

Construction and optimization of ecological networks in the metro-politan area of the west bank of the Pearl River Estuary, China based on MSPA-linkage mapper

Abstract

This study addresses the imbalance between ecological networks and socio-economic development in the Pearl River West Metropolitan Area. Using Morphological Spatial Pattern Analysis (MSPA) and Linkage Mapper tools, we systematically identified core ecological sources, potential ecological corridors, and critical ecological nodes across the region. Results show that forest and grassland dominate the core landscape, accounting for 83.62% of coverage. We identified 25 core ecological sources, extracted and prioritized 41 potential ecological corridors, and pinpointed 228 ecological nodes (comprising 86 pinch points and 142 barrier points). To enhance connectivity, we propose establishing seven additional ecological sources and 14 planned corridors in the central-western zone. This optimization substantially improves regional ecosystem connectivity, evidenced by a 29.7% increase in the Integral Index of Connectivity (IIC) and a 73.8% increase in the Probability of Connectivity (PC). The findings provide a scientific basis and technical framework for advancing ecological conservation and sustainable development in the metropolitan area.

Keywords: MSPA, linkage mapper, pearl river delta urban agglomeration, ecological network, landscape pattern

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Introduction

Optimizing the territorial ecological security pattern stands as a central pillar in advancing ecological civilization for the new era.^{1,2} Globally, the accelerating pace of urbanization and intensive land development has precipitated widespread fragmentation of ecological spaces.^{3,5} This fragmentation manifests in alarming biodiversity decline and the degradation of critical ecosystem services, presenting a formidable transboundary challenge.⁶ Consequently, constructing scientifically robust ecological networks has emerged as an essential strategy. By identifying and strategically connecting key ecological sources while delineating priority conservation corridors, these networks aim to maintain regional ecological integrity and bolster landscape resilience.^{7,9} Methodologically, the integration of Morphological Spatial Pattern Analysis (MSPA) with tools like Linkage Mapper has significantly advanced the capacity for multi-scale ecological network modeling in recent years.¹⁰ Despite these advancements, substantial limitations persist within the current research landscape. A primary concern is the prevalent reliance on administrative boundaries as the default spatial unit for analysis, which often disregards the inherent continuity of natural geographic units.^{11,12} This artificial segmentation risks generating fragmented and misaligned ecological network structures that poorly reflect ecological realities.^{13,14} Furthermore, the conventional construction of resistance surfaces frequently depends on expert-based assignment schemes. This approach tends to underrepresent the complex, dynamic coupling mechanisms between socio-economic drivers—quantified through proxies like nighttime light intensity—and critical landscape pattern indices, limiting the temporal and spatial accuracy of corridor identification.¹⁵ Additionally, the identification and optimization of key ecological nodes often overlook the synergistic potential of concurrently addressing pinch points (areas of high current density and

vulnerability) and barrier points (critical obstacles to connectivity). This oversight constrains the operational effectiveness and robustness of proposed network optimization strategies.¹⁶

As a pivotal strategic pillar within the Guangdong-Hong Kong-Macao Greater Bay Area, the Western Pearl River Delta Metropolitan Area embodies the acute tension between rapid urban development and the imperative for ecological conservation. This region faces intensifying dual pressures: the relentless expansion of urban and industrial land uses directly encroaches upon vital natural habitats, while the concurrent demand for robust ecological protection grows ever more urgent.^{3,4,17} Quantifying this pressure, 2022 data reveals a striking 27.4% of the region's total area occupied by construction land, driving an 18.6% reduction in core ecological source areas since 2010. This significant habitat loss has precipitated a marked deterioration in landscape connectivity, particularly manifesting as a substantial and widening disparity in ecological connectivity between the eastern and western sectors of the metropolitan area.^{18,19} While the Development Plan for the Western Bank of the Pearl River Estuary Metropolitan Area explicitly acknowledges these challenges and proposes the strategic construction of a regional ecological barrier network to enhance resilience, current research efforts remain largely constrained. Existing studies predominantly operate at the scale of individual cities, resulting in a critical gap: the lack of quantitative methodologies and systematic frameworks capable of optimizing ecological corridors that inherently span administrative boundaries.²⁰⁻²³ This limitation is acutely felt in the densely urbanized central and southern zones, where spatial conflicts between essential ecological nodes—such as critical wildlife corridors or stepping-stone habitats—and proliferating transportation infrastructure are intensifying at an alarming rate. Consequently, there exists an urgent and growing need for adaptive spatial planning solutions that can effectively reconcile the fundamental requirements of maintaining natural ecological

connectivity with the pervasive realities and pressures of intense anthropogenic disturbance across the metropolitan landscape.²⁴⁻²⁶

