Postprint: Assessment of Ecological Network Structural Elements in Qingdao City Based on the CL-PIOP Method

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Abstract

The concept of ecological networks in landscape ecology has been increasingly accepted by institutions and scholars both domestically and internationally. Quantitative evaluation of ecological network structural elements constitutes a critical factor in determining whether ecological networks can effectively fulfill their function of spatially harmonizing ecological conservation and social development. Relevant evaluation indices from graph theory provide methodological frameworks for such quantitative assessment. This study investigates how to identify ecological network structural elements—including patches and corridors—that significantly influence regional ecological network connectivity, based on evaluation result data derived from graph theory. Employing Qingdao as the case study area, we constructed two types of ecological networks (wetland and forest) using the minimum cost path model, hierarchically classified these networks based on specific thresholds, adopted the CL-PIOP evaluation method from graph theory as our fundamental analytical approach, and proposed two evaluation criteria for ecological network structural elements to conduct in-depth analysis of the resultant data. The analysis results demonstrate that: CL-PIOP importance frequency statistics based on patches across different hierarchical ecological networks can effectively identify patches that play crucial roles in network connectivity, encompassing nearly all large-area patches while also incorporating a certain number of small-area patches; the CL-PIOP evaluation method can rapidly identify corridors with irreplaceable functions among numerous candidates, and further determine corridor importance levels based on CL-PIOP value magnitudes and frequency statistics of non-zero CL-PIOP values across various hierarchical networks. Moreover, patches exhibiting abnormally increased CL-PIOP values in different hierarchical networks, along with their associated corridors, play pivotal roles in network construction and connectivity enhancement; these patches are typically unrelated to intrinsic attributes such as area, but rather associated with their positions within the network. The integration of ecological network models and graph theory-related methods can efficiently and effectively identify regionally important ecological lands, providing quantitative foundations for the protection and restoration of ecological lands in relevant planning frameworks.

Full Text

Evaluation of the Structural Elements of Qingdao Ecological Network Based on the CL-PIOP Method

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Abstract

The concept of ecological networks in landscape ecology has been increasingly accepted by institutions and scholars worldwide. Quantitative evaluation of structural elements within ecological networks is critical for ensuring these networks can effectively reconcile nature conservation with socioeconomic development at the spatial scale. Graph theory provides methodological tools for such quantitative assessment through relevant evaluation indices.

Based on data evaluated using graph theory indices, this study identifies patches and corridors that significantly influence regional ecological network connectivity. Taking Qingdao as a case study, we constructed wetland and woodland ecological networks using the least-cost path model and classified these networks into hierarchical levels based on specific thresholds. Using graph theory evaluation methods as the foundation, we proposed two standards for analyzing the structural elements of both ecological networks. Statistical analysis of importance frequency can effectively identify patches crucial for network connectivity. Standard I primarily encompasses large patches across different network levels, while also including certain small patches.

By analyzing the magnitude of CL-PIOP values and the frequency of nonzero values across network levels, we further determined corridor importance. Patches exhibiting anomalously large CL-PIOP values and their associated corridors play key roles in network construction and connectivity enhancement. The importance of these patches is typically unrelated to their intrinsic attributes such as area, but rather to their position within the network structure. Integrating ecological network models with graph theory methods enables rapid and effective identification of regionally important ecological lands. The CL-PIOP evaluation method can quickly identify corridors with irreplaceable functions among numerous alternatives.

Keywords: woodland ecological network; wetland ecological network; correlation length; PIOP; Qingdao City

1. Introduction

Habitat fragmentation represents one of the two major problems arising from human land use, manifested as reduced natural habitat area and weakened connections between habitats, which limits opportunities for species dispersal, migration, and genetic exchange, thereby increasing ecosystem vulnerability. China is experiencing an unprecedented period of rapid urbanization, with urban permanent population reaching 54.77% in 2014. The urbanization process will continue at a high rate, generating substantial demand for land resources. Against this backdrop of large populations and limited land, ensuring necessary land for urban development while minimizing ecosystem damage is critical.

The ecological network concept in landscape ecology, which describes the spatial organization of habitats under fragmented conditions, has been accepted by an increasing number of institutions and scholars worldwide. Due to the networked connections among structural elements in ecological networks, the disappearance of individual components does not alter the overall function of regional ecosystems, providing flexibility in spatial structure and adjustment. This characteristic offers possibilities for reconciling spatial conflicts between ecological protection and socioeconomic development accompanying rapid urbanization. Research and practice on ecological networks have been conducted at various spatial scales across countries and regions. Compared with nature reserves, ecological networks emphasize connectivity between ecological lands. Graph theory provides effective methods for quantitatively evaluating ecological network connectivity, with numerous scholars proposing corresponding evaluation indices and software tools. These indices reflect the importance of ecological network structural elements in maintaining connectivity and integrity from different perspectives.

