Multidimensional Assessment System for Economic Network Resilience of Bohai Rim Region Based on Listed Enterprise Data

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Abstract. Improving the economic network resilience of urban regions is conducive to alleviating regional development imbalances and promoting planning decisions to support the in-depth combination of theoretical methods and practical applications and the development of informatization and intelligence in national territory spatial planning. However, existing studies have not captured complexity and multidimensionality of urban economic resilience comprehensively, making it difficult to guide the development and maintenance of urban economic networks effectively. Therefore, based on the data of listed companies in the Bohai Rim Region, this study establishes a directed economic network model through composite factor weighting and constructs a multi-dimensional assessment system of urban economic network resilience to measure and assess the resilience of the overall economic network and the economic resilience of the node cities in 2010, 2015, and 2021. The results found the economic network in the Bohai Rim Region has strong structural resilience, forming a spatial pattern of double-core and multiple points around Beijing and Tianjin. The resilience level of the economic network has been increasing, but the evolution level of resilience in different dimensions is heterogeneous, and the spatial matching still needs to be improved. This study helps to identify regional economic network links, improve regional economic resilience, enhance regional synergistic development, improve urban governance, and promote high-quality regional economic development.

Keywords: Economic Network; Bohai Rim Region; Resilience; Multi-dimensional Assessment

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1 Introduction

With the development of globalization, the organization of the urban system has gradually changed from a central place to a multi-center networked model [1,2]. Economic activities are an integral part of cities, and thus, the construction of urban economic networks plays an important role in regional complex network systems, among which the correlated network model proposed by the GaWC research group through the headquarter-branch method is more widely recognized [3]. The network structure reflects the state of its constituent elements in space, and the differences in structural indicators such as node location, connection status, path length, etc., directly reflect the spatial layout and agglomeration characteristics of urban economic activities [4,5], and affect the regional function and resilience [6,7]. Resilience refers to the ability of an object to recover from deformation under external forces [8]. The concept extends to a wide range of economic, ecological, and social fields, in which the combination of the resilience concept with regional space emphasizes the resilience of urban survival and change [9]. The resilience of a regional economic network refers to its ability to cope with shocks and to recover, maintain, or improve its original system characteristics and key functions in the face of external disturbances [10]. With the acceleration of urbanization and the deepening of regional cooperation, studies on the resilience of regional economic networks can provide decision-making references for the government and enterprises, optimize resource allocation, promote high-quality development, optimize the spatial pattern of the national territory, and promote the urban region to achieve high-quality development.

The current research on the assessment of the resilience of regional economic networks focuses on two aspects. One is the assessment of the overall network resilience measurement, such as J. Crespo from the perspective of industrial clusters to study the influence factors of resilience, the degree distribution characterized by network hierarchy, and the degree correlation characterized by network assortativity as important indicators to measure the resilience of regional network structure [11]. However, the study only evaluates the network through partial indicators and does not unify and generalize the indicators into a method that can be easily replicated. P. Hall focuses on the assessment of the resilience of the spatial structure of regional economic networks through the data on business linkage networks and commuting in eight polycentric city regions in Europe [12]. In addition, R. Lang also conducts an in-depth study on the relationship between cluster networks and population, public policy, etc., in 10 megapolitan areas in the United States [13]. However, such studies only focus on the overall regional network resilience and neglect the interaction between the economic resilience of node cities and overall network resilience.

The second is the assessment of the economic resilience of node cities. Some scholars analyze it through the core variable method, such as S. Brakman using the number of unemployed and GDP changes to measure regional economic resilience [14], and R. Martin who measures the economic resilience of cities through the ratio of the change in actual economic output to the expected change in output [15]. Scholars have also used the construction of a reasonably weighted indicator system for multi-dimensional comprehensive analysis of economic resilience. For example, the European

Commission put forward the Regional Competitiveness Index, wherein the resilience strength distribution in each region was categorized into five grades based on multiple urban indicators [16]. However, the selection and weight distribution of indicators of such research often suffers from issues such as reliance on a single indicator, lack of standardized criteria, and absence of an objective basis, and thus, the complexity and multidimensionality of urban economic resilience cannot be fully captured.