To bridge the critical gaps identified, this study innovatively develops a collaborative optimization framework centered on the synergistic integration of “morphological structure” and “functional connectivity.”²⁷ Recognizing the limitations of constrained administrative units, the methodology first transcends city boundaries to delineate core ecological sources at a regionally coherent scale.²⁸ This is achieved by strategically integrating Morphological Spatial Pattern Analysis (MSPA) with established landscape connectivity indices—such as the Probability of Connectivity (PC) or Integral Index of Connectivity (IIC)—which collectively assess patch importance based on both physical configuration and their functional role in facilitating ecological flows.²⁹⁻³¹ Building upon this foundation, a significant methodological advancement is introduced: the construction of a spatially and temporally dynamic resistance surface.³² Utilizing a robust entropy method-Analytic Hierarchy Process (AHP) coupling model, this surface objectively integrates multifaceted data layers, including nighttime light intensity (as a proxy for pervasive human activity pressure), key landscape pattern indices (quantifying fragmentation and configuration), and essential traditional natural factors (e.g., terrain, land cover, water bodies).³³ Complementing this, the Pinpoint/Barrier Mapper module within the Linkage Mapper toolkit is leveraged to precisely quantify the current density indicating areas of concentrated ecological flow vulnerable to disruption and the improvement potential of strategically vital nodes across the network.^{34,35} This critical analysis directly informs the formulation of a hierarchical optimization strategy, prioritizing “pinpoint strengthening” to fortify critical bottlenecks and “barrier point repairing” to mitigate major connectivity obstacles.^{36,37} Collectively, this integrated framework is designed to address three pivotal scientific questions: (1) how to overcome the fragmentation imposed by administrative boundaries to successfully construct an ecologically coherent network grounded in intact natural geographic units;³⁸ (2) how to effectively quantify the spatiotemporal influence of human activity intensity, derived from dynamic data like nocturnal illumination, on the realized effectiveness of ecological corridors;³⁹ and (3) how to enhance overall network robustness and resilience through targeted, hierarchical regulation focused on optimizing key node functionality.⁴⁰

This research offers innovative methodologies for optimizing the ecological security pattern of the Guangdong-Hong Kong-Macao Greater Bay Area. Furthermore, it provides empirical references to inform ecological restoration decisions in areas undergoing high-density urbanization.

Research area, data source and methods

Research area

Located in the southern part of Guangdong Province of China, the Western Pearl River Estuary Metropolitan Area (hereinafter referred to as “the Western PRD Metropolitan Area”) encompasses the four cities of Zhuhai, Zhongshan, Jiangmen, and Yangjiang (Figure 1), covering a total area of approximately 21,000 square kilometers. Positioned west of the Pearl River Estuary and connected to western Guangdong, it serves as a gateway connecting the Guangdong-Hong Kong-Macao Greater Bay Area with the southwestern hinterland. The region is centered on the alluvial plain of the western Pearl River Delta, distinguished by a dense network of rivers and crisscrossing waterways, including the Xijiang and Tanjiang Rivers, which create a typical Lingnan water town landscape. Extensive tidal

flats characterize the west coast due to the influence of Pearl River sediment deposition and tidal action, leading to a continuous seaward extension of the coastline. The terrain exhibits diversity, featuring low mountains and hills in the upper reaches, plains in the middle and lower reaches, and coastal wetlands like the Qi’ao mangrove forest, contributing to a complex and diverse ecosystem.

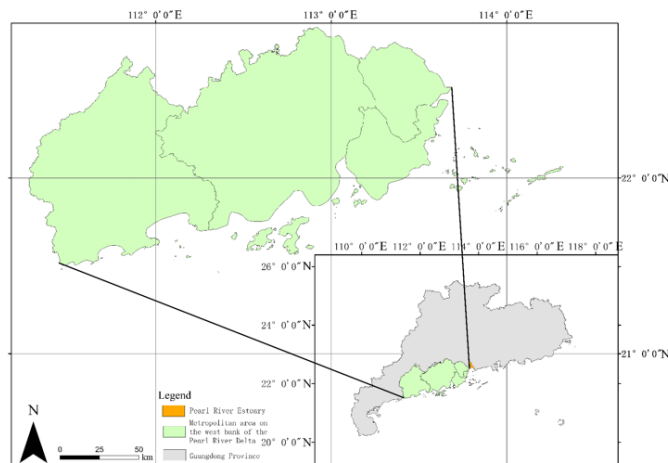


Figure 1 Location of the study area.

The climate is subtropical monsoon, characterized by abundant rainfall and heat. However, the region is frequently hit by typhoons in summer, making the estuary area prone to flooding and saltwater intrusion. Simultaneously, the upstream mountainous areas face risks of flash floods and landslides. The region benefits from rich water resources, leveraging the Pearl River’s flow to support development. However, balancing ecological protection with urban demands requires water conservancy projects. Overall, the natural geographical pattern is characterized by “mountains and seas intertwined, rivers and seas interwoven.”

In recent years, the West Pearl River Delta Metropolitan Area has ushered in significant development opportunities with the successive release of the “14th Five-Year Plan for National Economic and Social Development of Guangdong Province and the Outline of Long-term Goals for 2035” and the “Development Plan for the West Bank of the Pearl River Estuary Metropolitan Area”. These plans not only clarify the overall direction of regional development but also emphasize the importance of ecological and environmental protection, thus providing guidance for achieving sustainable development.

Data sources and preprocessing

The data used in this study mainly include remote sensing data products, a Digital Elevation Model (DEM), nighttime light data, and water body data (Table 1). Land use data, including cultivated land and grassland, were extracted for the study area from ArcGIS using clipping, mosaicking, and other operations to obtain 8 land use types. Slope was derived from the DEM. The Normalized Difference Vegetation Index (NDVI) data were obtained through analysis using ENVI. Nighttime light data were processed with ArcGIS using buffer analysis. Water body data were also processed using buffer analysis in ArcGIS.

