. Spatially, the corridors around the central area have the densest connections, and the corridors around Yueyang and Jiujiang are the closest; the distribution of corridors is the second densest in Xiaogan in the northwest and Hengyang in the south; whereas the corridors in the western mountainous areas are relatively few. Classified by relative resistance, there are 67 corridors with low resistance, which are mainly distributed around large-scale ecological sources with short lengths; 554 corridors with medium resistance, the largest type in number, which are distributed in plain and hilly zones and need to cross human activity areas with their stability dependent on regulation; and 274 corridors with high resistance, which are located around provincial capitals and significantly disturbed by construction land.

Sixty ecological pinch points are identified with severe fragmentation, and the larger pinch points are located in the north of the research area, usually in the transition zones between ecological sources and plain areas. As bottleneck control points for ecological connectivity between ecological sources, pinch points determine the connectivity efficiency and stability on the one hand, and on the other hand face a higher risk of degradation due to greater vulnerability to external disturbances in their spatial environment. Therefore, they should be taken as priority intervention units for ecological restoration.

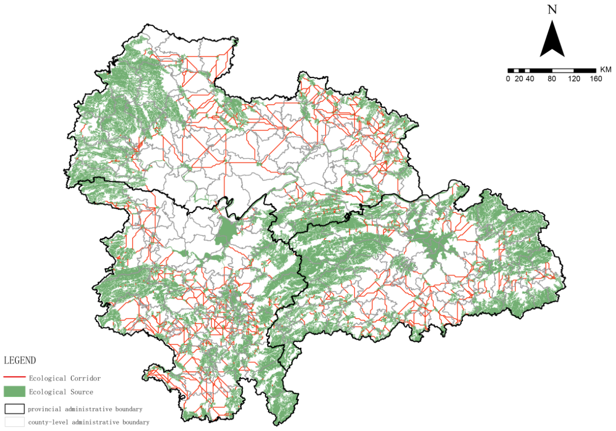

Figure 7. Ecological corridors

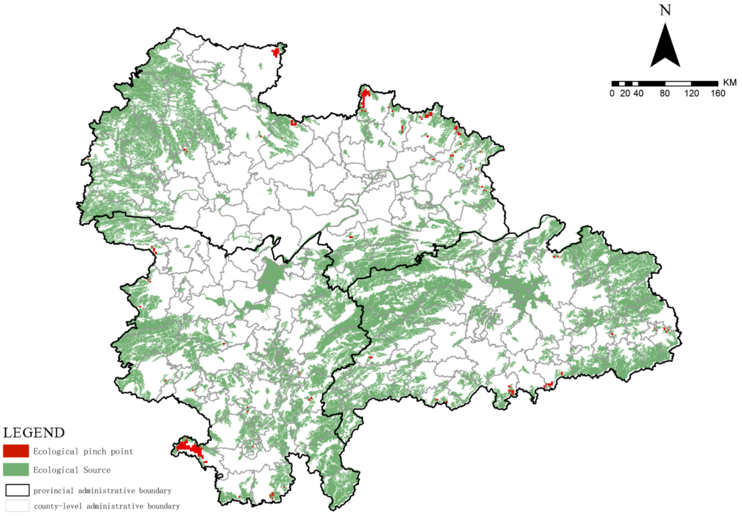

Figure 8. Ecological pinch points

5. Discussion and strategic suggestions

This study embeds the carbon sequestration goal into the construction of ecological security pattern and forms a coupling framework of "ecological quality - carbon storage capacity - connectivity process". Different from the identification only based on morphology or a single ecological service index, carbon sequestration constraints lead to a significant decrease in the number of ecological sources with only a 10.7% reduction in total area, which realizes the functional concentration of ecological sources and the concentration of carbon sequestration capacity. In addition, the spatial distribution of the optimized ecological source is basically consistent with the ecological pattern of ' one core, two lakes, four rivers, five screens and multiple points ' proposed by the ' 14 th Five-Year Plan Implementation Plan ', indicating that the research results can provide quantitative support for the implementation of the planning objectives.

The correction of the resistance surface based on carbon sequestration endows some regions with higher protection attention, and it also changes the preference of potential ecological flow passage, thus avoiding the excessive crossing of ecological corridors through low carbon sequestration value areas. The classification results of corridors reveal that most corridors are at the medium resistance level and cross plain and urbanized areas, which leads to uncertainty in the stability of ecological processes. In addition, the ecological pinch points are significantly fragmented and located in transition zones, which suggests that the key of ecological restoration does not lie in increasing the number of corridors, but in carrying out targeted restoration for bottleneck nodes and high resistance passages.

At the strategic level, the optimization of the ecological security pattern in the research area can be promoted at three levels. At the regional pattern level, it is necessary to strengthen the inter-provincial collaborative protection of the Mufu Mountains-Luoxiao Mountains as the "green core", jointly build the five ecological barriers of the Daba Mountains, Dabie Mountains, Xuefeng Mountains, Huaiyu Mountains and Wuyi Mountains, and connect the ecological corridors of the Xiang River, Gan River, Han River and the two lakes with the middle reaches of the Yangtze River basin as the link, thereby forming a blue-green space skeleton of "three circles, three zones and four corridors". At the county-level regulation level, county-level regions can be divided into core carbon sequestration restoration type, important carbon sequestration enhancement type and general carbon sequestration potential type according to carbon sequestration importance, and differentiated regulation can be implemented for each type. At the node restoration level, a priority restoration list should be established for the 60 ecological pinch points, the continuity of ecological land in transition zones should be strengthened and construction occupation should be restricted. For corridors with high resistance, broken points should be connected by building shelterbelts and river buffer zones, so as to obtain the maximum benefit of connectivity improvement with relatively low engineering investment.

