

Original Articles

Sustainability-based evolution of port hinterlands: green performance and spatial impacts in the Bohai Rim

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ABSTRACT

Global net-zero targets are reshaping port clusters toward greener and more coordinated development. However, the performance and hinterland influence of hub ports from a sustainability perspective remain underexplored. The Bohai Rim, with its high port density and early green transition efforts, offers a representative case for studying spatiotemporal hinterland evolution in this context. This study uses panel data from six major container ports over the period 2011–2023 to build a multidimensional sustainability indicator system that includes carbon emissions and sea-rail intermodal throughput. The sustainability scores are first applied in a Wilson model to estimate general port influence, and then integrated with OD-cost distance in a field strength model to delineate county-level hinterland patterns. The results show that port hinterlands generally expanded during the study period, with increased overlap, stronger connectivity, and more intense regional competition. Qingdao and Tianjin evolved into dual spatial cores, and Rizhao accelerated inland expansion via multimodal transport. In contrast, Dalian and Yingkou showed limited hinterland growth and constrained spatial influence. This study proposes a transferable integrated framework for sustainability-based hinterland analysis, offering cross-port and cross-regional applicability to support planning and policymaking under green development goals.

1. Introduction

Port sustainability has become a pressing concern under stricter environmental regulations and rising decarbonization targets (Guo et al., 2022). In China, the Bohai Rim port cluster plays a strategic role in advancing regional programs such as the Northeast Revitalization and the Beijing-Tianjin-Hebei integration (Liu et al., 2025; Zhao et al., 2024). However, this region faces growing challenges, including inefficient inland transport, rapid hinterland expansion, and increasing environmental pressure (Li et al., 2020; Song et al., 2020; UNCTAD, 2021). Green port development has increasingly emphasized emissions control, modal shift, clean energy use, and ecological protection (Acciaro, 2015; Bergqvist and Monios, 2019). Among green transport strategies, sea-rail intermodal transport is considered effective in reducing emissions and easing road congestion. These practices are likely to influence the spatial structure of port hinterlands, especially by improving inland accessibility (Huang et al., 2023; Notteboom et al., 2020).

Measurement of hinterland evolution under green development

requires spatial models that capture changes in extent and connectivity. Existing research on sustainable ports has largely developed along two main directions. The first examines green port performance through multi-indicator evaluation systems, with methods such as Data Envelopment Analysis (DEA) and Analytic Hierarchy Process (AHP) (Bhatti and Hanjra, 2019; Park et al., 2019). Although these methods consider both economic and environmental performance, they often fail to adequately address ecological indicators such as port carbon emissions and sea-rail intermodal throughput (Chen et al., 2025; Zhang et al., 2022a). Subjective weighting is also prevalent, introducing potential bias (Guo et al., 2015). The second direction focuses on modeling the spatial extent of port hinterlands. The Wilson model remains popular for estimating hinterland boundaries due to its ability to capture distance decay (Chen and Di, 2023). However, it assumes spatial homogeneity, which limits its capacity to reflect diverse transport conditions. GIS-based field strength models incorporating OD-based accessibility offer certain improvements (Wu et al., 2020), yet they are seldom combined with sustainability metrics. As a result, current frameworks tend to be either too localized—focusing on terminal technologies—or too

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abstract—overlooking regional logistics dynamics. Integrating sustainability indicators into hinterland modeling remains uncommon, leaving a critical gap in linking environmental performance with spatial port analysis.

To address these challenges, this study investigates how green development reshapes the spatial influence of major ports in the Bohai Rim. A multi-dimensional evaluation system is constructed to measure port sustainability, covering economic performance, infrastructure, transportation, and environmental impact. Composite sustainability scores are calculated through an integrated weighting scheme combining Entropy Weight Method (EWM), Criteria Importance Through Intercriteria Correlation (CRITIC), and principal component analysis (PCA), followed by TOPSIS method. Based on sustainability scores, the number of influential ports, and the average spatial extent of the port-hosting cities, the Wilson model is used to estimate each port's rough hinterland coverage. OD cost distances are then calculated and combined with sustainability scores in a field strength model to refine the hinterland at the county level for each major port in the Bohai Rim.

We find that the spatial influence of port hinterlands, particularly in terms of their size and connectivity, is increasingly shaped by green development strategies. Ports with higher sustainability scores demonstrate a broader and deeper hinterland influence. The empirical results suggest that port hinterlands in the Bohai Rim have expanded and overlapped over time, with key regional ports such as Qingdao and Tianjin emerging as dominant cores. In contrast, other ports such as Dalian and Yingkou have experienced slower growth, highlighting the differential impact of green development policies and infrastructure investments.

The study builds a framework for assessing the spatial influence of port clusters from a sustainability perspective, with three main contributions. First, it develops a multi-dimensional port sustainability evaluation system that includes two key indicators, port carbon emissions and sea-rail intermodal throughput. Second, a dual-scale hinterland delineation method is proposed, combining the Wilson model for macro-level boundary estimation with a field strength model integrating sustainability and accessibility for fine-grained spatial refinement. Third, the framework is broadly applicable across different ports and regions. It helps analyze how green development shapes hinterland structures over time and offers practical guidance for low-carbon planning, regional coordination, and sustainable transport policies for port clusters.

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature. Section 3 introduces the methodology. Section 4 presents the main empirical results. Section 5 discusses the main findings and offers policy recommendations and Section 6 concludes the study.

2. Literature review

Port sustainability has become one of the central critical issues in the global maritime industry's transition to a greener future, receiving increasing scholarly and policy attention (Alamouh et al., 2021). Port development should not only stimulate economic growth within port areas but also align with environmental sustainability objectives (Fahimnia et al., 2015; Platias et al., 2025). Traditionally, port studies have focused on economic indicators, including cargo throughput, container handling capacity, berth occupancy, and equipment utilization rates (Asgari et al., 2015). These metrics are direct measures of operational efficiency and economic vitality, forming the basis for short-term planning and resource allocation (Notteboom and Haralambides, 2020). However, in recent years, sustainability metrics have been progressively incorporated into port evaluation frameworks (Liu et al., 2021). Among the emerging sustainability indicators, carbon emissions have gained significant attention as a direct measure of greenhouse gas output during port operations, providing crucial insights into environmental performance (Chakrabarty, 2024; Vitiello et al., 2024; Zeng et al., 2023). Sea-rail intermodal throughput reflects the integration

efficiency between ports and railway networks, a vital element of sustainable multimodal freight systems (Bouchery and Fransoo, 2015). Notably, improved sea-rail interconnectivity enhances logistics efficiency while significantly reducing carbon emissions, making it an essential component in assessing port sustainability (Huang et al., 2023; Li et al., 2024a).

While the inclusion of carbon emissions and sea-rail throughput marks a shift toward a more integrated, multidimensional evaluation framework, many traditional evaluations still overly rely on either economic or environmental indicators in isolation, inadequately capturing the full scope of port sustainability. In contrast, the proposed green index, integrating these key environmental indicators, provides a more comprehensive measure of port performance by addressing the economic, environmental, and logistical dimensions simultaneously. This multidimensional framework is essential in steering ports toward a low-carbon, environmentally responsible, and highly efficient development path.

In the assessment of port development, selecting appropriate methods for determining indicator weights constitutes a critical component in the construction of comprehensive evaluation frameworks. Methodologies for weight determination are broadly categorized into single-weight and hybrid-weight approaches. Single-weight methods encompass either subjective or objective techniques.

Subjective weighting methodologies, exemplified by the AHP and the Delphi method, rely fundamentally on expert judgment (Asgari et al., 2015; Bhatti and Hanjra, 2019; Feng et al., 2020; Zhang et al., 2022b), but they exhibit a high degree of subjectivity in determining indicator weights, which can potentially lead to biased outcomes (Georgoulas et al., 2023). Conversely, objective weighting methods are data-driven. In port evaluation, PCA reduces dimensionality by identifying principal components that retain most of the information embedded in the original indicators (Abbes, 2015; Cao et al., 2016). The EWM is highly regarded for its ability to reduce subjectivity in the weighting process, making it particularly useful when dealing with large datasets and ensuring a more objective evaluation of port sustainability (Chen, 2022; He et al., 2016; Liu et al., 2023; Ren, 2020). The CRITIC method, considering both data contrast and intercorrelation between indicators to identify the most informative and independent criteria (Akyol Özcan, 2023; Du et al., 2024). The TOPSIS approach ranks alternatives based on their proximity to ideal and negative-ideal solutions, providing a comprehensive framework for multi-criteria decision-making; additionally, it has been extensively applied in numerous port development studies for comprehensive performance evaluations covering environmental, economic, and operational factors (Lang et al., 2023; Lu et al., 2010; Madanchian and Taherdoost, 2023; Yang et al., 2022).

Despite their respective merits, single-weight methods often face limitations stemming from either subjective biases or dependence on specific data characteristics. This has motivated a growing adoption of hybrid weighting approaches, which integrate subjective and objective techniques to enhance the robustness and scientific validity of assessments. For example, some studies combine AHP with objective methods such as Evidential Reasoning (ER), Grey Relational Analysis, or Fuzzy Comprehensive Evaluation to assess port sustainability (Akyol Özcan, 2023; Hua et al., 2020; Wan et al., 2018; Yang et al., 2022; Yang, 2015).

Furthermore, DEA, a non-parametric linear programming technique used for evaluating the relative efficiency of multi-input-multi-output decision-making units, has seen widespread application in port performance assessments (Chang, 2013; Chang and Park, 2016; Dong et al., 2019; Wang et al., 2020). A key limitation of DEA, however, is its inability to ascertain whether observed operational levels represent genuinely optimal performance (Wang and Wu, 2017).

In port development evaluations, the reliance on single-weighting methods restricts the adaptability of assessment models to the complex realities of port operations. Consequently, integrated weighting techniques are increasingly adopted, it enhances the scientific rigor of

evaluations and offers a more holistic view of port development (Chen, 2021; Gök-Kısa et al., 2021; Liu et al., 2022a; Özcan, 2023).

Accurate delineation of port hinterlands is crucial for assessing the economic impact of ports and regional development (Gattuso and Casone, 2020). Field strength models have been widely used for hinterland delineation due to their ability to evaluate the spatial influence of ports based on their size, economic strength, and distance-related friction factors (Ba et al., 2023; Li et al., 2022). However, one of the limitations of this approach is its lack of consideration for spatial distance in the context of regional heterogeneity. This shortcoming has prompted subsequent studies to integrate Geographic Information Systems (GIS) and OD cost matrix analysis, which factor in spatial variability by incorporating actual travel distances and times (Limbourg and Jourquin, 2010; Zhuang and Yu, 2014). These improvements have significantly enhanced the precision of hinterland boundary definition by accounting for the physical geography and transportation accessibility (Cao et al., 2016; Thill and Venkatasubramanian, 2015; Zhuang and Yu, 2014).

However, the integration of spatial analysis and field strength models still faces restrictions in breaking through regional boundaries, often limiting spatial analysis to predefined zones to calculate port hinterlands (Zhuang et al., 2017). While this improves accuracy within the boundaries, it does not fully capture the broader, regional economic interdependencies that shape hinterland dynamics (Wang, 2022). To overcome this limitation, the Wilson model—a foundational spatial interaction framework—has emerged as a solution, effectively combining origin-destination attributes with impedance factors (Chen et al., 2017). The Wilson model provides a more flexible delineation by estimating the hinterland radius and offering a broader scope of port influence, which extends beyond administrative boundaries (Deng, 2010).