To fill the above research gap, this study selects the Bohai Rim Region as the research scope, establishes a directed economic network model through the weighting of composite enterprise economic indicators, and constructs a multi-dimensional assessment system of the resilience of the regional economic network. Then, it measures and evaluates the economic resilience of the overall economic network and node cities and explores the interplay of the resilience of the node cities with the resilience of the overall network. This study evaluates the overall resilience of the economic network from five dimensions: hierarchy, assortativity, transmission, redundancy, and agglomeration. It enriches the assessment indicators from the multi-dimensional perspectives of resistance dimension, recovery dimension, and evolution dimension and objectively allocates weights to measure and assess the economic resilience of the network's node cities. The conclusions of the study provide insights to optimize the spatial development pattern of the national territory and explore the application of the new assessment system for assessing the resilience of urban economic networks.

2 Method

2.1 Study Area and Data Sources

The Bohai Rim Region in northern China is chosen as the study area. The region contains municipalities directly under the Central Government of Beijing and Tianjin and the provinces of Hebei, Shandong, and Liaoning. The region covers an area of 518,000 square kilometers, has a population of about 230 million people, and is known as one of the three largest urban regions in China, together with the Yangtze River Delta region and the Guangdong-Hong Kong-Macao Greater Bay Area. The Bohai Rim Region is less frequently mentioned in current research on the resilience of urban economic networks, and its importance and development potential in the regional economy have been neglected to a certain extent.

Three sources of data provided the basis for this study. This study counts 929 enterprise head offices that can check registered capital in 2010, 2015, and 2021. The relationship between corporate headquarters and branches is derived from the Green Shield Enterprise Credit System (https://www.11315.com/), and data retrieval through the headquarters' corporate name yielded a total of 41,486 data on the names and registered locations of branches in the study area. At the same time, a secondary query is conducted using Tianyancha (https://www.tianyancha.com/) to eliminate anomalous information and make additional corrections to the missing information. The data on enterprise registered capital and inter-annual changes are obtained from the China Stock Market & Accounting Research Database (CSMAR) (https://data.csmar.com/). The data are obtained through the registered capital library of invested units in its corporate financial statement library. After screening and elimination, the changes in registered capital and enterprise reserves in 2010, 2015, and 2021 were obtained, totaling 8066 rules. Finally, the relevant statistical yearbook data are downloaded through the official website of each city's statistical bureau to obtain basic data on the municipalities therein.

2.2 Network Construction and Overall Resilience Assessment

This study is based on the correlated network model constructed by the GaWC research group, which responds to inter-city connectivity in terms of the distributional relationship of corporate headquarters and branches [3]. However, because the single data of enterprise headquarters branches between different cities often cannot accurately summarize the complexity of the urban network, this study innovatively calculates the linkage strength between city nodes through the weighting of enterprise's scale and registered capital based on the number of enterprise headquarter-branches. It constructs a directed urban economic network matrix. This study defines the formula of linkage strength as follows:

$$X_{ij} = a_{ij}c_{ij}\frac{B_i}{H_i} + a_{ji}c_{ji}\frac{B_j}{H_j} \quad (1)$$

where X_{ij} is the linkage strength between network nodes i and j; a_{ij} is the total number of branches in node j of the enterprises, headquarters of which are in node i; c_{ij} is the average registered capital of enterprises with headquarters in node i when they register branch offices in node j; $\frac{B_i}{H_i}$ is the ratio of the total number of global branches owned by all headquarters in node i to the total number of headquarters in node i; a_{ij} and c_{ij} are the corresponding opposite vector values; and $\frac{B_i}{H_i}$ is the ratio of the total number of global branches owned by all headquarters in node j to the total number of headquarters in node j.

In terms of the assessment of the overall network structure resilience of urban regions, this study comprehensively draws on relevant studies, takes hierarchy, assortativity, transmission, redundancy, and agglomeration as the main influencing factors affecting the structural resilience of the economic network, and determines the degree distribution, degree correlation, average path length, average number of independent paths, local clustering coefficient, and average clustering coefficient as the assessment indices of overall network structure resilience. The specific calculation methods and assessment indices are as follows (Table 1.).

Table 1. The overall resilience of the regional economic network structure assessment.

Indicator	Computational formula	Explanation and meaning of formula
Hierarchy	$\log(K_i) = \log(C) + a\log(K_i^*) \quad (2)$	Where K_i is the weighted degree of node i, K_i^* is the rank of the weighted degree of node i in the network, C is a constant; a is the slope of the degree distribution curve.