Research methods

Morphological spatial pattern analysis: Morphological Spatial Pattern Analysis (MSPA), grounded in mathematical morphology principles, identifies ecological sources and corridors by recognizing

the spatial topological relationships between pixels and structural elements. With its emphasis on structural connectivity, MSPA is well-suited for assessing and optimizing multi-scale urban green space patterns. In this study, land use data from the Pearl River West Metropolitan Area were utilized. Specifically, forest and grassland were extracted as foreground elements in ArcGIS 10.7, while other

land use types were designated as background elements to generate a binary raster map. Subsequently, the Guidos Toolbox software was employed to analyze the map, resulting in the identification of seven landscape types: core, islet, edge, perforation, connector, branch, and loop.

Table 1 Data sources and processing

| Data name | Data source | Data type and accuracy |
|-------------------------------|--|------------------------|
| Land use data (2022) | National Geographic Information Resource Directory Service System, http://globeland30.org | Raster, 30m×30m |
| Digital Elevation Model (DEM) | Geospatial Data Cloud, http://www.gscloud.cn/ | Raster, 30m×30m |
| Nighttime light data (2022) | Earth Resource Data Cloud, http://www.gis5g.com/ | Raster, 1000m×1000m |
| Water body data (2022) | Global Geographic Information Resource Directory Service System, http://www.webmap.cn/ | Raster, 30m×30m |

To avoid the limitations of subjective judgment methods, the core area was selected as the alternative ecological source, and ecological sources were scientifically classified from the aspects of spatial form and structural connectivity.

Landscape connectivity index analysis: Landscape connectivity theory describes the degree to which a particular landscape type hinders or promotes species movement between source patches. The probability of connectivity (PC) and the integral index of connectivity (IIC) are used to evaluate the overall connectivity of the landscape and can also be applied to evaluate the effect of landscape optimization.

Construction of resistance surface: In this study, 10 index factors were selected to construct the ecological resistance surface of the Pearl

River West Metropolitan Area. Elevation, slope, distance to water bodies, land cover type, and distance to roads have been widely used in previous studies. In addition, this study also incorporates several landscape indices, including Shannon diversity, Shannon evenness, aggregation index, and contagion index.

Natural breaks are used to assign ranks from 1 to 5, reflecting the degree of resistance encountered by biological species during migration and energy exchange. A higher resistance rank indicates a stronger hindering effect of the area on biological activity and energy flow, with relevant indicators shown in Table 2.

Table 2 Classification index and evaluation and grading standard of ecological resistance in the metropolitan area on the west bank of the Pearl River Estuary

| Index type | Evaluation factor | Grading standard | | | | | Analytic Hierarchy Process weights | Entropy method weight | Weight coefficient |
|---------------------|-----------------------------|-------------------|------------------|-------------------|-----------------|-----------------|------------------------------------|-----------------------|--------------------|
| | | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | | | |
| Natural environment | Elevation (m) | < 70 | [70, 196) | [196, 367) | [367, 593) | ≥ 593 | 0.186 | 0.091 | 0.135 |
| | Slope (°) | [0, 2) | [2, 5) | [5, 10) | [10, 15) | ≥ 15 | 0.061 | 0.093 | 0.07 |
| | Distance from the water (m) | [0, 1000) | [1000, 2000) | [2000, 3000) | [3000, 4000) | ≥ 4000 | 0.061 | 0.107 | 0.1 |
| | Surface cover type | Water、Tree Canopy | Shrub、Herbaceous | Vegetation、Sparse | Cropland | Urban、Bare Land | 0.288 | 0.107 | 0.209 |
| Social factors | Distance from the road (m) | [0, 500) | [500, 1000) | [1000, 2000) | [2000, 3000) | ≥ 3000 | 0.074 | 0.094 | 0.074 |
| | Nighttime lighting data | [0, 6859) | [6859, 24006) | [24006, 61730) | [61730, 181819) | ≥ 181819 | 0.122 | 0.076 | 0.092 |
| | Shannon Diversity | ≥ 0.91 | [0.7, 0.91) | [0.46, 0.7) | [0.17, 0.46) | [0, 0.17) | 0.043 | 0.116 | 0.084 |
| | Shannon's evenness | [0.81, 1] | [0.61, 0.81) | [0.38, 0.61) | [0.14, 0.38) | [0, 0.14) | 0.06 | 0.12 | 0.088 |
| Landscape index | Aggregation Index | [95.68, 100) | [89.01, 95.68) | [81.56, 89.01) | [70.98, 81.56) | [0, 70.98) | 0.012 | 0.074 | 0.057 |
| | Contagion index | ≥ 73.72 | [52.94, 73.72) | [33.33, 52.94) | [12.15, 33.33) | [0, 12.15) | 0.032 | 0.122 | 0.091 |

The entropy weight method-analytic hierarchy process (AHP) is a weighting method that combines subjective and objective approaches. It enhances the scientific rigor of weight allocation by integrating expert judgment from AHP with the data-driven characteristics of the entropy weight method. AHP calculates subjective weights based on hierarchical structures and judgment matrices but is susceptible to expert subjectivity. In contrast, the entropy weight method calculates objective weights based on the dispersion of index data, reflecting the data's inherent patterns.