Current port hinterland delineation studies often focus on predefined, localized regions, with less attention given to a broader, macro-level assessment of port influence (Cao et al., 2016; Zhuang et al., 2017). Additionally, the integration of sustainability factors into hinterland delineation remains limited, despite its growing importance in assessing ports' environmental and economic performance. Few studies incorporate sustainability dimensions, which are crucial for understanding the long-term impacts of port development on regional ecosystems and economies.

To address the existing gaps in port hinterland research, this study introduces several key methodological innovations. First, it enhances the port sustainability evaluation framework by incorporating green indicators, specifically port-related carbon emissions and sea-rail intermodal throughput, into a comprehensive multi-dimensional index system. This integration is supported by a hybrid approach combining EWM, CRITIC, and PCA methods, alongside the TOPSIS model, which allows for an objective and systematic assessment of port sustainability levels. Second, the Wilson model is employed to estimate each port's initial hinterland radius, establishing the spatial scope of the study. Building on this foundation, an OD cost-based accessibility analysis is performed to evaluate the overland transport connectivity between ports and their hinterlands. Finally, the port sustainability scores and OD cost accessibility analysis are integrated into a field strength model, which provides a more accurate delineation of the port's direct hinterland from a sustainability perspective, while also accounting for spatial factors.

Accordingly, this study not only deepens the theoretical understanding of port sustainability but also contributes to the delineation of port hinterlands under varying sustainability levels, providing practical insights for coordinated port development and policymaking in the Bohai Bay region.

3. Research model

3.1. Research framework

This study assesses port sustainability levels and analyzes the spatiotemporal evolution of hinterland areas through a multi-stage framework (Fig. 1). Initially, a multidimensional port sustainability evaluation index is developed, combining EWM, CRITIC, and PCA methods with the TOPSIS model to calculate sustainability scores, overcoming the limitations of single-method approaches. These scores are then integrated with the Wilson model to preliminarily delineate the radius of port hinterlands and identify county-level areas for further analysis. Following the identification of hinterland regions, the OD cost matrix model is applied to compute port land accessibility from a spatial perspective. Finally, sustainability scores and land accessibility are integrated into an enhanced field strength model to determine hinterland field strength. By employing the maximum membership principle, the direct hinterlands are identified, and their evolution is systematically analyzed.

This multi-stage framework offers a comprehensive analysis of port hinterland evolution from a sustainability perspective, addressing the dynamics of spatial changes across regional scales. It combines a macro-micro viewpoint, conducting both a broad-scale estimation of port hinterland scope and a detailed, spatially focused investigation of direct hinterlands. This methodology overcomes the spatial analysis limitations of traditional studies, offering a more accurate and dynamic understanding of hinterland evolution in the context of port sustainability. The approach is broadly applicable for studying the spatiotemporal dynamics of hinterlands across various ports.

3.2. EWM-CRITIC-PCA model

This study integrates three objective weighting methods—EWM, CRITIC, and PCA—to calculate the comprehensive weights for port sustainability indicators, ensuring a data-driven, robust, and unbiased weighting process (Tan and Lu, 2015; Yin et al., 2021a). The detailed computational formulas are provided in Appendix B of the Supplementary Material. To eliminate scale effects and enhance comparability across indicators, all data (x_{ij}) are standardized before the weighting process (Wang et al., 2024). The standardization procedure is as follows:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \text{ (Positive indicator)} \quad (1)$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \text{ (Negative indicator)} \quad (2)$$

where x_{ij} represents the original value of indicator j for observation i , and x_j denotes the dataset for indicator j . This normalization step ensures that all indicators are on a comparable scale, facilitating a fair evaluation.

3.2.1. EWM model

The EWM is first applied to assess the information level in each sustainability indicator. By calculating the entropy value, we quantify the degree of uncertainty or randomness in the data (Qian et al., 2023). A lower entropy value indicates that the indicator provides more information for distinguishing sustainability performance levels. The entropy value e_j for indicator j is given by Lu et al. (Lu et al., 2022):

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^n \left(\frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \right) \ln \left(\frac{x'_{ij}}{\sum_{i=1}^n x'_{ij}} \right) \quad (3)$$

where x'_{ij} represents the normalized value of indicator j for observation i , and n is the number of observations. The corresponding weight w_j is then calculated by (Lu et al., 2022):

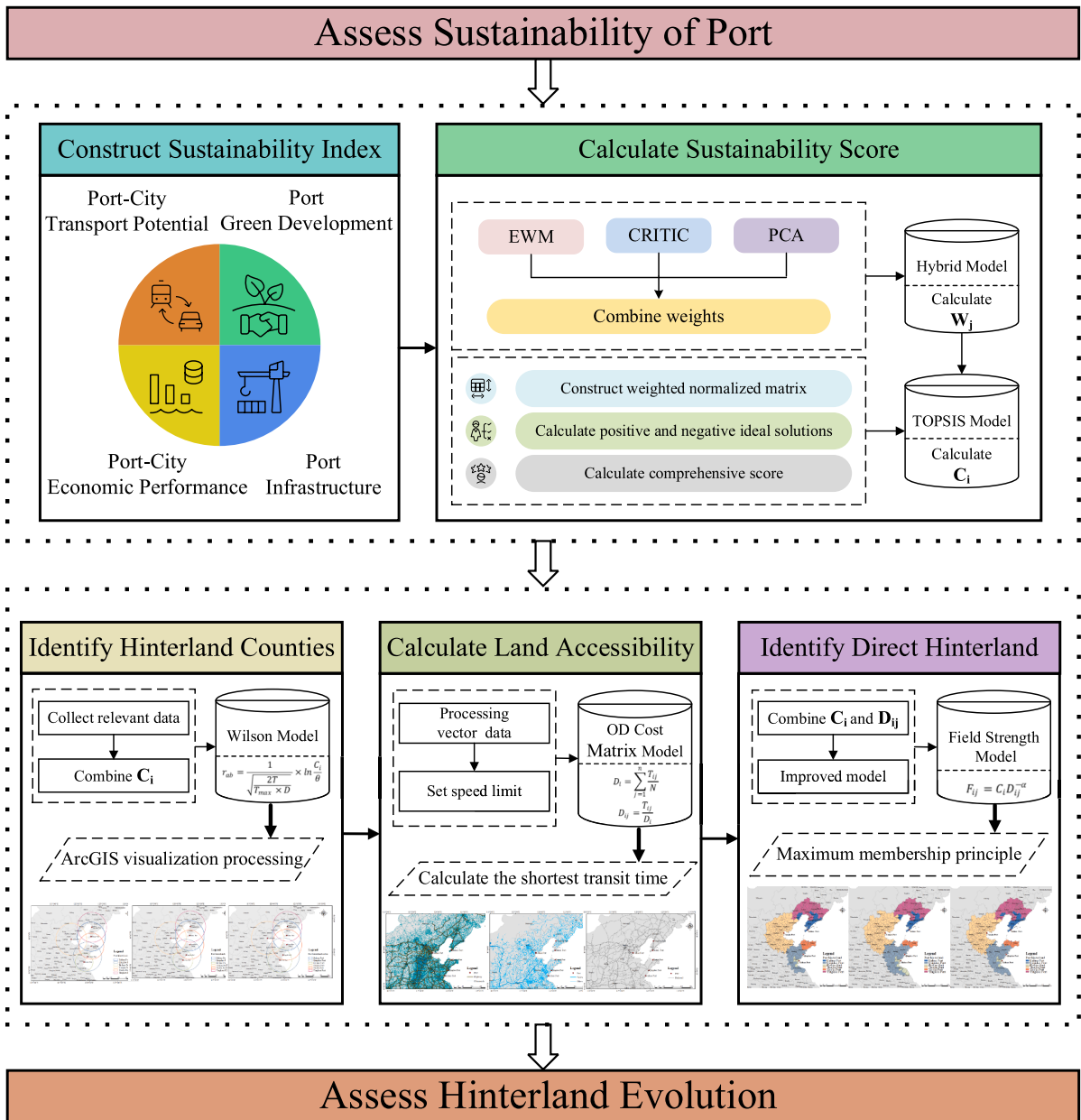


Fig. 1. Research framework.

$$w_j^{EWM} = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \quad (4)$$

where m is the total number of indicators.

3.2.2. CRITIC model

The CRITIC method is an objective weighting technique that considers both the contrast intensity and the conflict among indicators to determine their weights (Yin et al., 2021a). Contrast intensity is measured by the standard deviation of each indicator. A higher standard deviation indicates more contrast, meaning the indicator provides greater discriminating power. The formula for calculating the contrast intensity σ_j of indicator j is given by Du et al. (2024):

$$\sigma_j = \sqrt{\frac{1}{n} \sum_{i=1}^n (x'_{ij} - \bar{x}_j)^2} \quad (5)$$

where \bar{x}_j is the mean of the normalized values for indicator j . The conflict

between indicators is captured by their correlation coefficient ρ_{jk} , defined as:

$$\rho_{jk} = \frac{\text{cov}(x'_j, x'_k)}{\sigma_j \sigma_k} \quad (6)$$

where $\text{cov}(x'_j, x'_k)$ represents the covariance between indicators j and k , and σ_j and σ_k are their standard deviations. The weight for each indicator j is determined by Wang and Zhang (2025):

$$w_j^{CRITIC} = \frac{\sigma_j \sum_{k \neq j} (1 - \rho_{jk})}{\sum_{j=1}^m \sigma_j \sum_{k \neq j} (1 - \rho_{jk})} \quad (7)$$

3.2.3. PCA model

The PCA is a dimensionality reduction technique that transforms correlated indicators into a smaller set of uncorrelated principal components, which capture the majority of the variance in the data (Merk

and Dang, 2013). PCA is used here to identify the key factors explaining variation in the sustainability indicators, allowing us to determine their relative importance. The principal components $\lambda_1, \lambda_2, \dots, \lambda_p$ are derived from the original dataset, with eigenvalues λ_j representing the amount of variance explained by each component.

The weight w_j^{PCA} for indicator j is calculated as the proportion of the total variance explained by the principal component that the indicator contributes to Tan and Lu (2015):

$$w_j^{PCA} = \frac{\lambda_j}{\sum_{k=1}^p \lambda_k} \quad (8)$$

where λ_j is the eigenvalue corresponding to indicator j and p is the total number of principal components.

3.2.4. Calculation of composite weights

To integrate the advantages of the EWM, CRITIC, and PCA methods, this study proposes a weighted combination model to compute the final sustainability indicator weights. Specifically, the composite weight w_j is derived by calculating a weighted average of the individual weights obtained from each method (w_j^{EWM} , w_j^{CRITIC} , and w_j^{PCA}). The formula for calculating the composite weight is given as Liu et al. (2022a) and Yin et al. (2021b):

$$w_j = \alpha w_j^{EWM} + \beta w_j^{CRITIC} + \gamma w_j^{PCA} \quad (9)$$

$$\alpha + \beta + \gamma = 1 \quad (10)$$

where α , β , and γ are the weighting coefficients for each method (Liu et al., 2022b). These coefficients are determined based on the relative reliability and importance of each method in the context of port sustainability assessment. By adjusting these coefficients, the relative importance of each method can be flexibly controlled. This approach combines the strengths of each method, ensuring a more balanced and comprehensive weight calculation, thereby minimizing potential biases from any single method and providing a more precise and systematic framework for port sustainability assessment. The specific parameter settings are detailed in Appendix C of the Supplementary Material.