		It measures the capacity and distribution characteristics of the hierarchy that accommodates the nodes in the network from the degree distribution response.
Assortativity	$\bar{K_i} = \frac{1}{K_j}\sum_{i \neq j \in G} K_i$ (3) $\bar{K_i} = B + bK_i$ (4)	Where K_i is the weighted degree of node i, K_j is the weighted degree of the neighboring node j of the node i, $\bar{K_i}$ indicates the average of the weighted degree of the neighboring node j of the node i, G is the set of all neighboring nodes of the city, B is a constant, b is the degree correlation coefficient. It measures the correlation between nodes in a network from degree correlation response.
Transmission	$L = \frac{2}{n(n+1)}\sum_{i \geq j} d_{ij}$ (5)	Where L is the average path length of the network, n is the sum of the number of nodes, d_{ij} is the shortest paths from node i to node j. It measures the access efficiency of each type of flow in the network, in terms of average path length response.
Redundancy	$V = \frac{1}{n(n-1)}\sum_{i \neq j \in G} n_{ij}$ (6)	Where V is the average number of independent paths in the urban region,n_{ij} is the number of independent paths between node i and node j, n is the sum of the number of nodes. It measures the fault tolerance of transmission paths in the network, as reflected by the average number of independent paths.
Agglomeration	$C_i = \frac{2E_i}{W_i(W_i-1)}$ (7) $C = \frac{1}{n\sum_i^n C_i}$ (8)	Where W_i is the sum of the number of edges from nodei connected to neighbors, E_i is the number of edges that actually generated between the node i and its neighbors. It measures the the denseness of the network, in terms of local clustering coefficients and average clustering coefficient responses.

2.3 Cities Resilience Assessment

In this study, 12 secondary indicators that correspond to the resilience level of network node cities in three dimensions, namely resistance, recovery, and evolution, are selected to respond to the ability of cities to cope with risks and changes.

Second, to avoid the subjectivity of artificial judgment, the entropy value method is used to determine the weights of the indicators in the evaluation of urban economic resilience. At the same time, the linear weighted synthesis method is used to calculate the value of urban economic resilience assessment. A larger value implies that the city has higher economic resilience level. Among them, the entropy value method illustrates the importance of the indicators through the degree of variation of each indicator value, and the smaller the information entropy of the indicators means the larger their weights are, and vice versa [17]. The specific calculation method is as follows:

All the indicators are first normalized. A larger positive indicator represents a more resilient city economy, and the opposite is true for a negative indicator.

$$\text{Positive indicators: } x'_{ij} = \frac{x_{ij} - \min\{x_{1j}, \cdots, x_{nj}\}}{\max\{x_{1j}, \cdots, x_{nj}\} - \min\{x_{1j}, \cdots, x_{nj}\}} \tag{9}$$

$$\text{Negative indicators: } x'_{ij} = \frac{\max\{x_{1j}, \cdots, x_{nj}\} - x_{ij}}{\max\{x_{1j}, \cdots, x_{nj}\} - \min\{x_{1j}, \cdots, x_{nj}\}} \tag{10}$$

Where x_{ij} is the value of the indicator j in the city i(i =1,2.$\cdots$,n;j =1,2,$\cdots$,m), x'_{ij} are normalized values, and for convenience, the normalized data in the following calculations are still noted as x_{ij}.

Calculate the proportion of city i under the indicator j:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{11}$$

Calculate the entropy value of the indicator j:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{12}$$

Where $k = 1/\ln(n)$, which satisfies $e_j \geq 0$.

Calculate the information entropy redundancy of the indicator j:

$$d_j = 1 - e_j \tag{13}$$

Calculate the weights of the indicators:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{14}$$

Specific indicators are obtained through the selection and weighting of the indicators and the positive and negative distinction of the impact of each indicator on urban resilience as shown in Table 2.

Table 2. Cities economic resilience assessment Indicators and measurement methods.