Integrating these two methods through multiplicative aggregation or a linear weighted combination preserves the systematic logic of AHP while using the entropy weight method to correct subjective biases. This approach is particularly well-suited for multi-criteria decision-making problems, such as ecological resistance surfaces.

Habitat connectivity analysis: Linkage Mapper is a valuable tool for analyzing wildlife habitat connectivity, effectively reducing the need for tedious manual screening.

(1) Ecological corridor Identification

Linkage Mapper identifies ecological corridor based on the least-cost path principle by constructing a cumulative cost resistance surface. In this method, core ecological source area are treated as nodes, and factors such as land use type and slope are used to build a resistance model to simulate energy consumption during species migration. A potential corridor network is then generated by calculating the least-cost path between each core area pair. A lower corridor cumulative cost value indicates stronger landscape connectivity, which is more favorable for species dispersal and gene flow.

By integrating corridor width and critical pinch points analysis, important ecological passage requiring prioritized protection can be further identified.

(2) Source importance identification

Although Centrality Mapper differs in principle from the gravity model, it can also be used to assess corridor importance. It calculates network current centrality based on Circuitscape, treating the core area as a node, and setting the link resistance equivalent to the cost-weighted distance of the least-cost corridor. A centrality score is then generated by injecting current into the core area and accumulating the results for all core area pairs. A higher score indicates a more important core ecological source area and a stronger corridor connection.

(3) Ecological nodes identification

Ecological Nodes are key areas for maintaining ecosystem stability and service function, are closely related to the core ecological source area, and either promote or inhibit biological migration and diffusion.

This study classifies Ecological Nodes into two categories: ecological pinch point and ecological barrier point, representing important channels and potential obstruction areas in ecological processes, respectively.

After comparing different datasets, the detection radius range was ultimately set from 100m to 1000m, with increments of 100m. Furthermore, a cross-core area pairs combination method that "calculates the sum of maximum values" was employed.

Results

Identification of ecological source areas

Woodland and grassland within the Western Pearl River Delta Metropolitan Area were used as the foreground in the Morphological

Spatial Pattern Analysis (Figure 2), and the distribution of each landscape type was statistically analyzed. The results revealed that core area, which can serve as Ecological Source Areas, constitutes 42.1% of the total landscape area. Furthermore, woodland and grassland patches suitable as Ecological Source Areas are predominantly large. The prominent connectivity of branch type patch suggests high internal and external connectivity within woodland and grassland patches, facilitating the spread of ecological service function and promoting the stability of the regional ecosystem. The small area occupied by bridge type patch indicates weak direct connectivity among woodland areas. Consequently, the construction of ecological corridor is crucial, as it can promote material and energy flow and enhance the stability and functionality of the Ecological Network.

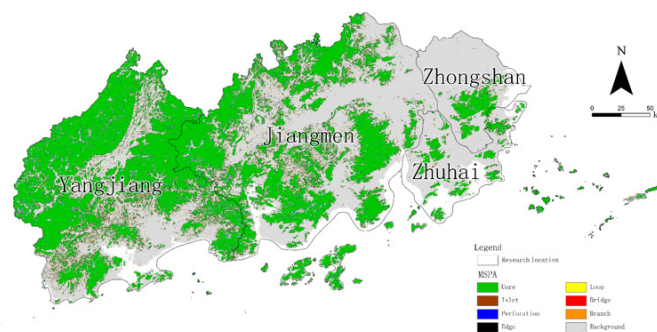


Figure 2 Spatial distribution of landscape types in the metropolitan area on the west bank of the Pearl River Estuary based on MSPA.

To calculate patch connectivity (delta of the Probability of Connectivity), a total of 39 patches with an area greater than 20Km² were selected. Subsequently, patches with connectivity values greater than 0.1 were chosen, and ultimately, the 25 patches exhibiting the highest connectivity were identified as core ecological source area, covering a total area of 2792.59Km². The results (Figure 3) indicate that ecological sources are unevenly distributed within the Western Pearl River Delta Metropolitan Area, with a higher concentration in the western and northern regions, forming a large, continuous system, while the southeastern and southern regions have significantly fewer sources. Yangjiang and Jiangmen account for a large proportion of ecological sources, while Zhongshan has fewer, and Zhuhai lacks sources altogether.

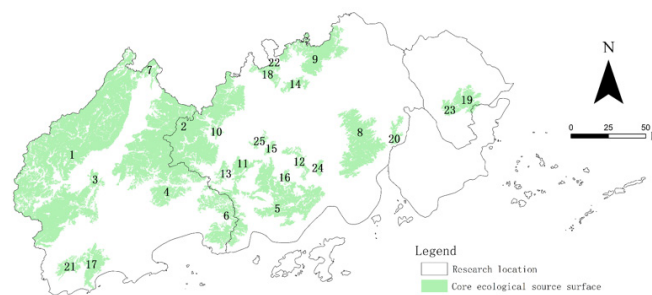


Figure 3 Spatial distribution of core ecological sources in the metropolitan area on the west bank of the Pearl River Estuary. 1 ~ 25: Number of ecological sources.