3.3. TOPSIS model

The TOPSIS method is a widely used comprehensive evaluation technique that leverages the full information available from the original data (Chen, 2021; Gök-Kısa et al., 2021). The evaluation results accurately reflect the overall performance and the relative gaps between different samples, making it a versatile and applicable method in various contexts.

Using the weights obtained from the EWM-CRITIC-PCA process for the indicator layer, the weighted matrix X_{ij} is calculated as follows (Wang et al., 2024):

$$X_{ij} = x'_{ij} \times \omega_j \quad (11)$$

where x'_{ij} represents the normalized value of indicator j for observation i , and ω_j is the weight for indicator j .

Next, the Euclidean distances from the positive ideal solution (D_i^+) and the negative ideal solution (D_i^-) are calculated for each evaluation object in the criterion layer (Akyol Özcan, 2023):

$$D_i^+ = \sqrt{\sum (Z_{ij} - Z_j^{*+})^2}, D_i^- = \sqrt{\sum (Z_{ij} - Z_j^{*-})^2} \quad (12)$$

where $Z_j^{*+} = \max(X_j)$ and $Z_j^{*-} = \min(X_j)$ represent the optimal and worst solutions for indicator j , respectively.

Finally, the closeness coefficient C_i of each evaluation object to the optimal solution is computed:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (13)$$

This coefficient C_i provides the final evaluation result, indicating how close each evaluation object is to the optimal solution, where a higher value reflects a better performance.

3.4. Wilson model

The Wilson model, a derivative framework within economic geography, is primarily employed to analyze spatial interactions within closed systems. Conceptualizing a region as a network of discrete nodes, the model quantifies the gravitational force between each pair of nodes. Due to its incorporation of distance decay and refined exponential correction mechanisms, the Wilson model has become a widely adopted tool for investigating regional diffusion effects.

To evaluate the spatial influence of ports, a simplified formulation of the Wilson model is utilized and expressed as follows (Yang and Wang, 2021):

$$\theta = C_i \exp(-\beta r_{ab}) \quad (14)$$

$$r_{ab} = \frac{1}{\beta} \times \ln \frac{C_i}{\theta} \quad (15)$$

In Equations (14) and (15), θ denotes a predefined threshold value below which the spatial influence intensity is considered negligible, implying that the port exerts no effective influence on the corresponding region (Wang and Tang, 2012). The specific parameter settings are detailed in Appendix C of the Supplementary Material. The term C_i represents the port's sustainable development score. The variable r_{ab} indicates the port's effective influence radius, while β serves as the decay coefficient, influenced by both the number of functional transmission elements and the spatial scale of grid cells.

Building upon Deng's (2010) methodology for assessing the spatial extent of technological diffusion, the decay factor β is further elaborated as:

$$\beta = \sqrt{\frac{2T}{T_{max} \times D}} \quad (16)$$

where T denotes the number of ports possessing effective hinterland influence capacity, T_{max} refers to those with strong interregional diffusion potential, and D represents the average area of spatial units within the port's host city. Substituting Equation (16) into Equation (15) yields the final form of the Wilson-based model for port influence radius under the condition $T_{max} \leq T$ (Wang and Tang, 2012):

$$r_{ab} = \frac{1}{\sqrt{\frac{2T}{T_{max} \times D}}} \times \ln \frac{C_i}{\theta} \quad (17)$$

3.5. OD cost matrix-based land accessibility model

The OD cost matrix, a spatial analytical technique, constructs a temporal matrix between supply and demand nodes based on real-world transportation networks. By computing transit times along actual routes rather than straight-line distances, it effectively captures the true accessibility between regions (Zhuang et al., 2017).

In the context of port systems, land-based accessibility typically refers to the time required to travel from a port to counties and districts within its hinterland. This metric serves as a proxy for the convenience and intensity of interaction between ports and inland areas. The assessment of land accessibility from ports follows a multi-step methodological framework:

First, national road vector data are preprocessed through classification, merging, and topological correction to ensure network continuity. Second, travel speeds are assigned to each road type according to

national railway standards, highway engineering specifications, and empirical regional traffic conditions. For continuous land areas without road coverage and lakes, default travel speeds are set at 15 km/h and 1 km/h. The detailed speed assignments are summarized in Table 1.

Third, travel time costs are normalized to represent the average time (in minutes) required to traverse 1 km for each road type. Using a mathematically rigorous accessibility algorithm, the core zones of six major ports are designated as origin nodes, from which the minimum travel time to each administrative unit is computed.

Finally, land accessibility values for each port are calculated using the following formula (He et al., 2019):

$$D_i = \sum_{j=1}^n \frac{T_{ij}}{N} \quad (18)$$

$$D_{ij} = \frac{T_{ij}}{D_i} \quad (19)$$

where D_i denotes the land accessibility of port i , T_{ij} represents the shortest travel time between port i and county/district j , N is the total number of counties/districts considered, and D_{ij} is the normalized land accessibility between port i and region j .

3.6. Field strength model

To delineate the hinterlands of major ports, this study employs an improved field strength model that integrates port sustainability levels with minimum land-based travel time costs as a composite measure of accessibility. Within this framework, the port hinterland is conceptualized as a “field center,” where the strength of influence represents the port’s relative attractiveness across a given spatial unit.

The model specifically incorporates sustainability performance scores of ports alongside land-based accessibility metrics. According to the maximum membership principle (Pan and Liu, 2014), determine the hinterland counties of the port. The gravitational influence F_{ij} of port i on county j is calculated using the following formulation:

$$F_{ij} = C_i D_{ij}^{-\alpha} \quad (20)$$

where F_{ij} denotes the gravitational field intensity of port i at county j , C_i represents the composite influence score of port i , and $D_{ij}^{-\alpha}$ quantifies the inverse accessibility between port i and county j , with D_{ij} obtained from land transportation data. The parameter α , known as the distance decay coefficient, is set to 2, aligning with empirical findings on spatial interactions at the provincial scale (Taaffe, 1962).

4. Results

4.1. Data

4.1.1. Research area

In terms of spatial scale, this study focuses on the Bohai Rim region, comprising the provinces and municipalities of Liaoning, Hebei, Beijing, Tianjin, and Shandong. This area features a concentrated cluster of

Table 1
Time costs of major space features.

Space object	Speed (km/h)	Time cost (min)
Railroad	90	0.68
Highway	100	0.60
National highway	80	0.75
Provincial highway	60	1.00
County highway	40	1.50
Yellow river	25	2.40
Land	15	4.00
Lakes	1	60.00
Major Rivers	1	60.00

ports, including six key container hubs: Tianjin, Dalian, Qingdao, Yingkou, Yantai, and Rizhao, as illustrated in Fig. 2. For hinterland delineation, counties and districts are used as the basic spatial units, resulting in 373 units for analysis.

This study investigates the evolution of port sustainability and hinterland dynamics in the Bohai Rim from 2011 to 2023. Three representative years are selected to trace changes in spatial accessibility and port influence, each marking a critical stage in port transformation of the region. In 2011, China’s 12th Five-Year Plan for Energy Conservation and Emission Reduction in Road and Water Transport first integrated emission targets into regional transport planning (Mao et al., 2014). By 2017, the issuance of the Guidance on Promoting Green Transport by the Ministry of Transport highlighted multimodal freight and logistics efficiency, reinforcing port-hinterland integration in northern China (Lam and Li, 2019). In 2023, Bohai Rim ports were designated as pilot sites under China’s Zero-Carbon Program for Road and Waterway Transport, promoting smart energy management, renewable energy adoption, and equipment efficiency improvements. These policy milestones provide a foundation for comparative assessment of spatial and ecological transitions throughout the study period.

4.1.2. Data sources

The research data employed in this study are categorized into two primary types: attribute data and spatial data.

The attribute data cover three essential dimensions-socioeconomic and transportation statistics, container port data, and port-related carbon emissions. Specifically, socioeconomic and transportation statistics were gathered from the statistical yearbooks of Tianjin Municipality, Liaoning Province, and Shandong Province. Container port data were sourced from the *China Port Yearbook* and the *China Shipping Gazette*. Due to the absence of standardized methodologies for port-level carbon emissions accounting and the limited availability of direct emissions data from relevant authorities, port-related carbon emissions were estimated indirectly using energy consumption data. Following the approach proposed by Ge and Wang (2021), comprehensive energy consumption per unit of cargo throughput is calculated using the standard coal equivalents of major energy sources-gasoline, diesel, heavy fuel oil, coal, and electricity-utilized by ports in the Bohai Rim. Carbon emissions are then derived by applying energy-specific emission factors to port throughput data. This methodology offers an indirect yet robust estimation of port-level carbon emissions. The estimation formula is as follows:

$$CO_i = SC_i \times HC_i \times \lambda \quad (21)$$

where SC_i represents the standard coal consumption per 10,000 tons of cargo throughput in year i (tce/10,000 t), HC_i is the total cargo throughput in the same year, and λ is the carbon emission coefficient, set at 2.4589.

In parallel, spatial data were integrated to contextualize the attribute information. Administrative boundaries and water bodies within the study area were derived from the 1:1,000,000 vector dataset provided by the National Geomatics Center of China. The locations of core port areas were identified via Google Earth and subsequently imported into ArcGIS for spatial analysis. Additionally, terrestrial transportation networks were digitized from authoritative sources, including the *Provincial Transportation Atlas of China* and the *Comprehensive Highway and Urban-Rural Road Network Atlas of China (Concise Edition)*.

4.2. Port sustainability indicators weights and scores

4.2.1. Port sustainability indicators weights

Port sustainability is influenced by a complex array of factors, including regional economic structure, infrastructure development, environmental protection measures, technological advancement, hinterland economic interaction, and resource allocation. In recent years,

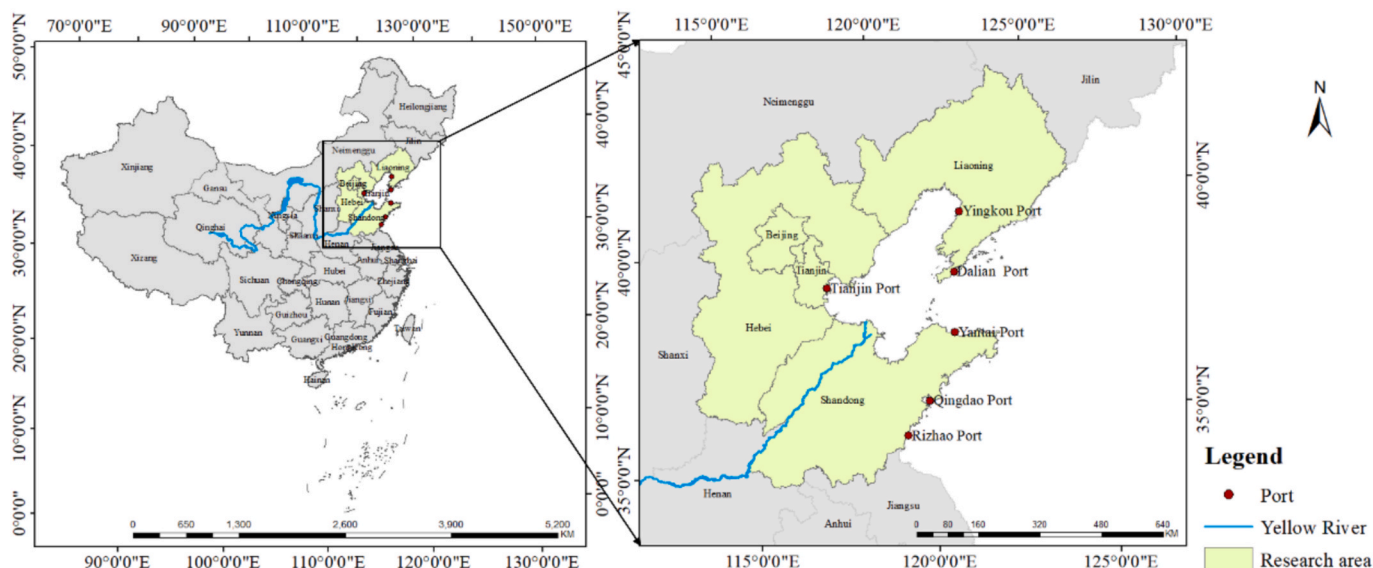


Fig. 2. Research area.

there has been a growing emphasis on integrating green development metrics into port sustainability assessment frameworks. This study introduces an innovative approach that incorporates port carbon emissions and sea-rail intermodal throughput as key indicators for evaluating port sustainability, with a focus on reducing greenhouse gas emissions and supporting the transition of ports towards sustainable development.