6. Conclusions

Taking the MRYRUA as the research area, this study constructs an ecological security pattern from the perspective of carbon sequestration enhancement. Carbon sequestration constraints optimize the number of ecological sources from 1344 to 377, with the total area adjusted from 105865 km² to 94501 km², and the spatial distribution is thus more focused on the overlapping areas of high carbon sequestration and high ecological quality. High-value areas of ecological environment quality are concentrated in mountain forest zones, and a significant ecological connectivity gap forms in the Jianghan Plain, while high carbon sequestration areas are concentrated in mountain barrier belts such as the Daba Mountains, Mufu Mountains-Luoxiao Mountains and Huaiyu Mountains-Wuyi Mountains. In addition, high-value areas of the comprehensive resistance surface distribute around provincial capitals, and the area of medium resistance zones increases by 16.27% after correction based on carbon sequestration importance. A total of 895 ecological corridors and 60 ecological pinch points are identified in the study, and the pinch points are located in the transition zones between ecological sources and plain areas with severe fragmentation. In general, this study has formed a technical path for identifying the priority order of regional ecological protection and restoration, which provides a spatial basis for the realization of the ecological pattern goal of the urban agglomeration in the middle reaches of the Yangtze River.

References

[1] Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, B., ... & Liang, X. (2022). Challenges and opportunities for carbon neutrality in China. Nature Reviews Earth & Environment, 3(2), 141-155.

[2] Piao, S., Fang, J., Ciais, P., Peylin, P., Huang, Y., Sitch, S., & Wang, T. (2009). The carbon balance of terrestrial ecosystems in China. Nature, 458(7241), 1009-1013.

[3] Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J. (2017). Natural climate solutions. Proceedings of the National Academy of Sciences, 114(44), 11645-11650.

[4] Lu, F., Hu, H., Sun, W., Zhu, J., Liu, G., Zhou, W., ... & Fu, B. (2018). Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. Proceedings of the National Academy of Sciences, 115(16), 4039-4044.

[5] Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., ... & Daily, G. C. (2016). Improvements in ecosystem services from investments in natural capital. Science, 352(6292), 1455-1459.

[6] Yu, K. (1996). Security patterns and surface model in landscape ecological planning. Landscape and Urban Planning, 36(1), 1-17.

[7] Peng, J., Zhao, H., & Liu, Y. (2017). Urban ecological corridors construction: A review. Acta Ecologica Sinica, 37(1), 23-30.

[8] Bryan, B. A., Gao, L., Ye, Y., Sun, X., Connor, J. D., Crossman, N. D., ... & Li, Z. (2018). China’s response to a national land-system sustainability emergency. Nature, 559(7713), 193-204.

[9] Li, S., Xiao, W., Zhao, Y., & Lv, X. (2020). Incorporating ecological risk index in the multi-process MSPA-MCR model for ecological security pattern optimization. Ecological Indicators, 113, 106226.

[10] Bai, Y., Wong, C. P., Jiang, B., Hughes, A. C., Wang, M., & Wang, Q. (2018). Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. Nature Communications, 9(1), 3034.

[11] Zhai, T., & Huang, L. (2022). Linking MSPA and Circuit Theory to identify the spatial range of ecological networks and its priority areas for conservation and restoration in urban agglomeration. Frontiers in Ecology and Evolution, 10, 828526.

[12] Wang, S., Wu, M., Hu, M., Fan, C., Wang, T., & Xia, B. (2021). Promoting ecosystem connectivity by constructing an ecological network based on the upper reaches of the Yangtze River. Ecological Indicators, 124, 107386.

[13] Fang, C., & Yu, D. (2017). Urban agglomeration: An evolving concept of an emerging phenomenon. Landscape and Urban Planning, 162, 126-136.

[14] Chen, W., Chi, G., & Li, J. (2019). The spatial association of ecosystem services with land use and land cover change in China. Geographical Journal, 185(1), 39-55.

[15] Tang, L., Ke, X., Chen, Y., Wang, L., Zhou, Q., & Zheng, W. (2020). Use of InVEST model to assess the impacts of land use/cover change on carbon storage in the Middle Reaches of the Yangtze River Urban Agglomeration. Journal of Geo-information Science, 22(12), 2261-2272.

[16] Yang, J., Xie, B., & Zhang, D. (2021). Spatial-temporal evolution of carbon emission and its driving factors in the Yangtze River Economic Belt. International Journal of Environmental Research and Public Health, 18(4), 1642.

[17] Soille, P., & Vogt, P. (2009). Morphological segmentation of binary patterns. Pattern Recognition Letters, 30(4), 456-459.

[18] Sharp, R., Chaplin-Kramer, R., Wood, S., Guerry, A., Tallis, H., Ricketts, T., ... & Vogl, A. L. (2018). InVEST 3.6.0 User’s Guide. The Natural Capital Project, Stanford University.

[19] Keeley, A. T., Beier, P., & Gagnon, J. W. (2016). Estimating landscape resistance from habitat suitability: effects of data source and nonlinearities. Landscape Ecology, 31, 2151-2162.

[20] McRae, B. H., Dickson, B. G., Keitt, T. H., & Shah, V. B. (2008). Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology, 89(10), 2712-2724.