Resistance surface construction

The eastern and southern coastal areas of the Western Pearl River Delta Metropolitan Area exhibit higher ecological resistance. This is primarily attributed to the accelerated urbanization process and increased construction land in Zhongshan and Zhuhai, leading to a resistance distribution pattern that is high in the east and south, and low

in the west and north, consequently affecting regional connectivity. In terms of the natural environment, the area is characterized by gentle terrain, resulting in low altitude and slope resistance, with distance to water bodies and land cover resistance being moderate. Considering social factors, the resistance associated with distance to roads is high in the east, and the nighttime light data is high in the east and low in the west. Landscape index analysis reveals that the Western Pearl River Delta Metropolitan Area demonstrates high landscape diversity and aggregation index, but the uneven distribution may compromise the balance of ecological service functions; the sprawl index suggests that while the landscape possesses some continuity, isolation and fragmentation are also present.

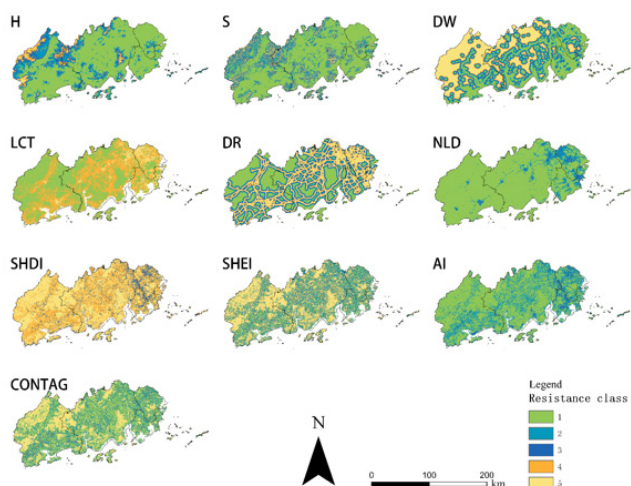


Figure 4 Ten factors of ecological resistance in the metropolitan area on the west bank of the Pearl River Estuary.

H, high; S, slope; DW, distance from water; LCT, land cover type; NLD, nighttime light data; DR, distance from road; SHDI, shannon's diversity index; SHEI, shannon's evenness index; AI, aggregation index; CONTAG, contagion index

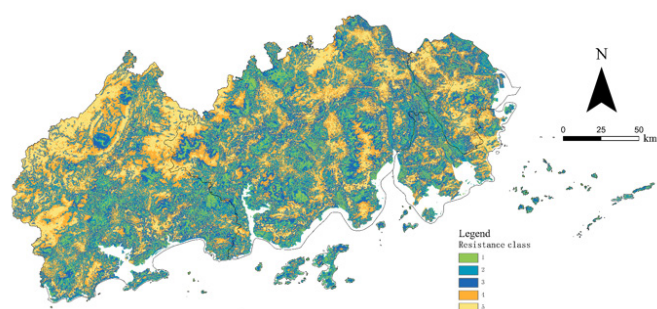


Figure 5 Ecological resistance surface.

Ecological network pattern construction

Based on the Ecological Source Areas and ecological resistance surface of the West Pearl River Delta Metropolitan Area, ecological corridor were extracted using the Linkage Mapper tool, identifying a total of 51 potential ecological corridor. The Centrality Mapper tool was then employed to calculate the centrality of the 25 Ecological Source Areas, and 44 corridors with a centrality greater than 10 were selected and categorized into three levels (Figure 6). This included 19 primary corridor (centrality > 30), 12 secondary corridor (20 < centrality ≤ 30), and 13 tertiary corridor (10 < centrality ≤ 20).

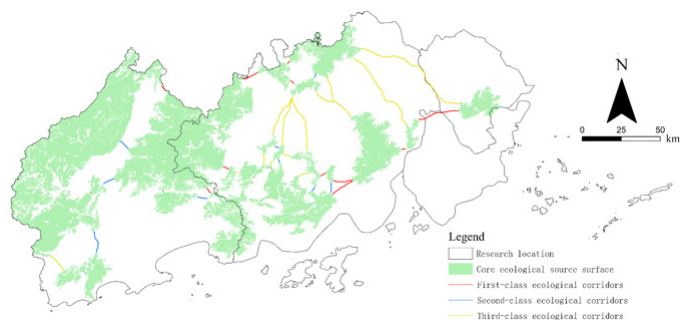


Figure 6 Comprehensive ecological corridor in the metropolitan area on the west bank of the Pearl River Estuary.

These ecological corridor facilitate the basic connectivity between Ecological Source Areas within the study area, resulting in a landscape structure of “three horizontal axes, four vertical axes, and five clusters” (Figure 7).

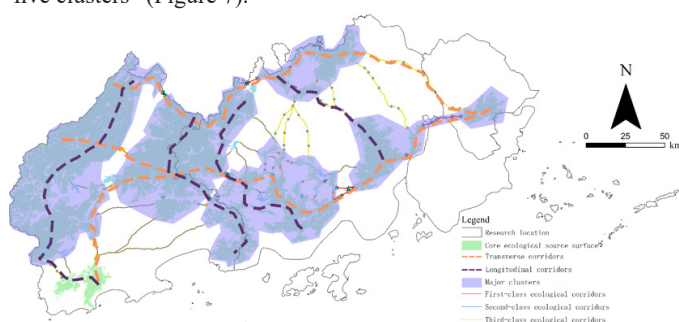


Figure 7 Spatial morphological characteristics of the Western Pearl urban agglomeration.