Building upon existing literature and available data, this study establishes a comprehensive multi-dimensional evaluation system using 17 objective indicators, categorized into four key domains: port infrastructure, green development, port-city economic performance, and port-city transport potential, as presented in Table 2. For a detailed explanation of the indicators and their reference bases, please refer to Appendix A of the Supplementary Material.

To assess the relative importance of each indicator, the EWM-CRITIC-PCA hybrid model is employed. This model combines the EWM, CRITIC, and PCA to ensure a robust and objective weighting process. The TOPSIS method is then applied to evaluate the sustainability levels of ports in the Bohai Rim region from 2011 to 2023, providing a comprehensive and dynamic assessment of port performance.

The detailed weights for each indicator, based on the EWM, CRITIC, and PCA methods, are presented in Table 3. The table shows the individual weights for each indicator across the three methods as well as

their average weights. These averages represent the overall importance of each indicator in the sustainability assessment. Additionally, the average criterion's weight for each domain is also provided, summarizing the relative importance of the broader sustainability aspects for the Bohai Rim ports.

Results from the hybrid weighting analysis reveal notable disparities in the relative importance of sustainability indicators. Among the four primary dimensions, port infrastructure development carries the greatest weight in the overall evaluation system, accounting for approximately 36.5 % of the total indicator weight. Within this dimension, port cargo throughput (X11) and number of 10,000-ton-class berths (X15) emerge as the most influential indicators, reflecting the continued relevance of physical capacity in shaping port performance.

In the green development domain, sea-rail intermodal throughput (X22) and CO₂ emissions (X21) attain the highest weights (both averaging above 0.06), underscoring the centrality of decarbonization and modal shift in the evaluation of green port competitiveness. These findings reinforce the role of environmental metrics as strategic levers in port transformation agendas.

The port-city economic performance dimension exhibits relatively balanced weight distribution across indicators such as GDP (X31), tertiary industry share (X32), and per capita GDP (X33), suggesting that no single economic metric overwhelmingly dominates the assessment, but

Table 2
Port sustainability indicators for the Bohai Rim region.

Dimension	Sub-dimension	Indicator	Unit	Trend
Port sustainability performance	Port Infrastructure Development	Port Cargo Throughput	X11 10,000 tons	+
		Container Throughput	X12 10,000 TEUs	+
		Length of Quay Line for Productive Use	X13 meters	+
		Total Number of Berths	X14 units	+
		Number of 10,000-ton-class Operational Berths	X15 units	+
	Port Green Development	Port CO ₂ Emissions	X21 tons	-
		Sea-Rail Intermodal Throughput	X22 10,000 TEUs	+
		Growth in Freight Throughput	X23 %	+
		Percentage of Days with Air Quality Rated as Level II or Better	X24 %	+
	Port-City Economic Performance	Gross Domestic Product (GDP)	X31 100 million CNY	+
		Proportion of Tertiary Industry Output	X32 %	+
		Per Capita GDP	X33 CNY	+
		Total Retail Sales of Consumer Goods	X34 10,000 CNY	+
		Total Population at Year-End	X35 10,000 people	+
		Total Foreign Trade (Import and Export)	X36 10,000 USD	+
		Port-City Transport Potential	Road Network Length	X41 kilometers
Road Freight Volume	X42 million tons		+	

Table 3
Port sustainability indicators weights in the Bohai Rim region.

Category	Indicator	EWM	CRITIC	PCA	Average indicator weight	Average Sub-dimension weight
Port infrastructure development	X11	0.1545	0.1077	0.0576	0.1066	0.3646
	X12	0.0811	0.0463	0.0630	0.0635	
	X13	0.0477	0.0587	0.0884	0.0649	
	X14	0.0582	0.0701	0.0817	0.0700	
	X15	0.0437	0.0492	0.0859	0.0596	
Port green development	X21	0.0196	0.1115	0.0590	0.0634	0.1772
	X22	0.1120	0.0528	0.0581	0.0743	
	X23	0.0073	0.0379	0.0018	0.0157	
	X24	0.0092	0.0527	0.0097	0.0239	
Port-city economic performance	X31	0.0869	0.0494	0.0719	0.0694	0.3525
	X32	0.0311	0.0478	0.0628	0.0472	
	X33	0.0377	0.0428	0.0662	0.0489	
	X34	0.0772	0.0497	0.0642	0.0637	
	X35	0.0758	0.0545	0.0562	0.0622	
	X36	0.0695	0.0533	0.0606	0.0611	
Port-city transport potential	X41	0.0455	0.0677	0.0129	0.0420	0.1056
	X42	0.0430	0.0477	0.1002	0.0636	

that diversified urban economic capacity supports port sustainability. Lastly, the transport potential dimension shows meaningful contributions from both road network length (X41) and freight volume (X42), indicating that hinterland connectivity remains a vital enabler of sustainable port-inland integration.

4.2.2. Port sustainability indicators scores

Using the EWM-CRITIC-PCA composite model combined with the TOPSIS method, this study systematically evaluated the port sustainability levels of six major container ports in the Bohai Rim region from 2011 to 2023. The hybrid weighting scheme ensures a comprehensive and objective assignment of indicator importance, while the TOPSIS method enables the ranking of ports based on their proximity to an ideal sustainability benchmark. The resulting sustainability scores are reported in Table 4.

During the 13-year study period, the average regional sustainability score rose from 0.3386 in 2011 to 0.4867 in 2023, reflecting a steady improvement and a compound annual growth rate (CAGR) of 2.88 %. This consistent upward trend indicates gradual yet tangible progress in sustainable port development across the region, largely driven by policy initiatives promoting green infrastructure, emissions control, and multimodal transport integration (General Office of the State Council of the People’s Republic of China, 2018; Li et al., 2024a).

Among the six ports, Qingdao Port demonstrated the most substantial and sustained improvement, with its score increasing from 0.3668 in 2011 to 0.6389 in 2023 (CAGR = 4.3 %), allowing it to surpass Tianjin

Port as the regional leader in sustainability since 2020. This performance is closely linked to Qingdao’s early investment in sea-rail intermodal networks, renewable port operations, and industrial restructuring in its hinterland (Lam and Li, 2019).

Tianjin Port, traditionally the top performer, exhibited stable growth from 0.4818 to 0.6355, yet its relative advantage weakened over time, highlighting the diminishing marginal effect of its first-mover policies. Ports such as Yantai and Rizhao also experienced steady gains, with Rizhao’s sustainability performance showing marked improvement, its score rose significantly over the study period, driven in part by infrastructure-led revitalization, including recent rail upgrades along the Lunan Economic Belt (Shandong Provincial People’s Government, 2021).

By contrast, Yingkou and Dalian ports recorded relatively stagnant trajectories. Dalian’s score rose only marginally from 0.4117 to 0.4750, while Yingkou improved from 0.2661 to 0.3536, both failing to close the gap with more dynamic peers. This outcome reflects continued reliance on resource-based industries and limited integration of green innovation measures within their port-city ecosystems (Zhu and Hein, 2019).

Furthermore, spatial disparities have widened over time, as reflected in the increasing standard deviation of port scores. A correlation analysis suggests that high sustainability scores are strongly associated with ports located in economically diversified and industrially upgraded hinterlands, while ports constrained by single-sector economies or weaker hinterland connectivity tend to lag in sustainability performance.

Table 4
Sustainability scores of Bohai Rim ports (2011-2023).

Year	Dalian	Qingdao	Rizhao	Tianjin	Yantai	Yingkou	Average
2011	0.4117	0.3668	0.2089	0.4818	0.2965	0.2661	0.3386
2012	0.4459	0.3879	0.2177	0.5120	0.3103	0.2944	0.3614
2013	0.4631	0.4039	0.2216	0.5390	0.3254	0.3093	0.3770
2014	0.4756	0.4103	0.2180	0.5525	0.3297	0.3224	0.3848
2015	0.4819	0.4303	0.2153	0.5700	0.3394	0.3266	0.3939
2016	0.4835	0.4530	0.2235	0.5817	0.3533	0.3419	0.4061
2017	0.4978	0.4999	0.2411	0.5833	0.4288	0.3519	0.4338
2018	0.5081	0.5326	0.2513	0.5962	0.4429	0.3643	0.4492
2019	0.4833	0.5446	0.2663	0.5747	0.4411	0.3198	0.4383
2020	0.4609	0.5624	0.2724	0.5801	0.4594	0.3450	0.4467
2021	0.4653	0.6042	0.2864	0.6193	0.4803	0.3404	0.4660
2022	0.4711	0.6164	0.2914	0.6258	0.4972	0.3370	0.4732
2023	0.4750	0.6389	0.3027	0.6355	0.5143	0.3536	0.4867

4.3. Port hinterland division

4.3.1. Port hinterland radius measurement

Using the Wilson model, we calculated the hinterland radius of major container hub ports in the Bohai Rim region from 2011 to 2023 (Table 5).

To explore the spatiotemporal dynamics of port hinterlands, three representative years—2011, 2017, and 2023—were selected for comparative analysis. Figs. 3 to 5 visualize the estimated hinterland radii of major container ports in the Bohai Rim region for each respective year.

During the period from 2011 to 2023, the spatial influence of major container hub ports in the Bohai Rim region underwent a steady expansion and structural transformation. As shown in Figs. 3–5, the average hinterland radius of the six ports increased from 247.5 km in 2011 to 273.3 km in 2023, representing a CAGR of approximately 0.83 %. This growth suggests a gradual intensification of port-hinterland linkages and an enhanced capacity to serve inland markets.

However, the spatial expansion was markedly uneven across ports. Qingdao Port exhibited the most substantial increase in hinterland radius, expanding by 15.4 % over the study period. Rizhao Port followed closely with a 12.2 % increase, demonstrating a notable trajectory of hinterland integration, likely facilitated by recent investments in multimodal transport infrastructure and its growing role as a strategic southern gateway. In contrast, Yingkou and Dalian ports showed only modest hinterland growth—8.7 % and 3.8 %, respectively—indicating a relative stagnation in inland market penetration, potentially due to slower regional economic restructuring and limited intermodal connectivity.