Based on graph theory indices, scholars have evaluated ecological network elements, employing methods such as betweenness, Pajek indices, and other approaches to calculate significant network components. Existing indices can answer questions about element importance within a single ecological network framework. However, different ecosystem protection objectives may result in different hierarchical levels of ecological networks within the same region. Structural elements playing important roles in transitions between network levels can make conservation efforts more efficient. Previous research has tended to focus on patch evaluation, with less explicit attention to corridor importance.

This study takes Qingdao, an economically developed coastal city in eastern China, as the research area. Using the least-cost path model, we constructed ecological networks for two major ecosystems (wetland and woodland) in the region. Based on correlation length indices from graph theory and the CL-PIOP method, we evaluated structural elements of both ecological networks through in-depth data analysis. The study addresses three questions: (1) How to identify network patches that play important roles in maintaining and enhancing ecological network connectivity? (2) How to determine patches that serve critical functions in network level transitions? (3) Which corridors play irreplaceable roles in connecting these two types of important patches?

2. Study Area and Data Sources

2.1 Study Area

Qingdao is located at the southern tip of the Shandong Peninsula (35°35 -37°09 N, 119°30 -121°00 E), bordering Rizhao City to the southwest and Weifang City to the west. Situated at the intersection of marine and terrestrial ecosystems, Qingdao’ s ecological environment is extremely fragile, susceptible to external disturbance and difficult to restore.

2.2 Data Sources

Data used in this study include: remote sensing imagery data, land use data for 2014 from the land cover remote sensing survey and monitoring database, and 30m-resolution Digital Elevation Model (DEM) data provided by the International Scientific Data Mirror Site of the Computer Network Information Center of the Chinese Academy of Sciences. Land use data were processed using ERDAS software, with relevant data generated through ARCGIS software.

3. Methods

3.1 Construction and Hierarchical Classification of Ecological Networks

The least-cost path (LCP) model can construct regional ecological networks even when data availability is limited. Since network construction is not the focus of this paper, we followed established research protocols, introducing surrogate species based on relevant species analysis and obtaining landscape cost values through expert scoring to generate cost surfaces. Ecological networks of different levels were formed by patches and corridors with different distance thresholds, corresponding to networks suitable for species with different dispersal abilities. The implementation was developed on the Microsoft Visual Studio.Net platform based on ARCGIS.

3.2 Selection of Evaluation Indices

We selected correlation length (CL) as the fundamental evaluation index. This index calculates the average distance species move when reaching the boundaries of accessible patches within their dispersal capacity, and is used to measure the connectivity of ecological networks. Larger CL values indicate stronger connectivity and tighter network connections. The index is defined as:

$$C = \sum_{i=1}^{m} n_i R_i$$

where m represents the number of patches in a patch set, n_i represents the number of pixels covered by patches in set i, and R_i represents the radius of gyration of patch set i:

$$R_i = \sqrt{\frac{\sum_{j=1}^{n_i}[(x_j - x_i)^2 + (y_j - y_i)^2]}{n_i}}$$

where x_j and y_j represent the horizontal and vertical coordinates of the jth patch pixel in patch set i, and x_i and y_i represent the average horizontal and vertical coordinates of all pixels in patch set i.

3.3 Evaluation of Importance of Ecological Network Structural Elements

Ecological network structural elements include ecological network patches (hereinafter "patches") and ecological network corridors (hereinafter "corridors").

3.3.1 CL-PIOP Method

The Percentage of Importance of Omitted Patches (PIOP) method evaluates the importance of each structural element in ecological network connectivity. The evaluation approach involves: removing each patch and its connected corridors from the network, calculating the CL value of the new network, and comparing it with the CL value of the original complete network to obtain the importance of each patch in the network. Since this study uses the CL index, this evaluation method is hereinafter referred to as CL-PIOP:

$$IC_k = \frac{C - C_k}{C}$$

where IC_k represents the importance value of patch k, C represents the CL value of the complete network, and C_k represents the CL value after removing patch k.