The three horizontal axes include the northern mountain forest axis, the central mountain-farmland crossing axis, and the southern built-up area and ecological land intersection axis; the four vertical axes are the western Ehuangzhang Mountain forest axis, the mid-western Qixingkeng Mountain forest axis, the central Fengcheshan forest axis, and the eastern Beifengshan and built-up area intersection axis; the five clusters are the western Ehuangzhang forest land, the mid-western Qixingkeng forest land, the mid-southern Fengcheshan forest land, the northern Longtanshan forest land, and the eastern Beifengshan forest land. These areas, characterized by large contiguous forest lands and a good ecological base, are the main distribution areas of Ecological Source Areas.

The “three horizontal and four vertical” corridor crosses the intersection of construction land and ecological land in the east and south, constructing the material and energy flow pathway and connecting the “five clusters” with other Ecological Source Areas. This plays an important role in maintaining the stability of the West Pearl River Delta Metropolitan Area ecosystem.

Ecological node identification

Habitat connectivity analysis: The Pinchpoint Mapper tool was employed to accurately identify key ecological pinch points in the ecological network of the Pearl River West Metropolitan Area, using both “Pairwise mode” and “All-to-one mode” modes. In pairwise mode, a high current density was observed in the eastern part of the study area, primarily concentrated in five locations, with a peak current density of 0.129 (Figure 8). Conversely, in all-to-one mode, the high-density areas were concentrated in the northwest, across

six locations, and the peak current density significantly increased to 11.437 (Figure 8). These areas are considered important for ecological flow. An overlay analysis of the identification results from both modes revealed a total of 86 ecological pinch points, which were further categorized based on their importance into 30 primary ecological pinch points, 13 Secondary ecological pinch point, and 43 tertiary ecological pinch points (Figure 9).

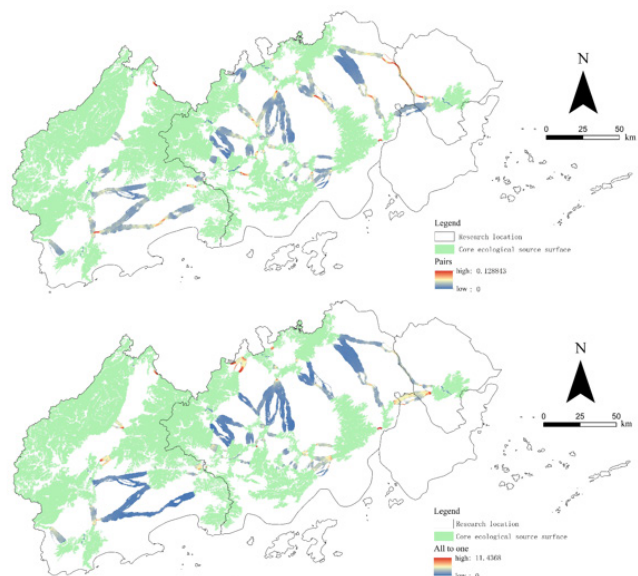


Figure 8 Based on Pinchpoint mapper ecological pinch point analysis.

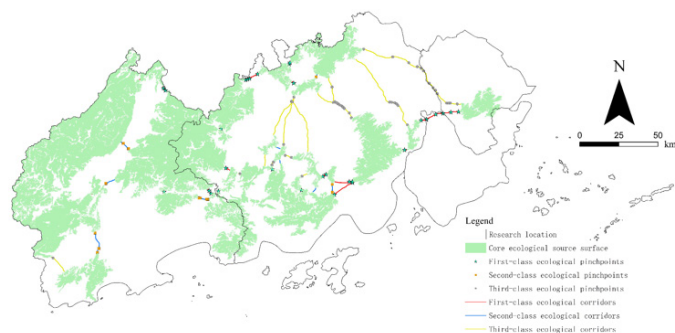


Figure 9 The metropolitan area on the west bank of the Pearl River Estuary is divided into hierarchical ecological pinch points.

Ecological barrier points Identification: Ecological barrier points were analyzed using the Barrier Mapper tool. Without setting a specific improvement score threshold, the analysis revealed that areas with higher improvement score were primarily concentrated in the central and southern parts of the study area (Figure 10). These areas, adjacent to ecological sources, serve as transit and aggregation hubs within the network system, making them crucial for maintaining regional connectivity. Examining the relationship between improvement score and LCD percentage, it was observed that high-value areas were relatively evenly distributed along the ecological corridor, mainly between the northern and southern core ecological source area (Figure 10). In total, 142 ecological barrier points were identified and graded (Figure 11), and these play a key role in maintaining regional ecological connectivity.

Ecological network pattern optimization: Before the Ecological Network Pattern Optimization of the Western Pearl River Delta Metropolitan Area, the Ring-shaped Cross-connected Layout of the “Three Horizontal, Four Vertical, Five Clusters” provided a foundational framework for the Connectivity of Ecological Source

Areas in the region. However, the pre-optimization configuration suffered from insufficient Ecological Corridor and source area density in areas such as southern and western Yangjiang City, northwestern and southern Jiangmen City, and southern Zhongshan. This resulted in low connectivity complexity and, consequently, weak Ecological Network Stability]]]. Furthermore, the sparse distribution of [{{T_ Ecological Source Areas within key corridors, including the “Three Horizontal” corridors, the western Ehuangzhang Mountain Forest Axis, and the central Fengcheshan Forest Axis, constrained the efficiency of both Species Dispersal and Material Flow.