By 2023, a more complex and differentiated hinterland configuration had emerged across the region. The overall structure evolved into a multi-layered, core-periphery pattern characterized by a “dual-core, hierarchical diffusion” model. Qingdao and Tianjin ports clearly established themselves as dominant regional cores, with the widest spatial influence and the strongest hinterland integration capabilities. Their overlapping hinterlands suggest intensified competition but also potential synergies in logistics network coordination. Yantai and Dalian functioned as sub-regional hubs, with relatively stable but more spatially constrained hinterlands. Meanwhile, Rizhao exhibited clear upward mobility, reshaping its spatial influence through improved rail-sea interconnectivity. Yingkou, despite early advantages, experienced a plateau in hinterland reach, reflecting a diminishing marginal influence from its traditional hinterland corridors.

These findings underscore the dynamic nature of hinterland evolution under the influence of green development metrics and intermodal integration. The results reflect both endogenous port strategies and exogenous factors such as regional industrial transformation, infrastructural upgrades, and environmental policy alignment. They also highlight the growing spatial polarization and functional differentiation among Bohai Rim ports, offering important implications for coordinated

regional port planning and hinterland development.

4.3.2. Analysis of port land accessibility

From 2011 to 2023, the average land-based accessibility of the six major container hub ports in the Bohai Rim region improved substantially, with mean travel time decreasing from 3.0725 h to 2.7174 h—a 11.5 % reduction over the study period. This steady improvement underscores the sustained investment in inland transportation networks and enhanced regional port connectivity (Table 6).

Accessibility improvements across the Bohai Rim ports were uneven, yet collectively significant. Yingkou Port consistently ranked as the most accessible, maintaining the lowest average travel time throughout the study period—reflecting its strong integration with inland transport corridors. Qingdao Port, a southern core hub, also exhibited stable and efficient accessibility, underscoring the benefits of sustained infrastructure investments and hinterland coordination. Rizhao Port closed much of its accessibility gap with peer ports, aided by incremental upgrades in regional connectivity. Tianjin Port, despite remaining a northern powerhouse, showed moderate improvement and retained higher average travel times than its southern counterparts. The most notable progress occurred at Yantai Port, which achieved the largest proportional gain in accessibility, indicative of significant advances in rail-road intermodal systems along the eastern Shandong axis. In contrast, Dalian Port—geographically more peripheral—recorded improvement but remained the least accessible overall, suggesting slower adaptation of inland connectivity.

Regionally, accessibility disparities among ports narrowed over time. The declining standard deviation of travel times signals a trend toward spatial equilibrium in inland connectivity. While early-stage improvements were uneven, later years showed a convergence effect driven by coordinated infrastructure development and the roll-out of national transport integration programs. This convergence, however, masks important structural nuances: ports achieving rapid accessibility gains, such as Yantai and Rizhao, often leveraged targeted provincial or corridor-specific investments, whereas ports with slower gains, like Dalian, are constrained by geography and slower intermodal expansion.

Overall, the evolving pattern reflects the positive impact of regional transport integration policies. Enhanced inland mobility not only improved individual port performance but also fostered a more balanced and resilient hinterland-port system across the Bohai Rim. Importantly, accessibility gains can act as a multiplier for sustainability-oriented initiatives by enabling smoother modal shifts and reducing the carbon intensity of hinterland logistics, thereby reinforcing the long-term competitiveness of ports that integrate infrastructure upgrades with green development strategies.

4.3.3. Evolutionary characteristics of port field strength

This study integrates land-based accessibility with port sustainability performance to derive port field strength using the maximum membership principle, thereby capturing both spatial influence and

Table 5

Estimated hinterland radius of major container ports in the Bohai Rim region, 2011–2023 (Unit: km).

Year	Dalian	Qingdao	Rizhao	Tianjin	Yantai	Yingkou	Average
2011	264.0510	255.8553	215.8639	275.2154	240.7461	233.0459	247.4630
2012	269.7129	259.8283	218.7831	279.5322	243.9709	240.2227	252.0084
2013	272.4103	262.6888	220.0409	283.1819	247.3499	243.7387	254.9018
2014	274.3041	263.8153	218.8998	284.9425	248.2843	246.6952	256.1569
2015	275.2377	267.1823	218.0068	287.1648	250.3377	247.6054	257.5891
2016	275.4680	270.8439	220.6608	288.5987	253.1903	250.8501	259.9353
2017	277.5442	277.8324	226.0322	288.7917	266.9402	252.9030	265.0073
2018	278.9882	282.3350	228.9796	290.3488	269.2359	255.3558	267.5406
2019	275.4455	283.9150	233.1147	287.7477	268.9446	246.1137	265.8802
2020	272.0736	286.2031	234.7273	288.4103	271.8301	251.4978	267.4571
2021	272.7454	291.2973	238.2859	293.0545	274.9960	250.5375	270.1528
2022	273.6207	292.7214	239.5076	293.7869	277.4587	249.8411	271.1561
2023	274.2067	295.2582	242.2139	294.8856	279.8538	253.2491	273.2779

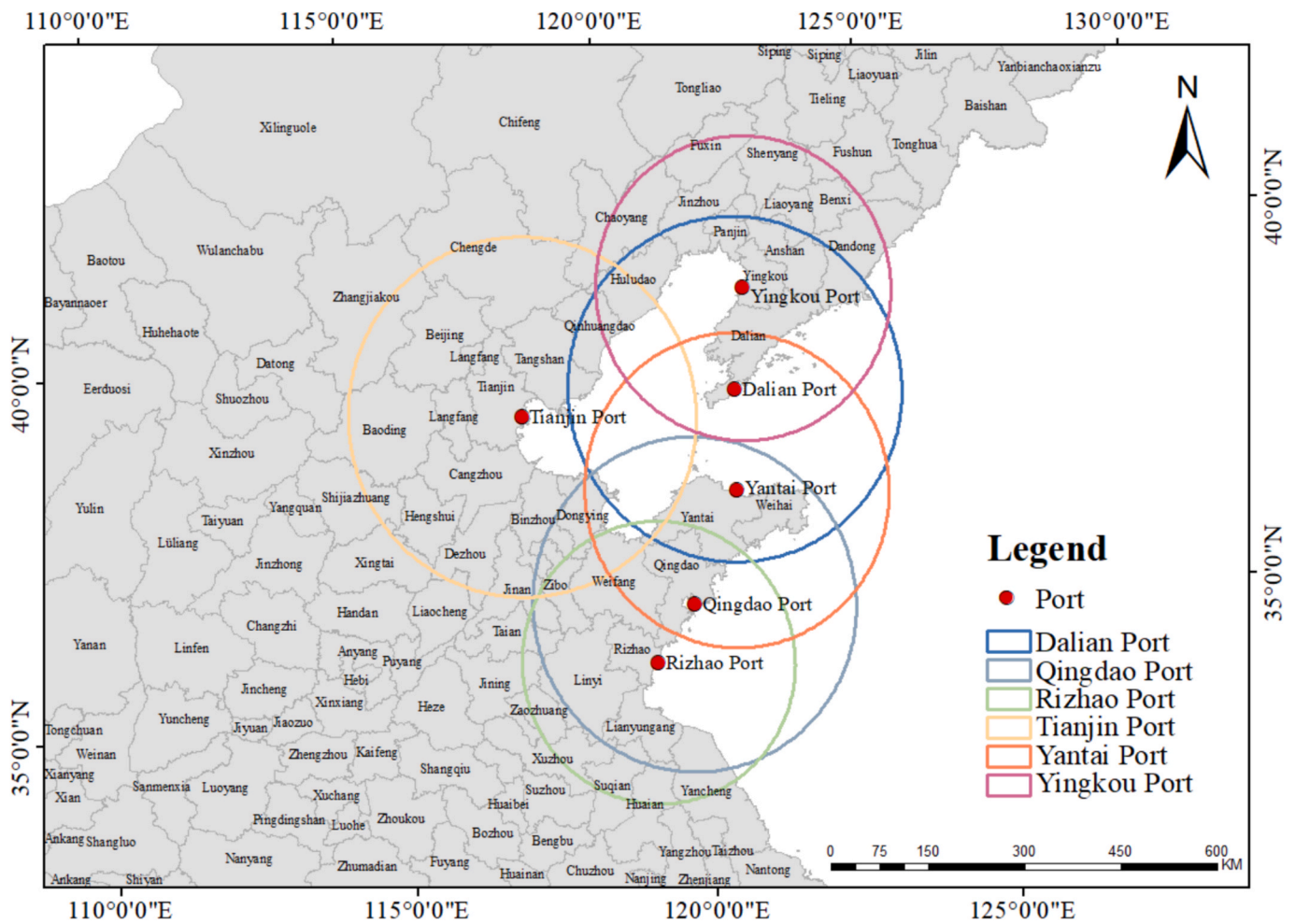


Fig. 3. Estimated hinterland radii of major container ports in the Bohai Rim region, 2011.

developmental intensity. As visualized in Fig. 6, the port hinterland field strength maps for 2011, 2017, and 2023 reveal the spatiotemporal evolution of influence zones across the Bohai Rim region.

The spatial configuration of port field strength consistently presents a clear “core-periphery” pattern, with high-strength zones clustered around major ports and gradually attenuating inland. Over the study period, three trends became evident: core zones expanded and intensified, inter-port overlaps increased, and secondary nodes achieved marginal inland growth—a pattern suggesting that hinterland interactions are no longer defined solely by geographic proximity, but increasingly by the differentiated capacity of ports to integrate sustainability-oriented transport infrastructure into regional corridors.

Tianjin Port, benefiting from its role as a national logistics hub and core node of the Jing-Jin-Ji integration strategy, sustained the most expansive and contiguous high-field strength zone throughout the study period. While dominating the Beijing-Tianjin-Hebei urban agglomeration, its influence field gradually extended westward into Shanxi and northward into Inner Mongolia. By 2023, spatial overlaps became increasingly evident with Dalian and Qingdao ports, suggesting deepened inland penetration and intensified regional competition that could either lead to intensified market rivalry or, if strategically coordinated, promote functional specialization across overlapping hinterland areas. This expansion is closely linked to strategic investments in inland dry ports and multimodal transport infrastructure upgrades, which strengthened both the extent and intensity of its hinterland influence.

Qingdao Port demonstrated the fastest inland expansion in terms of field strength diffusion. Its dominant zone evolved from the Shandong Peninsula outward to major cities such as Jinan, Zibo, and Weifang. This

rapid spatial growth aligns with Qingdao’s steadily improving sustainability scores—attributed to advancements in green technologies and intermodal systems like sea-rail corridors. Field expansion toward southwestern Shandong was especially prominent, likely supported by the Qingdao-Jinan-Heze logistics corridor and dry port integration, allowing Qingdao to bridge coastal and inland logistics nodes more effectively. Unlike Tianjin’s broad continuity, Qingdao’s field exhibited sharper gradients, suggesting strong yet more localized hinterland gravity that could make it more sensitive to future infrastructure shifts or policy incentives in the Shandong region.

Dalian Port’s spatial pattern remained relatively stable between 2011 and 2023, with its core field strength zone anchored in southern Liaoning—especially Shenyang, Anshan, and Fushun. Though the areal expansion was minimal, the internal field intensity rose noticeably, reflecting consolidation of port-inland logistics and steady demand accumulation within the mature industrial belt. This moderate dynamism may stem from Dalian’s peripheral location in the Bohai Rim logistics system and its slower adaptation to inland green transport upgrades—highlighting the structural constraints faced by ports situated on the geographic margins of integrated port clusters.