3.3.2 Two Standards for Evaluating Patch or Corridor Importance

This paper proposes two standards for evaluating the importance of patches or corridors:

Standard I: The CL-PIOP value itself can reflect the importance of each patch or corridor in the current level of ecological network. Analyzing CL-PIOP values is currently the mainstream approach for understanding patch and corridor importance based on graph theory evaluation indices. By statistically analyzing the frequency with which elements function above average across different network levels (hereinafter “importance frequency”), we can further evaluate the importance of core patches. If a patch’ s importance exceeds the patch average across all network levels, it indicates these patches are significant for species persistence with various dispersal abilities.

Standard II: Based on corridor length and distance thresholds, we obtained a series of ecological networks at different levels. By comparing CL-PIOP values of the same patch across different network levels, we can observe that patch importance varies with different network structures. By analyzing patches with anomalously large CL-PIOP values in ecological network n—which connect two sub-networks not previously connected in network $n-1$—we can identify critical patches. The corridors newly connected to these patches in network n also play important roles. Therefore, patches with anomalously large CL-PIOP values and their related corridors deserve sufficient attention. Standard II identifies patches with anomalously large CL-PIOP values at certain levels and the newly added corridors connected to them at that level. Based on these corridors’ CL-PIOP values and their irreplaceability (higher irreplaceability means higher importance), we can identify important corridors.

4. Results

4.1 Ecological Networks at Different Connectivity Thresholds

For the wetland ecological network, using rivers, lakes, and marsh beaches as wetland patches with 2000 as the interval threshold, we obtained networks at levels···

For the woodland ecological network, using mixed forests as woodland patches with 2000 as the interval threshold, we obtained networks at levels···

4.2 Importance of Patches and Corridors Within the Ecological Network Framework

4.2.1 Important Patches Based on Standard I

Using the average CL-PIOP value of patches at each level as the screening criterion for importance, we identified important patches. In the woodland ecological network, there were···In the wetland ecological network, there were···

4.2.2 Important Corridors Based on Standard I

A corridor whose removal changes the ecological network structure is an irreplaceable corridor. The magnitude of its CL-PIOP value indicates the degree of its irreplaceable function in the network.

4.2.3 Important Patches Based on Standard II

Using the exploratory tool for descriptive statistics in SPSS 17.0 software, we identified patches with anomalously large values based on boxplots of CL-PIOP values at each level.

4.2.4 Important Corridors Based on Standard II

Irreplaceable corridors connected to important patches in the new level network become important corridors.

4.3 Comparative Analysis of Results

The importance frequency of wetland patches did not show consistent characteristics with area ranking across network levels. While the general trend was somewhat consistent, numerous patches showed mismatches between importance and area ranking. Woodland patches showed more consistent trends between importance frequency and area ranking across levels, though many patches still displayed discrepancies.

Standard I identification of important patches included nearly all top-ranked area patches, suggesting this method can replace previous area-only evaluation approaches. However, the importance ranking based on CL-PIOP was not entirely consistent with area ranking, indicating that area cannot be the sole criterion for evaluating ecological land importance in regional ecosystem maintenance. Some small patches play significant roles.

Standard II substantially filtered patches. When comparing areas, we used the ratio of patch area to the largest patch area in the network. Among the selected important patches, the largest was only 3.9% of the network' s maximum patch area, with no clear relationship between importance frequency ranking and area ranking.

5. Discussion and Conclusion

Ecological networks represent the objective ecological space where regional ecosystems interconnect. The purpose of ecological network analysis is to enhance structural and functional connections between fragmented, isolated natural habitats through targeted measures, thereby promoting material and information flow and maintaining regional ecosystem stability.

In ecological network modeling, corridor selection is based on thresholds representing different species dispersal and migration abilities. Due to difficulties in ecological data collection, this threshold is often hard to determine in practice. Hierarchical classification can represent different conservation needs, making the threshold concept a relative ratio that solves the problem of unit determination. This also provides guidance for prioritized ecological land planning and protection.

Using the average CL-PIOP value across network levels as the criterion for identifying important patches (Standard I) includes nearly all top-ranked area patches. From this perspective, the method can replace previous area-only approaches. However, area cannot be the sole standard for evaluating ecological land importance, as some small patches play crucial roles. Standard I improves upon methods using area or single attributes as the only importance criteria.