Dimensionality	Indicator	Measurement methods	Variable symbol	Weight
Resistance dimension	Level of economic development	Gross Domestic Product (GDP)	+	0.1025
	External trade dependence	Total value of external import and export trade / GDP	-	0.0104
	Financial security	Balance of domestic and foreign currency deposits and loans of financial institutions	+	0.2215

	Employment level	Number of employees at the end of the year / total population	+	0.0125
Recovery dimension	Consumption potential	Balance of residents' RMB savings deposits / total population	+	0.0596
	Industrial structure	Primary industry value added share *1 + Secondary industry value added share *2 + Tertiary industry value added share *3	+	0.0037
	Industrial output	Gross industrial output value above scale	+	0.0763
	Reinstatement of guarantees	Number of public administration and social organizations (health, social security and social welfare sector)	+	0.0900
Evolution dimension	Factor configuration capacity	Total investment in fixed assets of the whole society	+	0.0824
	Financial support	General public budget expenditure	+	0.1596
	Innovation level	Number of patents authorized	+	0.1759
	Industrial level	Total electricity consumption/GDP	-	0.0057

Finally, using the K-means clustering algorithm, the three-year economic resilience assessment scores of 43 cities in the Bohai Rim Region were divided into eight subclasses and three major resilience levels and visualized in ArcGIS. The K-means clustering algorithm classification method can identify the city nodes with different types of economic resilience and divide them [18].

3 Results and Discussion

3.1 Overall Network Resilience Assessment Results

Table 3. show that the changes of the hierarchy, assortativity, transmission, redundancy and aggregation of economic network in the Bohai Rim Region by time period.

Table 3. Summary of measurement results of overall network structural resilience.

particular year	Hierarchy/a	Assortativity/b	Transmission/L	Redundancy/V	Aggregation/C
2010	-1.603	0.041	1.721	1.208	0.677
2015	-1.51	0.0262	1.639	1.914	0.72
2021	-1.564	0.0142	1.57	2.819	0.75

Hierarchy

All the slopes a of the three-degree distribution fitting curves are larger. The |a| is between 1.5 and 1.6, indicating that the economic network in the Bohai Rim Region has a significant hierarchy (hierarchical features). In the Bohai Rim Region, the development gap between core and node cities is large, and the network has obvious non-homogenization, with the core city currently pointing to Beijing, followed by Tianjin and Langfang. From the development and evolution of the degree distribution coefficient, the status and driving effect of the core city in the urban region has a process of decreasing and then increasing.

Beijing's neighboring cities, such as Tianjin, Langfang, and Tangshan, have a wider radius by adsorbing Beijing to upgrade their city hierarchies. Meanwhile, Jinan and Qingdao in Shandong Province and Dalian and Shenyang in Liaoning Province have higher city hierarchies and stronger economic resilience due to the characteristic industries or political factors of being located in the capitals of the provinces, among other reasons. In the Bohai Rim Region, the network led by Beijing as the core is more robust to disturbances from outside the system, and Beijing's significant position in the urban agglomeration can effectively trigger the conformity effect of other node cities, increasing the cohesion within the Bohai Rim Region. However, at the same time, Beijing's dominance is very serious, and the whole Bohai Rim Region adsorbs Beijing as a distribution point, forming an obvious regional lock [19]. In this case, if Beijing itself fails or breaks down, the entire economic network of the Bohai Rim region will likely lose its vitality, and the vulnerability of the network will be exacerbated.

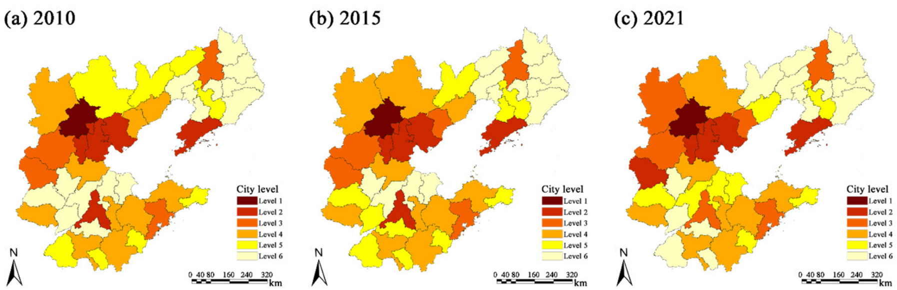

Fig. 1. Urban economic network city-level spatial pattern by time period.

Assortativity

The results of the degree correlation fitting curve (Fig. 2.) shows the economic network in the Bohai Rim Region has assortativity links. The core cities give more consideration to linking with cities of similar levels of aggregation and comparable scale in their external links, which is a "core-core" linkage network. Specifically, the degree of assortativity correlation decreases year by year, from 0.041 to 0.0142, and the assortativity in the network is gradually weakening.