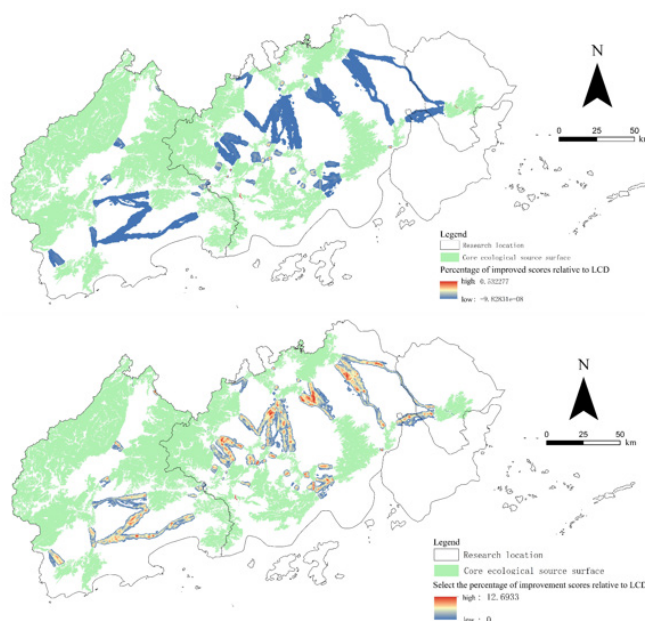


Figure 10 Based on barrier mapper ecological barrier point analysis.

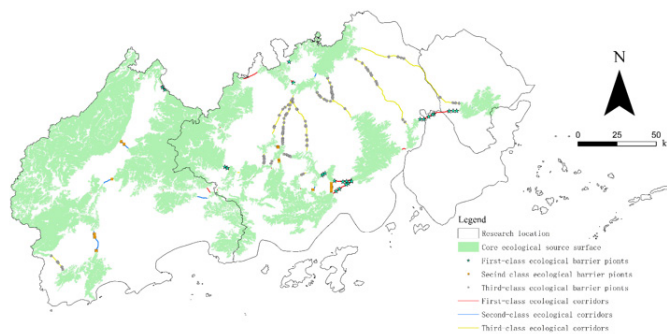


Figure 11 The metropolitan area on the west bank of the Pearl River Estuary is divided into hierarchical ecological barrier points.

To address these issues, the original network was optimized, with the addition of 7 Ecological Source Areas (total area of 86.7 km²) and 14 Ecological Corridor. Specifically, 3 of the newly added Ecological Source Areas are located in Yangjiang City, and 4 are in Jiangmen City. These additions significantly enhance Species Dispersal capacity and ecological connectivity within the region. Furthermore, based on 228 Ecological Nodes identified using the Linkage Mapper Toolbox (including 86 Ecological Pinch Point and 142 Ecological Barrier Point), and with reference to research by relevant scholars [26], 90 optimized Ecological Nodes were ultimately extracted, comprising 30 Primary Node, 18 Secondary Node, and 42 Tertiary Node (Fig. 12). These optimization measures effectively compensate for the shortcomings in the original network’s corridor and source area distribution, enhance Material Flow paths within the region, and

significantly improve the overall stability and connectivity of the Western Pearl River Delta Metropolitan Area Ecological Network.

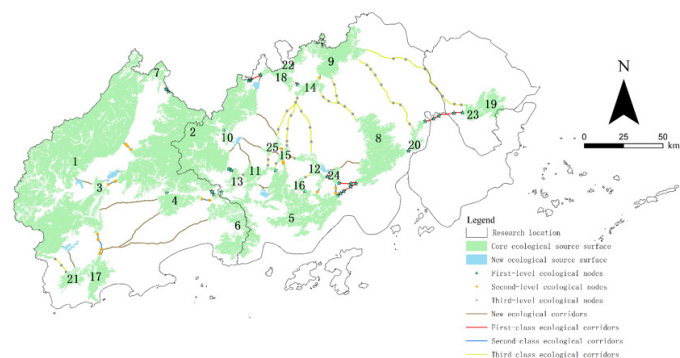


Figure 12 Optimization of the ecological network of the metropolitan area on the west bank of the Pearl River Estuary.

The optimized ecological network pattern (Figure 13) leads to a more reasonable layout of Ecological Source Areas and corridors within the region, smoother Species Dispersal paths, and a more complete spatial structure of the ecological network. Furthermore, the newly added Ecological Corridor and source areas strengthen the function of the “three horizontal and four vertical” framework, making the “five clusters” of Ecological Base more stable and providing a more scientific spatial guidance for Western Pearl River Delta Metropolitan Area Ecological Protection and Restoration.