Standard II can quickly and accurately identify patches and corridors with irreplaceable functions. By comparing CL-PIOP values across adjacent network levels to detect anomalous changes, we can identify key patches that play important roles in network level transitions. By locating corridors connected to these patches with non-zero CL-PIOP values, we can further determine critical corridors. These key patches may not be prominent initially (e.g., small area), and their connecting corridors may be hidden among thousands of similar corridors, making them difficult to identify through conventional methods. This approach is beneficial for discovering small but functionally important patches, emphasizing the significant role patches play in overall network connectivity—a focus gaining increasing attention in current research.

Both wetland and woodland networks showed clear correlations between importance frequency and area under Standard I. However, compared with the woodland network, the wetland network showed more pronounced positive correlation between importance frequency and area under Standard I, and between Standard II importance and Standard I importance. This occurs because woodland patches are denser than wetland patches, with more complex interconnections that dilute the advantage conferred by area alone. For regions with lower ecological land spatial density, network element evaluation should place greater emphasis on protecting large patches.

Our method still has limitations. The widely used least-cost path method involves significant subjectivity in species selection, resistance value assignment, and threshold determination for different network levels. If an area contains numerous ecological network structural elements, computational efficiency may require improvement, perhaps through graph theory-based ecological network construction. Future research should address these issues.

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Figure Captions

Wetland ecological network in the study area (examples of ecological networks with connectivity strength of 5000, 12000, and 20000)

Woodland ecological network in the study area (examples of ecological networks with connectivity strength of 5000, 12000, and 20000)

Important patches and corridors in wetland ecological networks based on Standard I

[FIGURE:4] Important patches and corridors in woodland ecological networks based on Standard I

Patches with anomalously large CL-PIOP values in wetland ecological networks

Patches with anomalously large CL-PIOP values in woodland ecological networks

Important patches and corridors in wetland ecological networks based on Standard II

Important patches and corridors in woodland ecological networks based on Standard II

[FIGURE:9] Distribution of patch importance frequency based on patch area ranking in wetland ecological networks (Standard I)

[FIGURE:10] Distribution of patch importance frequency based on patch area ranking in woodland ecological networks (Standard I)

[FIGURE:11] Distribution of patch importance frequency based on patch area ranking in wetland ecological networks (Standard II)

[FIGURE:12] Distribution of patch importance frequency based on patch area ranking in woodland ecological networks (Standard II)

[FIGURE:13] Comparison of important patches in wetland ecological network based on Standard I and Standard II

[FIGURE:14] Comparison of important patches in woodland ecological network based on Standard I and Standard II