The weak assortativity of the economic network of the Bohai Rim in the case of high hierarchy will lead to the neglect and limited development of the peripheral cities in the urban agglomeration, exacerbating the closed structure of the network and inhibiting the structural resilience of the network. Frequent exchanges between the core cities of the city cluster will bring regional functional conglomeration, reducing the chances of the occurrence of new information input in the Bohai Rim. Once the external environment changes or the core node city, such as Beijing, malfunctions, the entire Bohai Rim region will have difficulty to adapt and adjust in a timely manner, and the regional risk increases. However, the weakening of the assortativity in the network in the past ten years indicates that the degree of dependence of the city cluster on the core city is gradually weakening, which in turn can weaken the potential crises of path dependence and regional lock-in brought by the high-level hierarchy. However, the resilience of the network structure of city clusters is being gradually improved, and is in a state of healthy development.

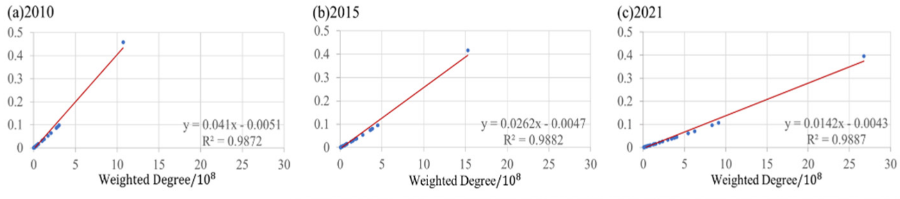

Fig. 2. Urban economic network degree correlation by time period.

Transmission

From the perspective of network transmission efficiency, the average path length of the economic network in the Bohai Rim Region narrows from 1.721 to 1.57, indicating that the overall path transmission efficiency is generally high, and the transmission of the flow transits to two nodes between node cities. From the perspective of node transmission efficiency, the Beijing-Tianjin-Hebei area led by Beijing and the central Bohai Rim Region formed by southern Liaoning Province and northeastern Shandong Province have a frequent occurrence of radiation and adsorption activities, high information transmission efficiency, and play a more important role in the flow of information.

The decrease in the average path length indicates that the extra cost of flow diffusion is decreasing, which is conducive to the occurrence of activities such as people's activities, enterprise investment, and information transmission in the Bohai Rim Region. The accessibility and diffusivity of the whole region is gradually increasing, enabling it to adapt and recover faster in the face of crises, significantly strengthening the resilience of the network. Meanwhile, combined with the hierarchy of the economic network, the Beijing-Tianjin-Hebei area led by Beijing clearly has the core position and the strongest intermediary role in the network transmission, followed by the central Bohai Rim formed by the south Liaoning Province and the northeast Shandong Province and that the core nodes are the key to improving the efficiency of the information transmission and the resilience of the economic network structure in the Bohai Rim Region.

Redundancy

In terms of network redundancy assessment, the average number of independent paths in the economic network of the Bohai Rim is increasing, indicating improved network stability. Specifically, the average number of independent paths grew from 1.208 to 2.819, indicating that the fault-tolerance of transmission paths is increasing annually, and the stability of the normal operation of city clusters after disturbances is improving annually. In terms of evolutionary characteristics, the growth rate of the average number of independent paths in the economic network of the Bohai Rim is significantly higher in 2015–2021, the alternate paths of the network gradually increased, the diversity of paths continued to improve, and the network stability grew rapidly, which is conducive to the strengthening of the network resilience of the urban agglomeration.

Agglomeration

The average clustering coefficient of the economic network in the Bohai Rim increased from 0.677 to 0.75, indicating that the Bohai Rim has a more obvious clustering effect in terms of enterprise investment and other aspects. The spatial distribution map of the local clustering coefficients (Fig. 3.) shows that the economic network is centered around the three core clusters of Beijing, Shenyang-Dalian, and Qingdao to form densely connected clusters.