Yingkou Port’s spatial footprint, in contrast, was marked by stagnation. Throughout the study period, its influence remained confined to western Liaoning and marginal areas in eastern Inner Mongolia. Despite early-stage gains, its field strength plateaued, largely due to unchanged OD accessibility and limited progress in sustainability initiatives. Additionally, competition from the proximate Dalian Port resulted in significant spatial overlaps and hinterland redundancy, diluting Yingkou’s unique regional role and underscoring the importance of niche

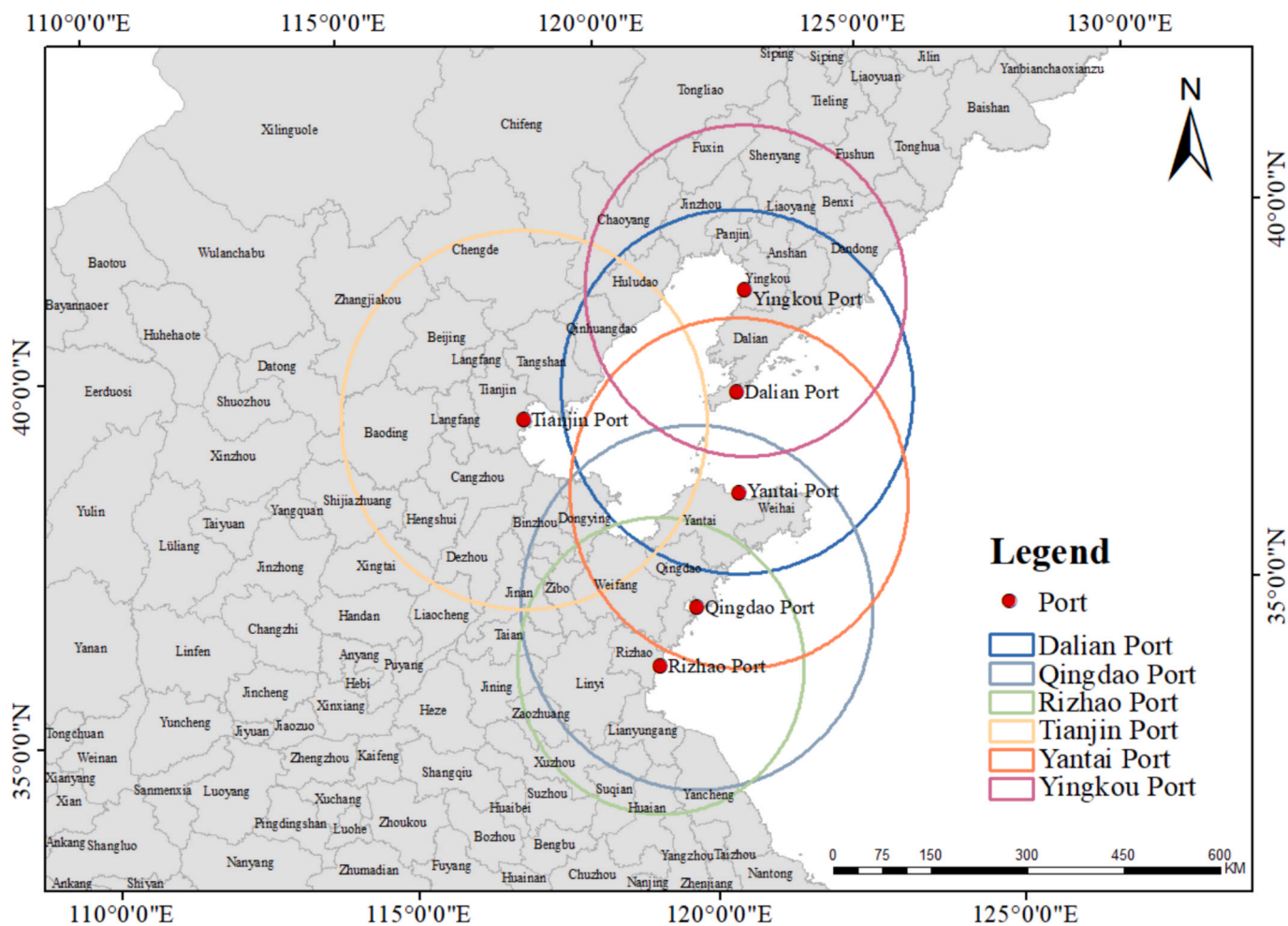


Fig. 4. Estimated hinterland radii of major container ports in the Bohai Rim region, 2017.

market positioning for mid-tier ports to avoid being overshadowed by proximate, larger competitors.

Rizhao and Yantai Ports exhibited more modest yet strategic hinterland gains. Rizhao’s influence zone progressively expanded westward and began merging with Qingdao’s secondary field by 2023, forming an emerging inland corridor of green connectivity across southwestern Shandong. This is largely attributed to Rizhao’s focus on rail-sea intermodality and inland logistics cooperation with resource-exporting regions—an approach that demonstrates how targeted green infrastructure can enable smaller ports to carve out complementary roles within overlapping hinterlands. Yantai, while still exhibiting a predominantly coastal hinterland, demonstrated improved spatial cohesion—likely supported by its integration into Shandong’s provincial transport plan and increased road-rail interface efficiency that has helped stabilize its competitive position despite limited inland reach.

Taken together, the spatiotemporal evolution of port hinterlands in the Bohai Rim illustrates a clear spectrum of developmental trajectories—from the expansive, high-intensity influence zones of Tianjin and Qingdao to the relative stagnation of Dalian and Yingkou. Notably, the emergence of overlapping hinterland fields, especially in Hebei and Shandong, reveals intensifying inter-port competition while also fostering the potential for synergistic coordination if policy frameworks can incentivize cooperative capacity planning and differentiated service strategies. This transition from fragmented dominance to a more tiered and interconnected spatial configuration reflects how green development and sustainability-driven logistics capacity are increasingly redefining not only the functional roles of individual ports, but also the broader spatial architecture of port clusters. As such, coordinated

regional planning becomes imperative to mitigate hinterland redundancy, enhance system-wide efficiency, and strengthen the Bohai Rim’s collective competitiveness in global maritime networks—a goal that will require balancing competitive dynamics with mechanisms for collaborative investment and shared sustainability targets.

4.3.4. Evolutionary characteristics of port hinterland extents

(1) General evolutionary trends

From a sustainability-oriented perspective, the spatiotemporal evolution of port hinterlands in the Bohai Rim region (Fig. 7) reflects both the dynamic expansion of regional logistics capacity and the increasing spatial coupling between port performance and inland integration. Between 2011 and 2023, the total number of hinterland counties grew from 346 to 373. This spatial expansion reflects the dynamic reconfiguration of port hinterlands driven by differentiated levels of port sustainability—particularly improvements in infrastructure capacity, green development performance, and inland accessibility. The assignment of hinterland counties follows the principle of maximum membership, based on a combined evaluation of these sustainability dimensions.

Across the region, hinterland coverage remained centered around key urban agglomerations, expanding in gradient diffusion rather than abrupt shifts. Notably, the combined hinterland coverage of Qingdao, Tianjin, and Yingkou consistently comprised over 80 % of the total counties, underscoring their dominant sustainability and accessibility performance. In contrast, Yantai and Rizhao ports remained spatially limited, though Rizhao displayed evident upward momentum (Table 7).

(2) Port-specific evolutionary dynamics

A sustainability-oriented analysis reveals divergent yet interrelated

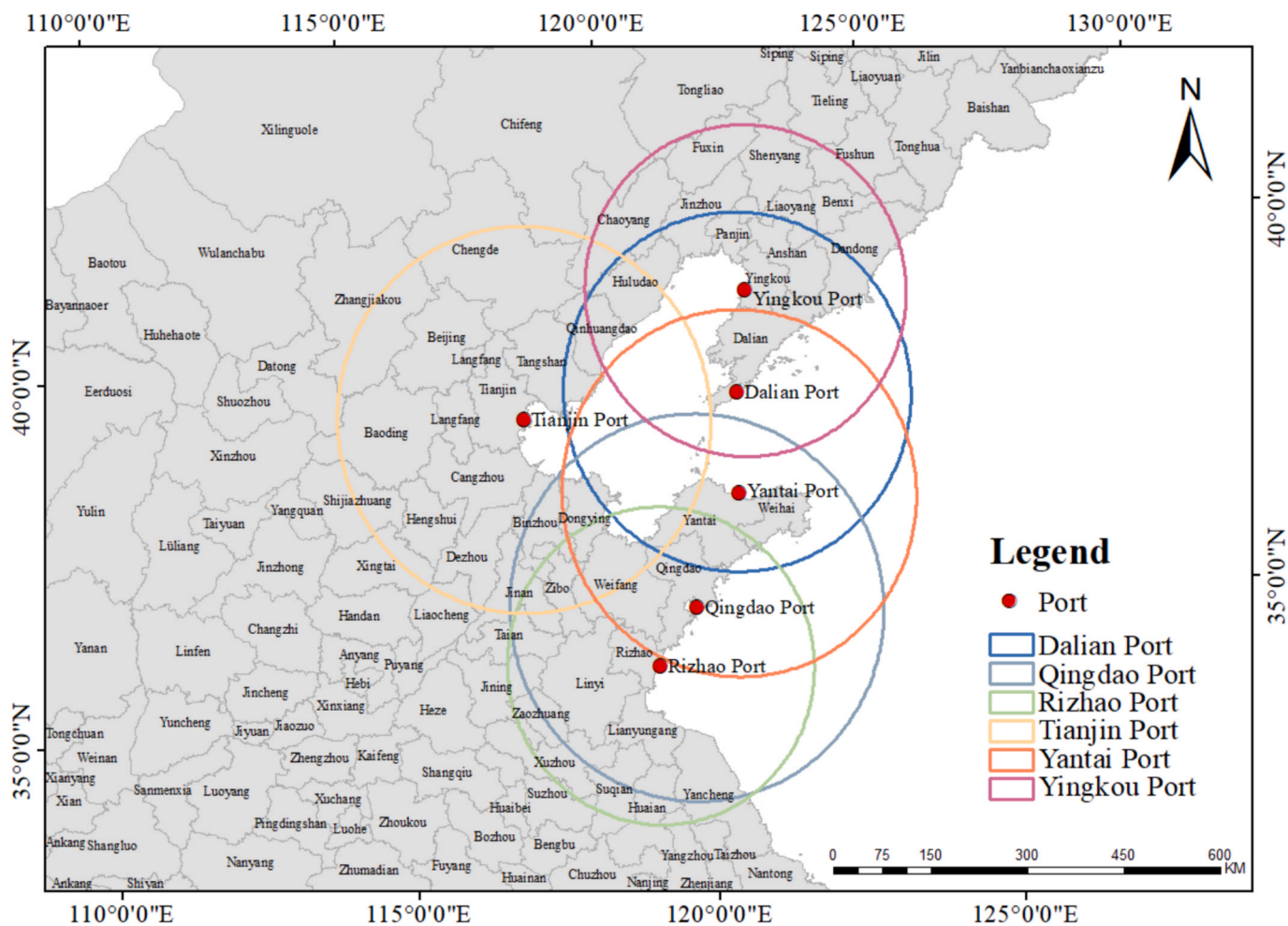


Fig. 5. Estimated hinterland radii of major container ports in the Bohai Rim region, 2023.