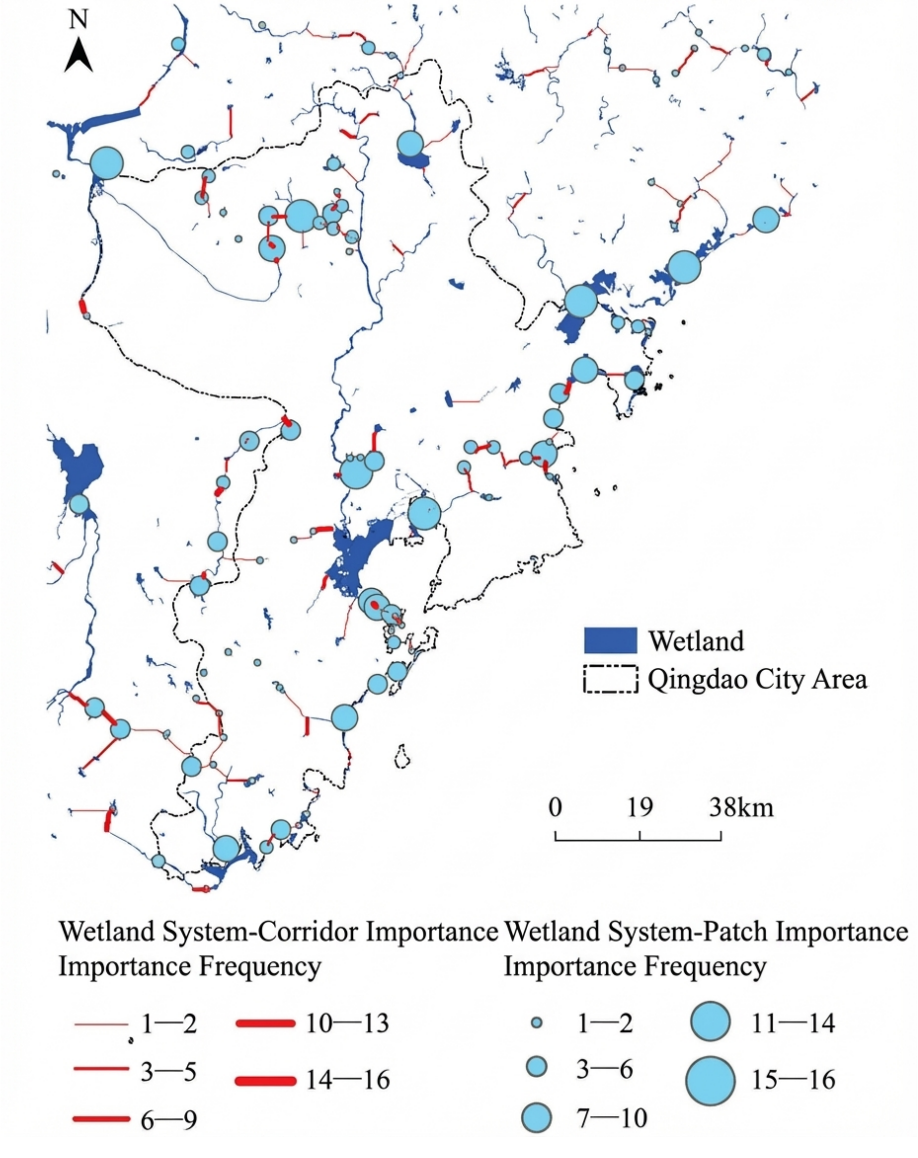


Figure 1: Figure 1

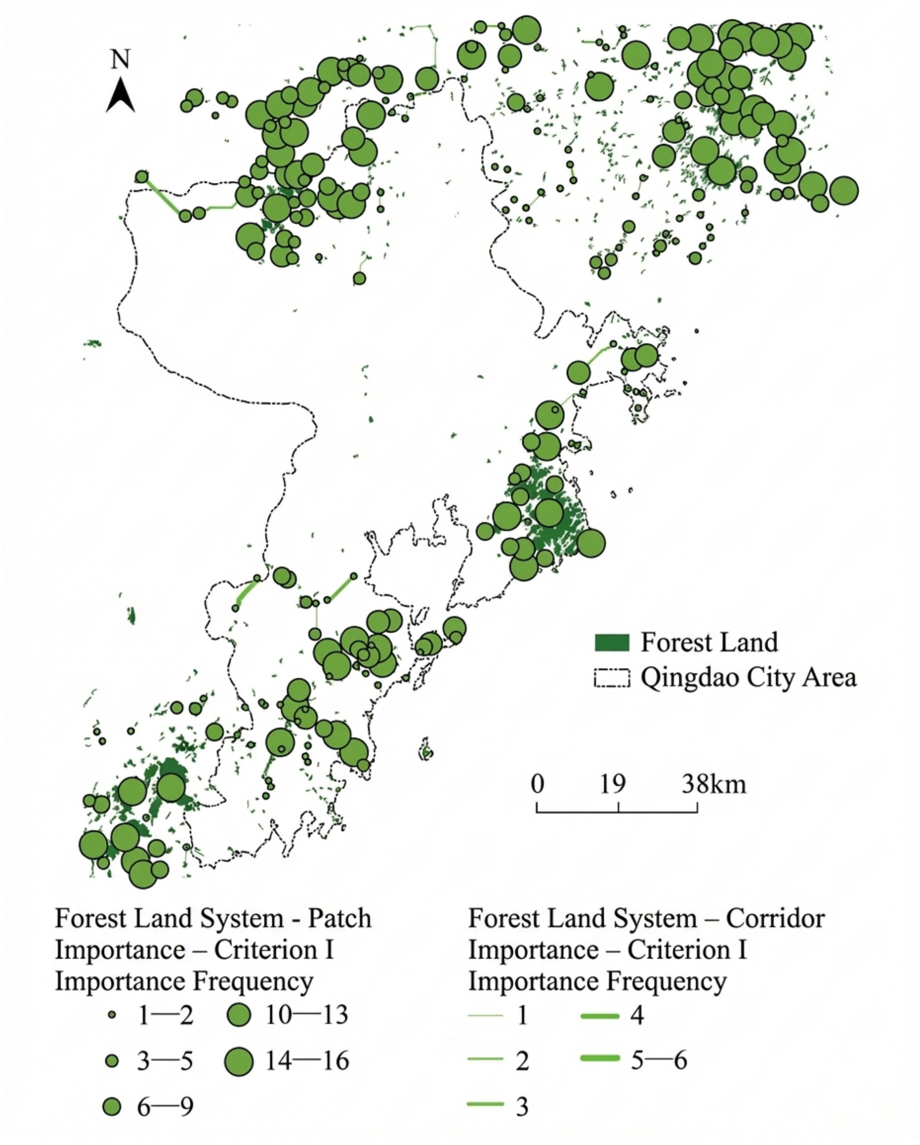
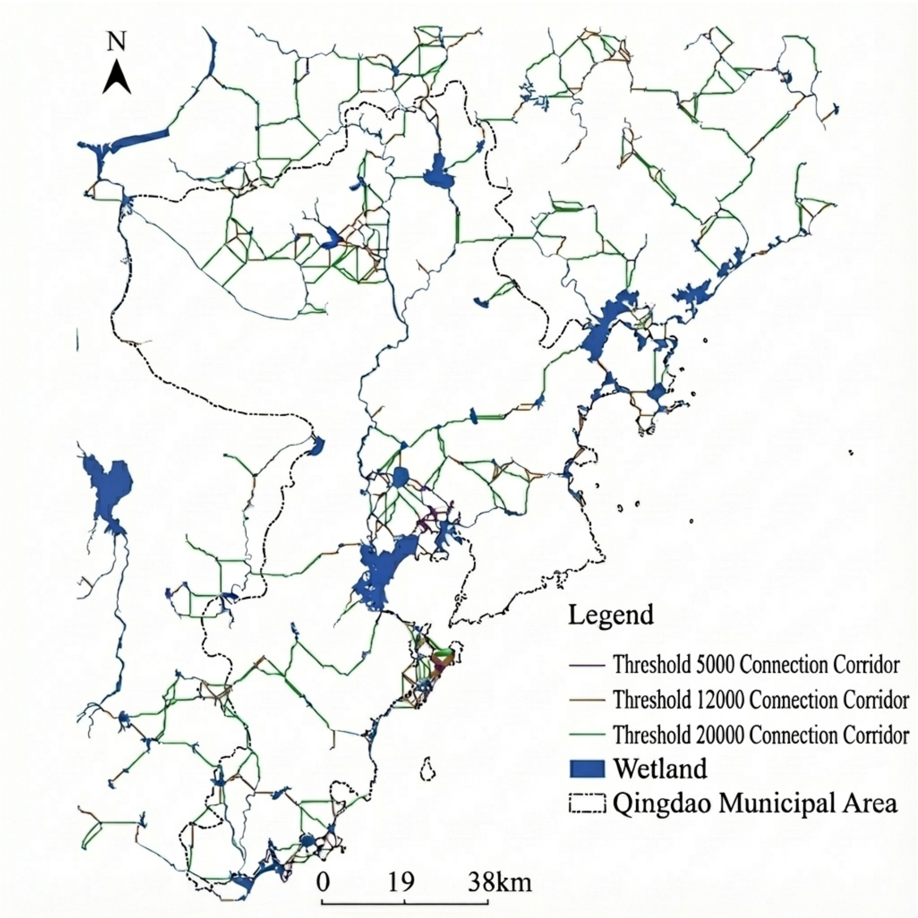


