Research on a Multiscale Urban Ecological Network Integration Method Based on Network Analysis: A Case Study of Hegang City

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Abstract: The ecological survival of resource-extractive cities like Hegang hinges on how effectively their green infrastructure connects across fragmented urban and regional landscapes. Moving beyond traditional single-scale assessments, this research integrates established GIS and network analysis protocols to diagnose the multiscale connectivity of Hegang's ecological network. By identifying 40 regional and 10 urban-scale sources, we built a comprehensive resistance framework that accounts for both mining-induced disturbances and urban expansion. Our findings reveal a precarious structural dependency: the entire cross-scale system relies heavily on a single "backbone" path, creating a bottleneck for ecological flows. Specifically, Node 2 in the western sector emerged as a vital node with high degree centrality, functioning as a primary gateway for regional biodiversity into the city center. Rather than seeking purely theoretical novelty, this study translates these topological insights into a three-tiered planning strategy – strengthening cores, adding paths, and cultivating nodes – offering a concrete spatial blueprint for planners to prioritize restoration efforts in declining industrial regions.

Keywords: Ecological networks, cross-scale connectivity, node degree centrality, Hegang City

1 Introduction

With the deepening of urbanization, the continuous expansion of built-up areas has resulted in increasingly severe ecological fragmentation and functional degradation (SERRET et al. 2014, YU et al. 2016). As a natural solution for maintaining biodiversity and ensuring ecological security, ecological networks have therefore become a core research focus in landscape ecology and urban planning (WANG et al. 2019A). Their theoretical evolution has shifted from early "patch-path-matrix" models toward the synergistic optimization of both ecological structure and process at multiple spatial scales (FU et al. 2025).

Ecological network research focuses predominantly on two key scales: the regional scale (e.g., city-region, metropolitan area), which emphasizes biodiversity, ecosystem integrity, and large-scale processes such as species migration. The urban scale, which addresses services directly benefiting residents, including recreation, microclimate regulation, and environmental quality (NING 2021). However, mechanisms that effectively link these scales remain lacking, weakening the integration of macro-scale ecological flows into the urban core and limiting the feedback of internal urban ecological needs into regional planning(WANG et al. 2019B, ZHONG et al. 2014). As a result, both the structure and function of ecological networks are fragmented. Addressing this gap by developing systematic multi-scale integration, identifying bridging nodes, and proposing spatial optimization strategies is now a central scientific challenge.

Journal of Digital Landscape Architecture, 11-2026, pp. 684-692. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-770-0, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537770065.
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The construction of ecological networks generally adopts the workflow: ecological source identification-resistance surface construction extraction. Among these, the Morphological Spatial Pattern Analysis (MSPA) method has significantly strengthened the scientific basis for source identification (CIMON-MORIN & POULIN 2018). Ecological paths are commonly generated using the Minimum Cumulative Resistance (MCR) model, whose reliability depends strongly on the rational weighting of resistance factors such as land use, slope, and road proximity (CUI et al. 2020). Although graph theory provides a robust framework for evaluating ecological networks, its advanced theories and diagnostic indicators remain underutilized, resulting in analyses that seldom move beyond basic topological description. Most studies use only fundamental indicators, such as the connectivity index and path density, for analysis (ZHU et al. 2020). We argue that the true utility of node degree centrality and Minimum Spanning Tree (MST) analysis lies in their ability to diagnose systemic vulnerabilities – yet these metrics are frequently relegated to basic descriptions rather than actionable insights.

This study addresses this practical need. Using Hegang City – a landscape profoundly altered by long-term coal mining – as a laboratory, we provide an integrated application of existing GIS and graph theory procedures to solve real-world connectivity problems. By characterizing "bridging nodes" through a systematic overlay of municipal and urban data, we move past the "executive summary" style of reporting toward a diagnostic logic that identifies where restoration is most urgent. Our goal is to demonstrate how these established technical procedures can be synthesized into a coherent strategy for ecological resilience in transitioning resource-based cities.