From the perspective of network structural resilience, the overall degree of agglomeration of city clusters is higher, and the efficiency of resource integration within the network is improving, which is conducive to the win-win cooperation of the city clusters, enhancing the overall risk-resistant ability of the region and providing a certain degree of robustness. However, preventing the uncontrolled increase of the agglomeration effect is also necessary because it can form a regional lock that leads to the rigidity of the network and reduces the adaptive capacity of the city cluster. Analyzing from the perspective of node resilience, the local clustering coefficient of Beijing, Tianjin, and Langfang fluctuates between 0.27 and 0.62, indicating that the radiation and dispersion ability of the core city led by Beijing is greater than its driving ability. Most of the network is a unidirectional link between the ordinary node cities and Beijing, and interactions among the non-core cities are lacking. In addition, Zhangjiakou, Chengde, Tieling, Fushun, and other edge cities have structural holes in the linkage coefficient [20]. These cities are have the advantage in the entry of outside information because of their proximity to the core cities and the relatively open network structure, enhancing the structural resilience of the economic network in the Bohai Rim.

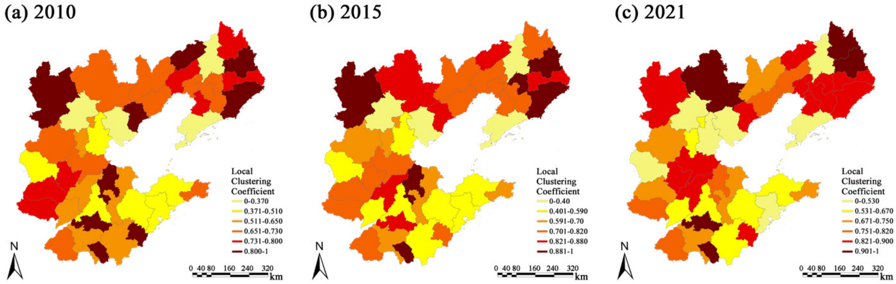

Fig. 3. Distribution of local clustering coefficients of urban nodes by time period.

3.2 Node cities resilience assessment results

Integrated Assessment Results

After normalizing the 12 secondary indicators of 43 cities within the Bohai Rim in the three dimensions, the weight share of each indicator is derived through the entropy value method. The linear weighted synthesis method was applied to calculate the cities' comprehensive economic resilience evaluation value, and the results for 2010, 2015, and 2021 were synthesized as follows:

Table 4. Weight values and level of cities economic resilience

City	2010		2015		2021	
Beijing	0.949517	1	0.91895	1	0.952839	1
Tianjin	0.497639	2	0.48988	2	0.433708	2
Qingdao	0.270557	3	0.27785	3	0.310435	3
Ji'nan	0.256728	4	0.22293	4	0.288814	3
Shijiazhuang	0.172003	5	0.18238	5	0.210605	4
Tangshan	0.170472	5	0.16258	5	0.20302	4
Shenyang	0.234439	4	0.20603	4	0.197061	4
Yantai	0.191935	5	0.18641	5	0.179399	5
Weifang	0.168553	5	0.174	5	0.172704	5
Dalian	0.290949	3	0.21031	4	0.170741	5

Through the K-means clustering algorithm of the results of the city economic resilience calculation, when k=8, the classification is obvious, indicating that it can better respond to the economic resilience level of different cities. The cities in the Bohai Rim Region will be divided into the Core Cities I, II, and III, Important Cities I and II, and Node Cities I, II, and III based on high and low comprehensive economic resilience score.

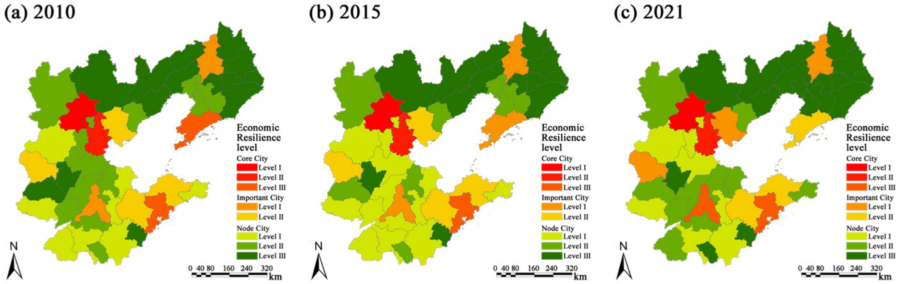

Fig. 4. Classification of resilience recovery in Bohai-Rim region by time period.

Hierarchical Relationship Analysis

Table 4. and Fig. 4. show that the economic resilience grade of the Bohai Rim Region presents the characteristics of two cores and multiple points, which generally shows Beijing and Tianjin as the regional economic core, Qingdao and Jinan, and the comprehensive economic resilience of Dalian and Shenyang in the two wings of the distribution of cities, and the rest of the cities as the complementary distribution characteristics.