Figure 2: Figure 2



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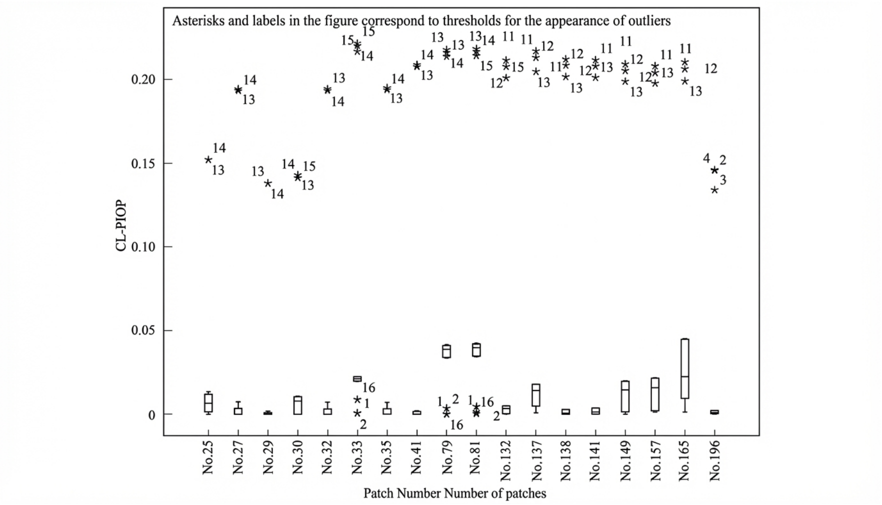