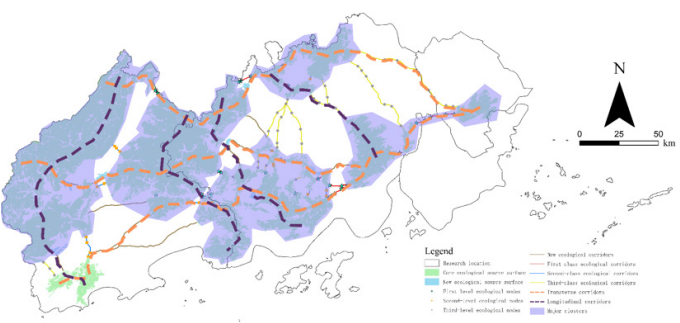


Figure 13 Optimization of the ecological network structure in the West Pearl River Delta Metropolitan Area.

Evaluation of landscape pattern optimization effect

The Integral Index of Connectivity (IIC) and Probability of Connectivity (PC) of the Western Pearl River Delta Metropolitan Area were calculated before and after landscape ecological pattern optimization. The results showed that after optimization, the IIC increased by 29.2% and the PC increased by 73.8% (Table 3). This indicates a significant optimization effect, with the newly added Ecological Source Areas playing a crucial role in further enhancing the overall ecological function and stability of the Western Pearl River Delta Metropolitan Area.

Table 3 Optimization evaluation of landscape pattern

| Evaluation index | Before optimization | After optimization | Change rate (%) |
|--|---------------------|--------------------|-----------------|
| Integral index of connectivity (IIC) | 0.249 | 0.323 | 29.7 |
| Probability of connectivity index (PC) | 0.275 | 0.478 | 73.8 |

Discussion

This study systematically proposes optimization strategies to address the imbalance between the construction of the Western Pearl River Delta Metropolitan Area Ecological Network and socio-economic development. By comprehensively employing Morphological Spatial Pattern Analysis (MSPA), landscape connectivity index analysis, Resistance Surface construction, and Habitat Connectivity analysis, key Ecological Source Areas, potential Ecological Corridor, and nodes within the region were accurately identified, providing a scientific basis for the optimization of the Ecological Network. The results indicate that the “three horizontal” and “four vertical” Ecological Corridor pattern in the Western Pearl River Delta Metropolitan Area effectively promotes the flow of matter and energy within the ecosystem, and the identification of key Ecological Nodes helps clarify priority areas for ecological protection.

This study demonstrates a high degree of comprehensiveness and diversity in data processing. It comprehensively considers data from multiple dimensions, such as the natural environment, social factors, and landscape index, to construct a comprehensive ecological resistance surface. This approach not only enriches the research content but also provides a more accurate basis for the optimization of the Ecological Network. However, the study also has certain limitations: the construction of the ecological resistance surface primarily focused on the needs of terrestrial species, without fully considering the particularities of aquatic species.

In summary, this study has made significant progress in the construction and optimization of the Western Pearl River Delta Metropolitan Area Ecological Network. The findings not only provide a scientific basis for the construction and optimization of the Western Pearl River Delta Metropolitan Area’s Ecological Network but also serve as an important reference for regional ecological protection and sustainable development planning.

However, further refinement and optimization of relevant methods and techniques will be necessary in future research. It is expected that continuous improvement of research methods and data updates will further enhance the scientific rigor and practical effectiveness of Ecological Network optimization.

Conclusions

This study comprehensively applied the scientific method of Morphological Spatial Pattern Analysis, in conjunction with tools such as Confer2.6 and Linkage Mapper, to systematically evaluate and optimize the Ecological Network of the Western Pearl River Estuary Metropolitan Area. The main research results and conclusions are as follows:

(1) The Morphological Spatial Pattern Analysis method identified seven landscape types in the Western Pearl River Delta Metropolitan Area. The Core Area was the largest, reaching 2792.59 square kilometers, accounting for 83.62% of the total area, and was predominantly woodland. Further analysis identified 25 Core Ecological Source Areas, representing a high proportion of the total area, but with an uneven distribution, mainly concentrated in the low mountains and hills of the west and north, and the central plain area. The eastern distribution was sparse, indicating poor Connectivity.

(2) Fifty-one potential Ecological Corridors were extracted using the Linkage Mapper tool, and these were then classified into 41 corridors using Centrality Mapper. The results indicated 19 primary corridors, primarily concentrated in the central and western regions; 12 secondary corridors, connecting the western and central regions;

and 13 tertiary corridors, distributed in the eastern and central regions. It was observed that the corridors in the eastern region have lower priority and are fewer in number, suggesting that ecological construction needs to be strengthened to promote ecological exchange.

(3) A total of 228 Ecological Nodes were identified by combining the Pinchpoint Mapper and Barrier Mapper tools, including 86 Ecological Pinchpoints and 142 ecological barrier points. Based on corridor distribution, these nodes were further categorized into 17 primary Ecological Nodes, 12 secondary Ecological Nodes, and 8 tertiary Ecological Nodes.

(4) Based on the analysis of key Ecological Corridors and nodes, seven Ecological Source Areas and 14 planned corridors were added to the mid-west of the Western Pearl River Delta Metropolitan Area. This measure significantly enhances east-west Species Dispersal paths, improving ecological connectivity and network stability. The overall Connectivity Change Rate is 29.7%, and the change rate of the Probability of Connectivity Index is 73.8%.

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Conflicts of interests

All of the authors have no conflict of interest.

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