2 Methods

2.1 Research Area and Data Sources

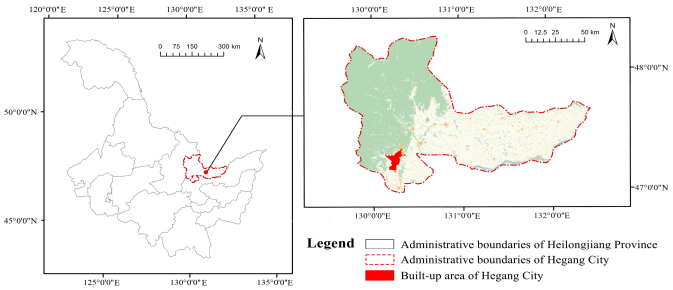


Fig. 1: Research area

Hegang City in Heilongjiang Province is a resource-based city with a high level of urbanization. It has undergone distinct developmental phases – coal-driven prosperity, resource depletion, and ongoing economic transformation – and currently faces significant challenges, including population decline and economic structural imbalance. Despite its ecological endowment from the surrounding Xiaoxing'anling forest, prolonged coal mining activities have caused severe geological disturbances and landscape fragmentation (ZHANG et al. 2022). In this context, its strategic shift toward "ecological city construction" offers a representative model for studying sustainable development pathways in resource-dependent cities. This

study uses 2024 30-meter-resolution raster data, incorporating land-use, topographic, and socioeconomic indicators to build the network.

2.2 Ecological Source Identification

MSPA was used to classify landscape elements into core areas, islands, and edges. Among them, core areas can provide sufficient habitats for species and ensure biodiversity (Yu et al. 2016). At the regional level, "Core areas" of large natural habitats (≥ 0.5 km²) were extracted. These were further screened using the Patch Connectivity (PC) index to ensure strong ecological functionality (MITCHELL et al. 2013). While at the urban level, we focused on the vital parks and green spaces within the built-up area.

2.3 Construction of the Comprehensive Resistance Surface

The resistance surface is the core carrier that reflects the difficulty of spatial movement for ecological processes. To accurately construct a comprehensive resistance surface that can represent the ecological security pattern of Hegang City, this study, based on traditional construction factors, supplements them with factors reflecting the intensity of human activities (nighttime light data and per capita GDP). At the same time, in the construction of the resistance surface in the built-up area, a natural attraction factor (the distribution of street trees) is also included. All selected factors are classified and standardized to eliminate the influence of different dimensions; the weights of each factor are determined using the Analytic Hierarchy Process (AHP) expert scoring method, and the comprehensive resistance surface is ultimately constructed in ArcGIS.

2.4 Building the Integrated Network

The potential ecological paths are extracted using the minimum cumulative resistance (MCR) model (YU et al. 2022). The Linkage Mapper toolbox is used to generate minimum-cost paths connecting the various source areas, which serve as potential paths.

1) Construction of basic ecological network: Classify the resistance values of potential paths at both the regional and built-up area scales. Select the paths with connectivity in the top 30% as critical ecological paths to construct the ecological network at both scales.
2) Cross-scale connection network extraction: Extract the municipal sub-networks associated with the built-up area, and perform spatial overlay with the built-up area network to identify the cross-scale correlation parts.
3) Identification of cross-scale backbone paths: Connectivity is both the core fundamental characteristic and one of the most critical functions of ecological paths. Therefore, based on the premise of connectivity between source points, this paper extracts the Minimum Spanning Tree (MST) of the ecological network as the backbone path (NEWMAN, M. E. J. 2010). This is obtained using the Kruskal algorithm.

To turn this topology into a planning tool, we calculated the degree centrality of nodes where regional and urban paths intersect. Finally, using the Natural Breaks method, we clustered these nodes into five distinct priority levels. This statistical grouping allows planners to dis-

tinguish “Critical” nodes from “Marginal” ones, transforming abstract graph theory into a clear hierarchy for land-use zoning and habitat reinforcement.