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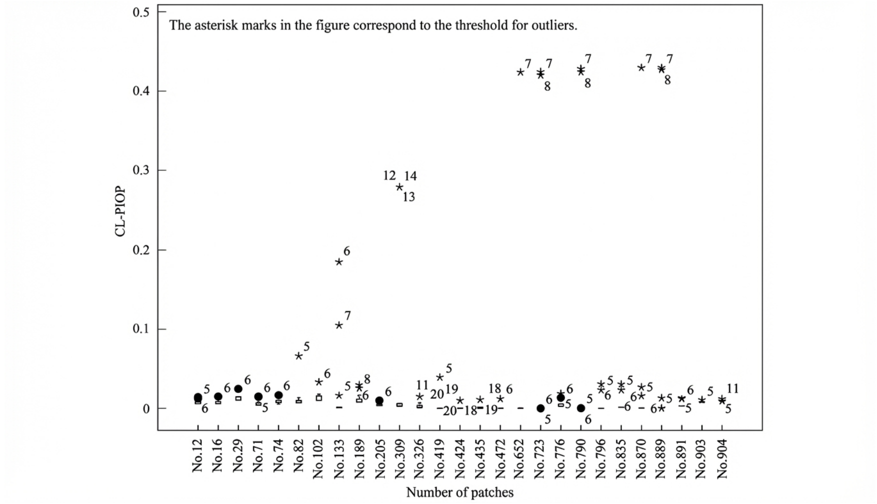