Table 6
Analysis of land accessibility of major container hub ports in Bohai Rim region.

Year Port	2011	2017	2023	Average port's land accessibility
Dalian	4.2834	3.9791	3.7507	4.0044
Qingdao	2.5893	2.6485	2.5324	2.5901
Rizhao	2.7929	2.6250	2.5396	2.6525
Tianjin	2.8937	2.8326	2.5981	2.7748
Yantai	3.3990	2.7914	2.6455	2.9453
Yingkou	2.4769	2.5282	2.2383	2.4145
Average annual land accessibility	3.0725	2.9008	2.7174	—

trajectories of hinterland evolution among the six major container ports in the Bohai Rim region.

Tianjin Port consistently maintained the broadest hinterland, averaging over 174 counties between 2011 and 2023. Its spatial coverage remained largely stable, supported by high composite sustainability scores and long-term investments in green corridor infrastructure. Functioning as the logistics backbone for the Beijing-Tianjin-Hebei region, Tianjin's reach extends deep into Shanxi and Inner Mongolia, consolidating its role as a national logistics hub.

In contrast, Qingdao and Rizhao Ports demonstrated the strongest upward momentum in hinterland expansion. Qingdao increased its hinterland from 45 to 65 counties, representing a 44 % rise. This growth is closely tied to its strategic deployment of electrified railways and inland dry ports, particularly in northern Jiangsu and southwestern

Shandong. Rizhao Port, despite a smaller base, registered a 32 % growth, with hinterland counties rising from 28 to 37. This expansion reflects the port's improving multimodal transport capacity and environmental performance, positioning it as a rising sub-regional node. Compared to Tianjin's stable dominance, Qingdao and Rizhao showcase an adaptive, growth-oriented trajectory driven by targeted green logistics enhancements.

Dalian and Yingkou Ports exhibited relatively stable hinterland patterns with slight fluctuations. Dalian's coverage remained steady around 26-27 counties across the three periods, constrained by geographical limitations and mature logistics corridors. However, it retained a solid sustainability profile, indicating a mature but capacity-limited hinterland structure that can remain competitive if operational efficiency and green performance are maintained. Yingkou peaked at 59 counties in 2017 but slightly declined by 2023, indicating initial gains from inland corridor initiatives but subsequent vulnerabilities to regional competition and shifting policy support that may require niche-market targeting or deeper integration with neighboring port systems to avoid further erosion. The parallel stability of Dalian and the mild contraction of Yingkou reflect two different outcomes of ports with limited expansion room—one sustained by equilibrium, the other challenged by external pressures.

In contrast, Yantai Port experienced a consistent reduction in hinterland counties, declining from 16 to 12 over the study period. This shrinkage highlights its relative underperformance in hinterland accessibility improvements and weaker sustainability evaluation—a signal that without targeted infrastructure or environmental upgrades, further marginalization in the regional port hierarchy is possible.

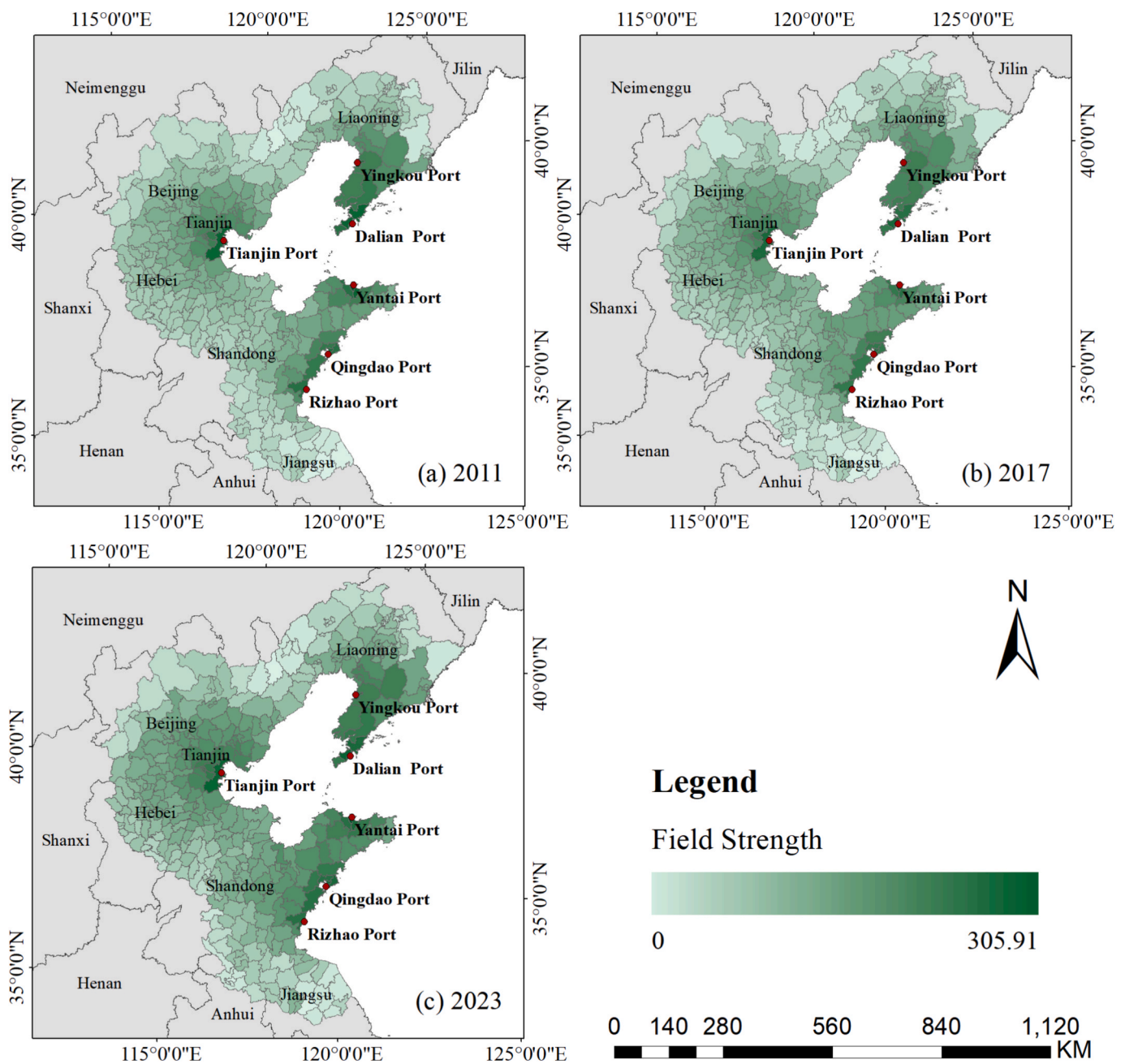


Fig. 6. Port hinterland field strength distribution for major container hub ports in the Bohai Rim region (2011, 2017, 2023).

Collectively, while Tianjin exemplifies sustained dominance, Qingdao and Rizhao represent emergent growth, and Dalian, Yingkou, and Yantai underscore varying degrees of spatial stagnation or retreat. These port-level differences reflect how sustainability performance and intermodal investment jointly shape the competitive reconfiguration of hinterlands.

(3) Driving mechanisms and strategic implications

The evolution of port hinterlands in the Bohai Rim region is influenced by multiple interconnected driving forces.

First and foremost, green development policies have become a primary driver of spatial change. The integration of sustainability measures—such as carbon emissions reduction and sea-rail intermodal transport—has increasingly shaped port hinterland boundaries (Gu and Lam, 2013; Yin et al., 2021b). Ports like Qingdao and Rizhao, which have heavily invested in green infrastructure and multimodal connectivity, have seen substantial hinterland expansion, driven by their high

sustainability performance. These investments in sustainability allow them to better serve regional economic activities while enhancing their competitiveness in global logistics networks (Li et al., 2024a).

In addition to green policies, regional transport network improvements play a pivotal role in the expansion of port hinterlands (Zhong et al., 2023). The development and integration of multimodal transport systems—comprising railways, highways, and ports—have extended the reach of ports like Tianjin and Qingdao. These ports benefit from stronger interconnections with the hinterland, improving the efficiency of cargo flow and logistics. On the other hand, ports such as Dalian and Yantai, which have made slower progress in expanding their inland transport networks, face challenges in increasing their hinterland influence. The evolution of these ports highlights the critical importance of transport infrastructure in enabling effective regional integration (Guo et al., 2023)—in part due to geographical constraints and the slower rollout of green-oriented intermodal upgrades. The evolution of

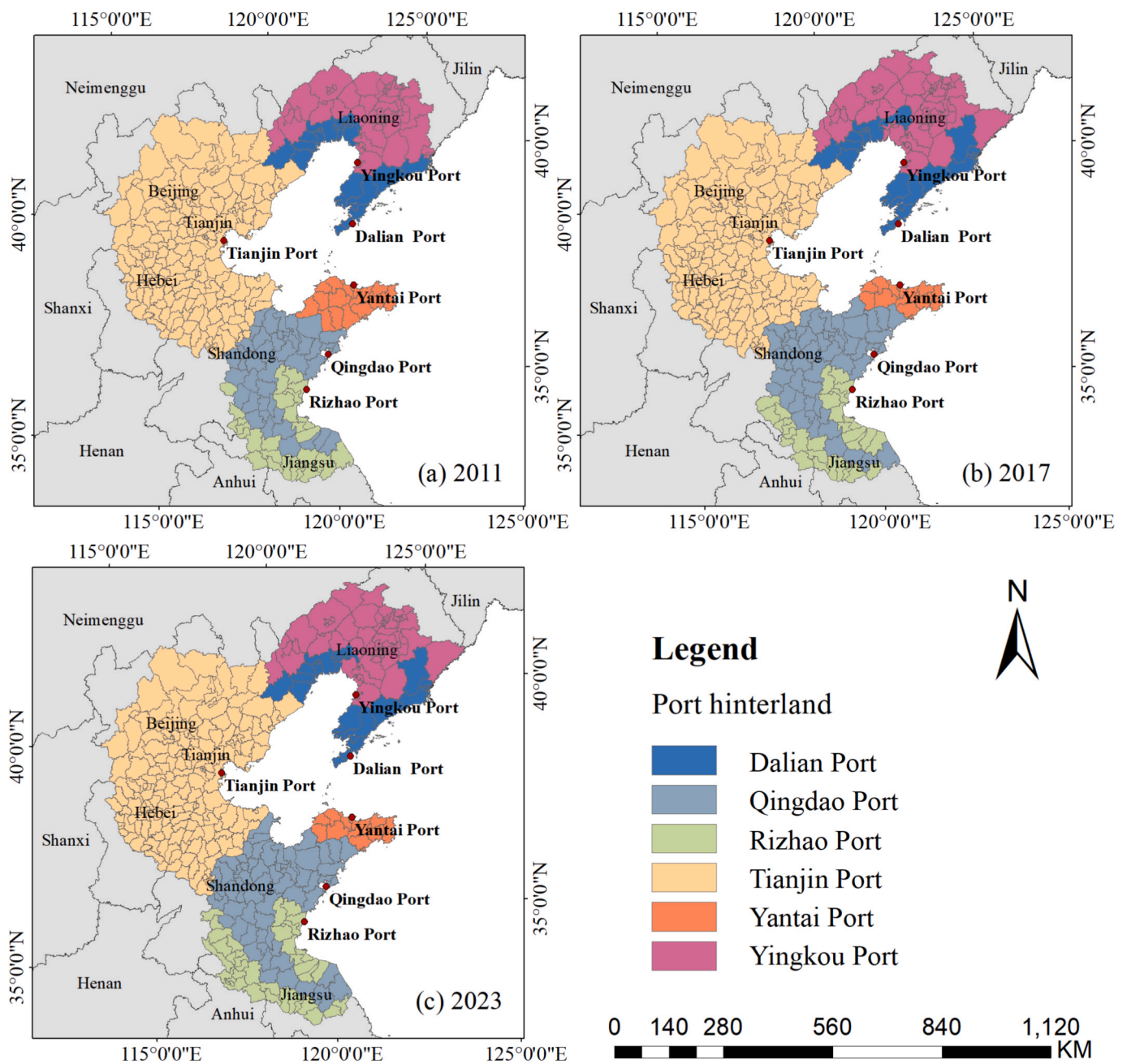


Fig. 7. Temporal dynamics of the hinterland distribution of major container hub ports in the Bohai Rim region (2011, 2017, 2023).