3 Results

3.1 Distributional Result of Ecological Sources

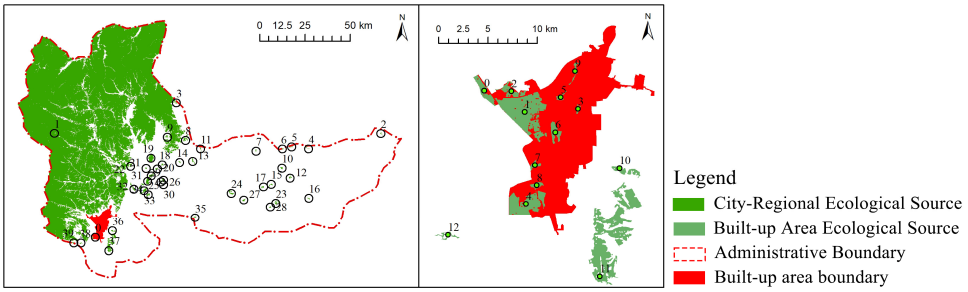


Fig. 2: Identification results of ecological sources

The geometric and functional evaluation of landscape elements identified 40 distinct ecological sources across the municipal territory. Spatially, these sources exhibit a stark “west-dense, east-sparse” configuration. The expansive natural habitats (totalling 5,921.3 km²) fringing the Xiao Xing'an Mountains in the west serve as the structural anchor for regional ecological security. In contrast, the 10 sources identified within the built-up area are smaller and more fragmented. This pattern – where high-energy regional sources envelop isolated urban patches – indicates that urban ecological functions are fundamentally subsidized by energy flows from the surrounding macro-landscape.

3.2 Resistance Surfaces and Ecological Paths

The comprehensive resistance analysis highlights that anthropogenic interference, measured by nighttime light and GDP intensity, remains the primary barrier to ecological movement. Out of an initial pool of 780 municipal paths, our screening process retained only 178 high-connectivity corridors to form the regional skeleton. Within the urban core, although 145 potential paths were generated, only 46 survived the low-resistance threshold. This drastic reduction reflects how urban sprawl has eroded natural conduits, leaving the internal network in a state of high structural fragility.

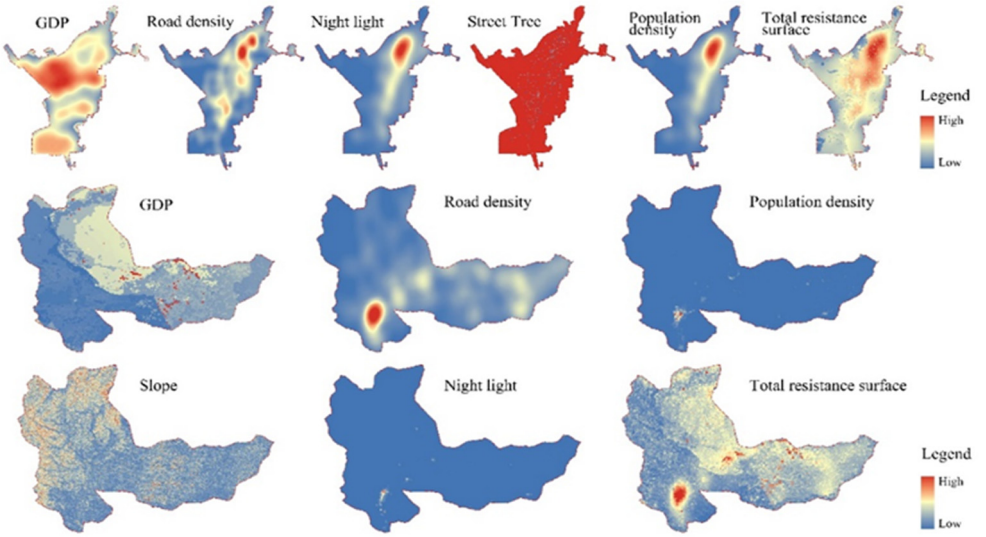


Fig. 3: The comprehensive resistance surface

3.3 Result of the Current Cross-Scale Connectivity

Further analysis revealed that within the municipal ecological network, a sub-network consisting of 10 nodes and 17 edges surrounds the built-up area. Moreover, this sub-network plays a crucial supporting role in the cross-scale connections of the ecological networks at both levels. Therefore, this study has isolated this sub-ecological network (with 15 edges) for analysis. The remaining parts make relatively weaker contributions to cross-scale connections and are thus not included in the following analysis.