Figure 5: Figure 6

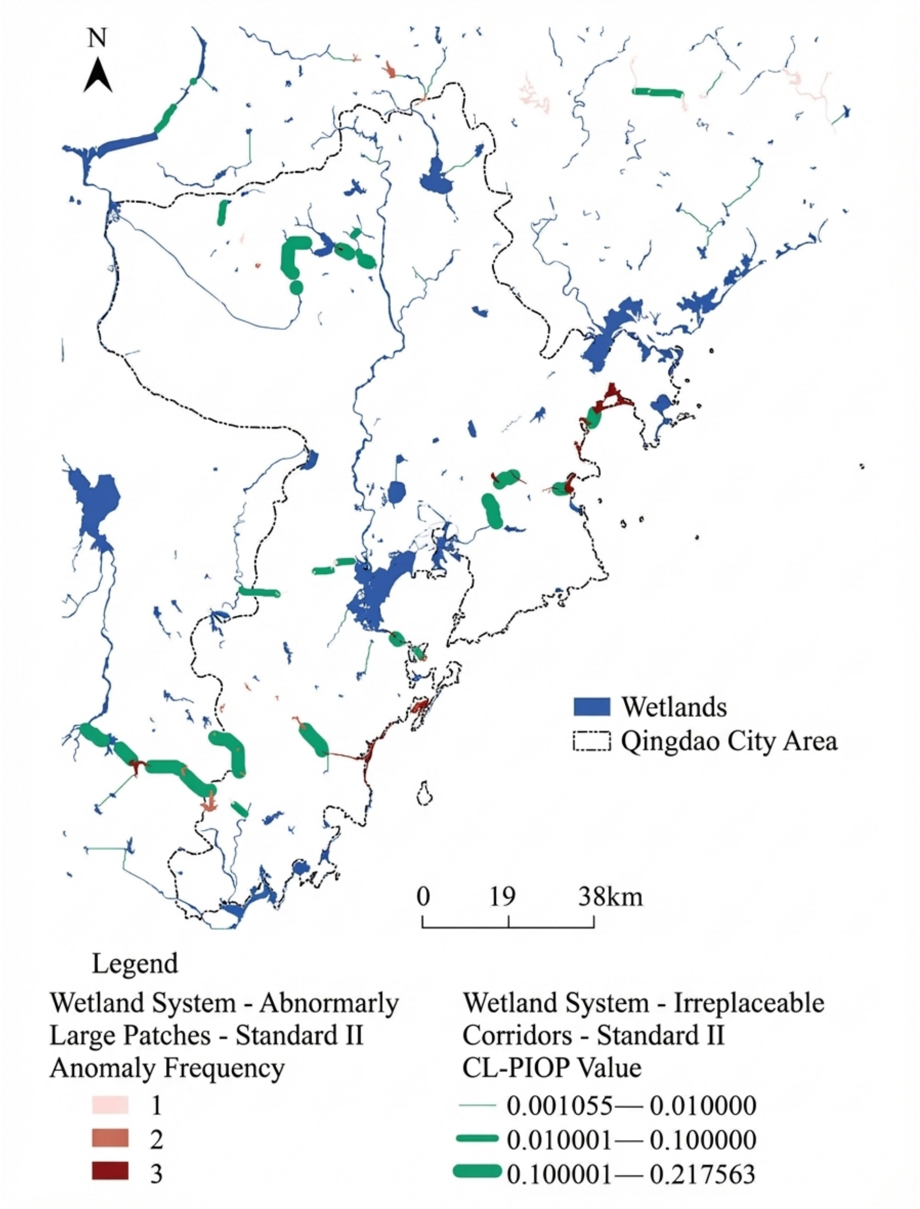

Figure 6: Figure 7

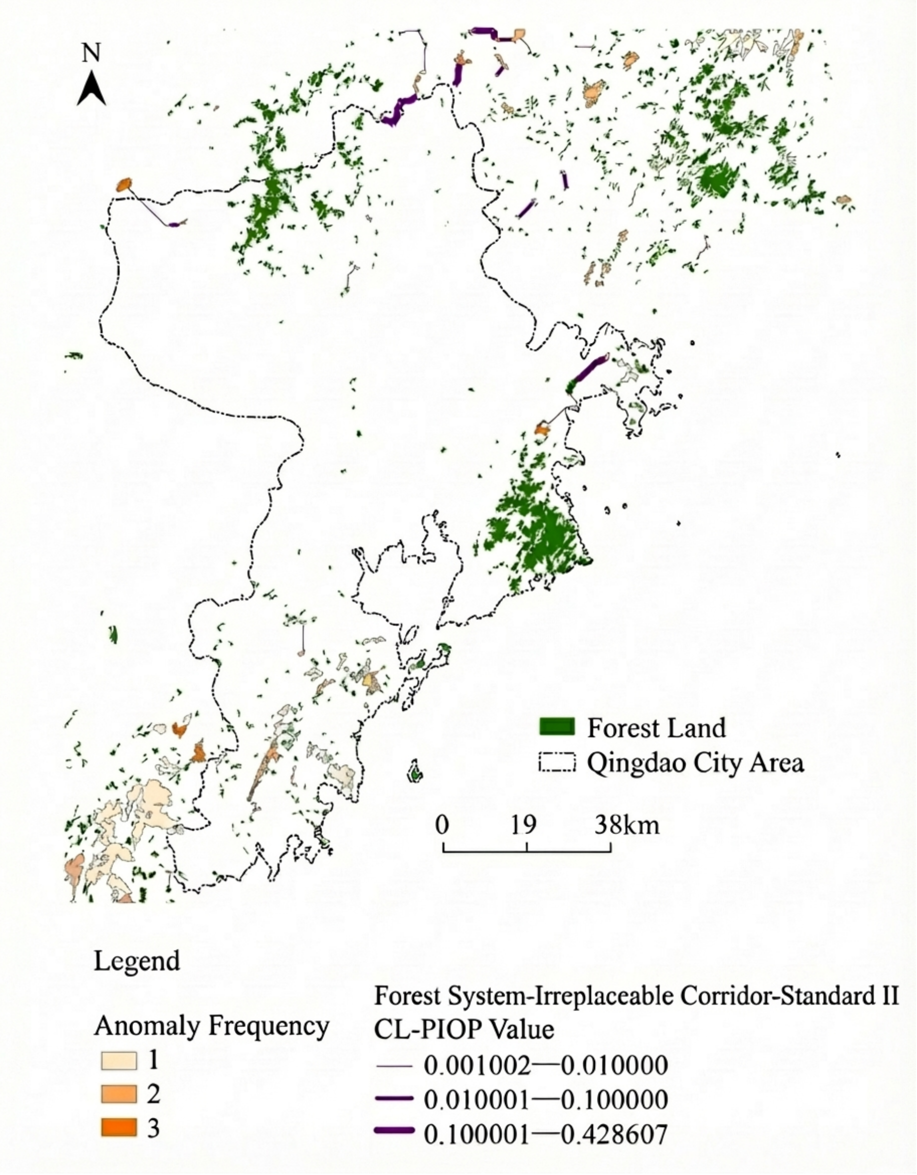

Figure 7: Figure 8