Table 7

Spatiotemporal evolution in the number of hinterland counties of major container hub ports in the Bohai Rim region (2011, 2017, 2023).

Year Port	2011	2017	2023	Average Number
Dalian	25	26	27	26
Qingdao	45	55	65	40.67
Rizhao	28	30	37	31.67
Tianjin	177	172	174	174.33
Yantai	16	12	12	13.33
Yingkou	55	59	58	57.33
Total Number	346	354	373	357.67

these ports highlights the critical importance of transport infrastructure in enabling effective regional integration.

Furthermore, economic development trends within the hinterland

regions significantly influence port hinterland dynamics (Hui and Hao, 2020). Ports situated in economically dynamic regions, such as Qingdao and Tianjin, exhibit faster hinterland growth due to strong synergies with industrial hubs. These ports benefit from the expanding industrial and commercial sectors in their hinterlands, facilitating smoother cargo flows and enhancing their economic integration. Conversely, ports like Yingkou and Dalian, which are more reliant on resource-based industries, show slower growth. This limited expansion is largely due to the slower pace of industrial diversification and regional economic transformation. Ports in more traditional industrial areas face greater challenges in tapping into new, emerging markets compared to those situated in rapidly evolving urban and industrial hubs (Wan, 2012).

An additional factor that must be considered is the policy-driven economic shifts within the region. Policy interventions, such as the establishment of special economic zones or regional industrial policies, can either promote or hinder hinterland growth (Zhong et al., 2023).

Ports situated in regions with favorable industrial and economic policies benefit from accelerated growth, while those in less dynamically supported areas face more significant obstacles in expanding their influence.

Inter-port competition and cooperation also play a critical role in shaping hinterland dynamics. As ports like Qingdao and Tianjin expand their territories, competition for regional cargo intensifies. However, this competition can sometimes lead to cooperative strategies, where ports collaborate on logistics services or infrastructure development to optimize resource usage. In practice, such cooperation—if embedded within formalized regional planning frameworks—could mitigate redundant infrastructure investments and help align green development goals across the cluster. This balance between competition and cooperation is crucial for maintaining efficiency in the regional logistics system.

These driving factors underscore the interrelationship between sustainability, infrastructure, and economic dynamics, emphasizing the need for ports to integrate green development strategies, enhance transport infrastructure, and foster regional economic integration. Policymakers and port authorities must prioritize investments in green technologies, multimodal transport systems, and the diversification of industrial activities within hinterland regions. By doing so, they can create more resilient, competitive, and sustainable port systems that not only expand their hinterlands but also ensure better economic and environmental outcomes for the region.

Strategically, these findings suggest that port authorities in the Bohai Rim region should focus on enhancing intermodal connectivity, promoting green transport solutions, and leveraging sustainability performance as a key driver for hinterland expansion. Moreover, fostering collaborative frameworks between competing ports could yield benefits in terms of shared resources, better logistical coordination, and overall improved regional efficiency. This approach will ensure more equitable access to markets, strengthen environmental performance, and solidify the competitiveness of Bohai Rim ports in the global arena—ensuring that growth trajectories are not only competitive but also complementary, thereby maximizing collective advantages in global maritime networks.

5. Discussion

The empirical analysis reveals that the spatiotemporal evolution of port hinterlands in the Bohai Rim region is not merely a result of geographical proximity or administrative delineation but is increasingly shaped by port sustainability performance. Ports demonstrating higher sustainability scores—driven by infrastructure modernization, carbon emission control, and intermodal connectivity—tend to exhibit stronger spatial influence and broader hinterland reach. This underscores the role of green competitiveness as a new determinant in shaping port-inland interactions, a conclusion that aligns with the findings of Yin et al. (2021b) and Li et al. (2024b).

The study also finds that the expansion and restructuring of hinterlands are strongly moderated by differentiated development strategies. Qingdao and Tianjin ports, for example, not only lead in sustainability metrics but also show robust inland penetration through multimodal transport integration (Guo et al., 2023) and sustained investment in hinterland transport corridors. Conversely, ports like Dalian and Yingkou, despite having established logistics foundations, exhibit limited hinterland dynamism, reflecting relatively stagnant progress in sustainability transformation and weaker alignment with emerging regional logistics demands. These findings suggest that sustainability transitions act not only as performance indicators but also as spatial drivers, amplifying or constraining the regional influence of ports (Li et al., 2024b).

To quantify this relationship, the enhanced field strength model integrates port sustainability assessments with land accessibility metrics to capture the composite forces driving hinterland formation. Compared

with traditional static boundary methods, this dynamic approach more accurately reflects how spatial influence shifts with port-level improvements in environmental and logistical performance. The analysis further reveals increasing inter-port spatial overlaps in areas such as Hebei, Shandong, and Liaoning, signaling intensified competition and potential synergy among regional ports. These overlaps not only illustrate the rising spatial reach of ports but also raise governance challenges in coordinating investment, cargo distribution, and environmental policies.

Moreover, the findings highlight the critical role of policy alignment and institutional coordination in shaping hinterland evolution (Zhong et al., 2023). Ports embedded in regions with consistent policy support for green logistics, multimodal transport integration, and regional planning—such as Qingdao—demonstrated stronger spatial gains. Conversely, ports lacking policy backing or regional cooperation frameworks have struggled to expand their hinterlands despite geographic or industrial advantages. This emphasizes that sustainability-led spatial expansion is not solely a technological or infrastructure-driven process, but also one that depends on cross-sector coordination and institutional capacity (Guo et al., 2023; Yin et al., 2021b).

From a policymaking and management perspective, these findings suggest that port authorities in the Bohai Rim region should strengthen multimodal transport corridors—particularly sea-rail interconnectivity—to support hinterland expansion while reducing environmental pressures from road freight. For ports constrained by geography or infrastructure, targeted strategies should prioritize operational efficiency, smart technology deployment, and low-carbon services over extensive spatial growth. Increasing spatial overlaps among core ports highlight the need for cross-port governance mechanisms to foster synergy, reduce redundancy, and improve overall logistics efficiency. Incorporating sustainability metrics—such as carbon intensity, modal shift performance, and inland accessibility—into planning frameworks and incentive schemes will further align port development with ecological goals.

At a system level, the increasing alignment of hinterland areas, the reduction in inter-port accessibility disparities, and the emergence of overlapping field zones all indicate a transition from fragmented port dominance to a more integrated and synergistic regional logistics landscape. These dynamics not only reflect competitive realignments but also offer strategic opportunities for functional complementarity and shared hinterland governance.

6. Conclusions

This paper presents an analytical framework to investigate how green development reshapes the spatial influence of hub ports in the Bohai Rim region. A multidimensional evaluation system is constructed to measure port sustainability, encompassing economic performance, infrastructure, transport integration, and environmental impact. Composite sustainability scores are derived through a hybrid weighting strategy that combines Entropy Weight Method (EWM), Criteria Importance Through Intercriteria Correlation (CRITIC), and Principal Component Analysis (PCA), followed by the TOPSIS method for comprehensive assessment. Based on these scores and regional port distribution, the Wilson model is employed to estimate the general hinterland reach. To further refine the spatial delineation, an enhanced field strength model is developed, integrating sustainability scores with OD-based land accessibility indicators. Hinterland boundaries are then determined using the maximum membership principle, allowing for a dynamic representation of evolving port-inland interactions driven by sustainability performance.

Empirical findings across the 2011-2023 period demonstrate that:

- (1) Sustainability performance is a key determinant of hinterland expansion. Ports that score higher on green development,

transport connectivity, and economic integration exhibit broader and deeper hinterland influence.

- (2) The Bohai Rim port system evolves toward a more integrated and overlapping spatial structure, particularly among Qingdao, Tianjin, and Rizhao, shifting from fragmented dominance to a more tiered, interlinked configuration.
- (3) The hinterland expansion patterns differ significantly across ports. Qingdao and Rizhao experienced pronounced inland growth, largely attributed to advances in multimodal transport and green logistics initiatives. In contrast, Dalian and Yantai remained relatively stagnant, hindered by geographical constraints and limited sustainability improvements.
- (4) Underlying these spatial dynamics are four driving mechanisms: (i) sustainability-oriented investment, (ii) upgrades in multimodal infrastructure, (iii) alignment with regional development policies, and (iv) adaptive strategies in response to geographical limitations.

In contrast to prior studies that focus solely on economic performance or omit hinterland dynamics altogether, this study introduces a comprehensive, sustainability-driven analytical system. The integrated use of the EWM-CRITIC-PCA weighting scheme and TOPSIS ensures a more robust and objective assessment of port sustainability. The combined application of the Wilson model and an enhanced field strength approach allows for a dynamic, spatially explicit evaluation of hinterland evolution. By embedding green development as a core performance lens, this research moves beyond traditional port evaluation to offer a forward-looking perspective aligned with global sustainability targets—providing actionable insights for coordinated port planning, regional logistics governance, and sustainable maritime network optimization.

However, this study has certain limitations. The analysis is based on six major ports due to data availability, and the accessibility and sustainability indicators rely partly on derived or aggregated sources rather than real-time transport flow data. Future research could expand the port sample, incorporate machine learning-based weighting schemes, and adopt higher-resolution spatiotemporal data to further refine and validate the proposed framework.

By addressing the intricate interplay between sustainability, transport integration, and spatial dynamics, this study not only advances the methodological toolkit for port hinterland analysis but also contributes to the broader discourse on sustainable infrastructure development in a globalized economy. The findings underscore that port systems, as critical nodes in international trade and regional economic integration, must embrace green and resilient strategies to remain competitive in an era of environmental constraints and shifting trade patterns. Insights from the Bohai Rim case can inform policymakers, planners, and industry stakeholders worldwide on how to harmonize economic efficiency with environmental stewardship, thereby fostering port networks that are not only competitive and connected, but also socially responsible and aligned with global sustainability agendas such as the United Nations Sustainable Development Goals (SDGs). In this way, the study's analytical framework and empirical evidence offer both a regional blueprint and a globally relevant reference for guiding the sustainable transformation of maritime logistics systems.

CRedit authorship contribution statement

Chong Ye: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Formal analysis, Conceptualization. **Tingshan Cai:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chenliang Zhang:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Wenting Cao:** Writing – review & editing, Visualization, Validation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2025.114095>.

Data availability

Data will be made available on request.

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