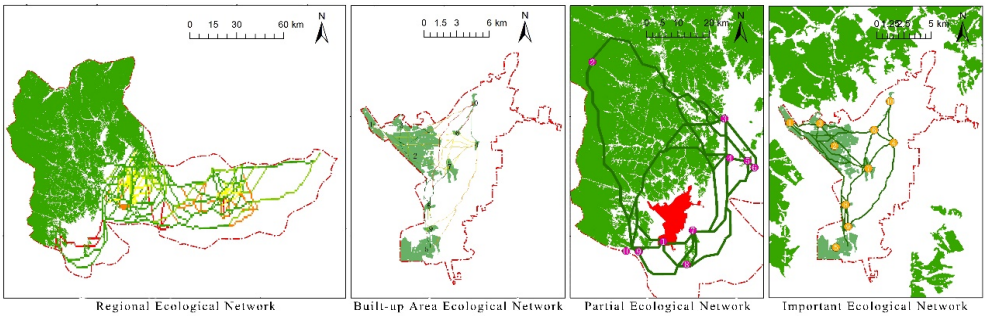


Fig. 4: The municipal ecological network

To clarify the key characteristics of the core elements of cross-scale connections in Hegang City, this study simplifies the ecological source areas and potential paths into a “node-edge” topological structure. It calculates the edge betweenness of 61 connection edges, and ultimately identifies 18 backbone paths and 7 newly formed nodes (Figure 5). Subsequently, the

newly formed nodes are combined with the ecological source points, and the node degree centrality is calculated (Figure 5). Moreover, using the natural discontinuity classification method of "minimum within-group difference and maximum between-group difference", it is divided into five levels (Figure 6).

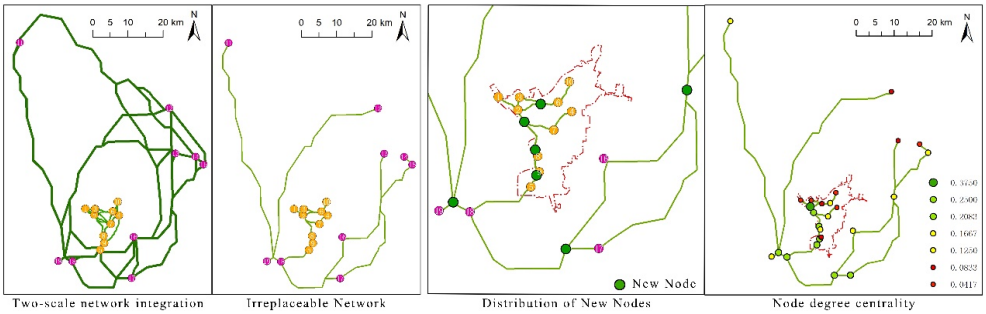


Fig. 5: The current cross-scale ecological network

The analysis of node degree centrality indicates that the most critical node is located on the west side of the built-up area (Node 2). Nodes with higher levels and higher degree centrality also mainly concentrate on the west side of the built-up area. Nodes with low degree centrality are mainly distributed at the network endpoints, and their connections with other nodes are weak, resulting in poor connectivity. Overall, the cross-scale connection paths with higher importance run north-south throughout the built-up area. Among them, the connection between nodes 5 and 18 in the southwest is a critical ecological node, and the backbone path connecting them serves as the primary cross-scale connection in the current situation.

3.4 Optimization of Cross-Scale Connectivity

Based on the diagnostic synthesis of topology and resistance, we propose a hierarchical intervention strategy (Figure 6):

1) The only cross-scale connecting backbone path between the two-tier ecological networks (2-5 path) needs to strengthen ecological restoration and protection efforts. Ensure that the ecological functions of the key structural nodes remain stable, prevent loss of ecological functions due to human construction interference, and prevent damage to the only connecting backbone path in the current situation.

2) There are three parallel backbone paths in the built-up area and the municipal area network, providing potential space for improving the connectivity between the networks. Among them, the 7th and 16th ecological sources are relatively close. The node centrality of both nodes is high, indicating a strong connection between them. If an ecological path is constructed to connect them, it can effectively improve the overall connectivity of the cross-scale network.

3) For the intersection points along the 19-11 and 5-17 corridors, targeted reforestation and "stepping-stone" habitats are required to boost the efficiency of material exchange across the network.

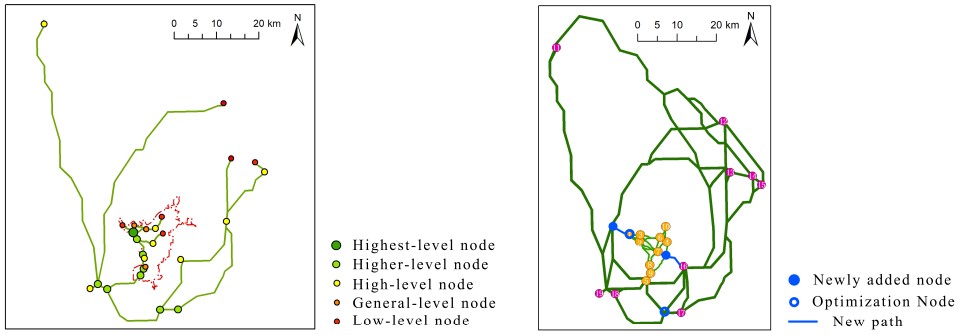


Fig. 6: Optimization plan of ecosystem network

4 Discussion

This study deepened understanding of the scale-transmission mechanism of ecological networks by constructing a systematic analytical process: "ecological source identification – resistance surface construction – cross-scale network integration – key node identification". The identified cross-scale connection key nodes, as spatial hubs guiding macroscopic ecological flows into built-up areas, have significant practical value for the precise restoration of ecological spaces in Hegang City through their priority control.

This study still has certain limitations: the weights of the resistance surface factors are determined by an expert scoring method, which is highly subjective; the analysis focuses on structural connectivity, and indicators reflecting functional connectivity, such as the transmission efficiency of ecological flows, are still insufficiently considered. Future research can introduce machine learning methods to optimize the weight distribution and conduct functional simulation and long-term monitoring verification in combination with the ecological requirements of typical species.

At the practical level, the system analysis framework proposed in this study not only provides scientific support for the ecological transformation of Hegang City but also serves as a reference for other resource-based and shrinking cities. Further work can further distinguish different types of ecological service functions, assess the controllability of each resistance factor, and then formulate more operational hierarchical restoration strategies.

5 Conclusion and Outlook

This study underscores that ecological resilience depends less on the total area of green space and more on the strategic integration of cross-scale paths. By synthesizing MSPA, MCR, and graph theory into a unified diagnostic framework, we have mapped the structural vulnerabilities that single-scale assessments often overlook.

The analysis confirms a stark spatial imbalance: while Hegang is buffered by robust municipal sources, its urban core remains ecologically isolated, tethered to the regional landscape by a precarious "single-path" backbone (Paths 2-5). The identification of Node 2 as a critical

"gatekeeper" provides a clear spatial priority for intervention. Our findings suggest that urban ecological planning must pivot from simple "greening" to "structural reinforcement" – specifically by safeguarding the identified western gateway and fostering redundant paths to mitigate the risk of network collapse.

Ultimately, this research transitions from a purely topological exercise to a practical planning tool. The "strengthening cores, adding paths, and cultivating nodes" strategy offers a scalable logic for other declining industrial or shrinking cities. While this integrated approach clarifies the "where" and "how" of restoration, future inquiries should further explore the dynamic influence of specific species' migration patterns on these resistance surfaces to refine the precision of these ecological linkages.

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