In the three time points measured, the comprehensive economic resilience ratings of Beijing and Tianjin are Core City I and II, respectively. Beijing, as the capital of the People's Republic of China and a national central city, is the most important political, economic, and cultural center in the Bohai Rim region, an important node in the city's economic network, and also the most economically resilient city in the Bohai Rim region. Tianjin, adjacent to Beijing, is Beijing's railroad transportation route to northeast and east China. It is also a port for ocean shipping, with a vast internal hinterland and convenient external transportation. As a municipality directly under the central government and the largest coastal open city in the north, Tianjin has strong comprehensive economic resilience as an important bipolar node in the Bohai Rim and Beijing. Tianjin also plays a decisive role in the overall economic resilience of the network and the composition of essential functions.

Ji'nan and Qingdao, Shijiazhuang and Tangshan, and Shenyang and Dalian are the corresponding provincial administrative centers and sub-provincial cities, all of which are above the level of important cities. The comprehensive economic resilience of these cities in the Bohai Rim Region are in the middle position, which is the regional scope of the important city nodes. These nodes include important provincial administrative centers, such as Jinan, Shijiazhuang, and Shenyang, regionally important industrial cities such as Tangshan, and foreign trade ports such as Dalian and Qingdao. Each of these cities has its strengths and contributes a different role in the resilience of the network economy.

Yantai and Weifang, as important nodes of the localized city cluster in Shandong Peninsula, have improved their economic resilience level in the city cluster over time, transforming from node to important cities, and together with Jinan and Qingdao, enrich the regional city tier in Shandong Peninsula, improving its economic resilience.

The remaining cities have relatively low economic resilience scores, performing at an ordinary level in the resilience domain, and are the node cities with the lowest rank, among which, most of the cities in the northern part of the Bohai Rim have relatively low levels of economic resilience. The lower comprehensive strength of these cities and the surrounding cities' competition and other limiting factor resulted in their weaker resistance, recovery, and evolution of the three dimensions of economic resilience. The poorer impact of the self-maintenance ability of these cities and the overall economic resilience of the regional city linkage network has a certain role in weakening the overall economic resilience. For the most important city cluster within the Bohai Rim, namely the Beijing-Tianjin-Hebei City Cluster, from 2010 to 2015, the level of economic resilience of the southern side of the city cluster, such as Dezhou, Tai'an, Liaocheng, etc., increased to the node city I. The city's impact resistance was enhanced, but from 2015 to 2021, it was once again downgraded to node city II level. Meanwhile, Langfang and Cangzhou were raised from node city II to node city I due to the support of regional economic policies and the construction of Xiong'an New Area.

Special Cities and Significant Urban Change

A comparison of the hierarchical nature of the economic network in the Bohai Rim and the economic resilience grade of the cities (Fig. 1. and 4.) shows that the two grades are basically the same, but there are still some special cities, such as Langfang. Due to its excellent geographic location near Beijing and Tianjin, it is the residence of a large number of Beijing-Tianjin enterprise branches, is close to the center of the network and has a prominent position in the urban economic network. A separate analysis of its urban economic resilience shows that Langfang does not have a city grade and economic risk resistance level that matches its location, and a grade mismatch can be observed in the urban economic network. Therefore, the development of cities near Beijing and Tianjin, such as Baoding, Xiong'an New Area, and Langfang, and the enhancement of their economic resilience level can further improve the overall stability of the network and the ability to resist risks.

The urban economic resilience ratings of some important cities have changed, such as Dalian's urban economic resilience rating dropping from Core City III to Important City II and Jinan's urban economic resilience rating rising to Core City III. The increasingly fierce competition in the international and domestic market of the traditional heavy and manufacturing industries gradually weakened Dalian's location advantages, and its overall income level became increasingly lower. The tense international trade policy environment and its impact on the import and export trade of Dalian resulted in the reduction of its economic resilience level. The economic resilience of Dalian has been reduced [21]. The Jinan metropolitan area planning [22] has resulted in the continuous development of the Jinan Metropolitan Area, with Jinan as the regional core, and the corresponding increase in the area's regional economic resilience level. The change in regional economic resilience level is influenced by regional economic development and national policy systems. The change in urban hierarchy also plays a certain role in the change of regional urban contact networks and overall economic resilience.

4 Conclusions

In this study, we constructed the economic network of the Bohai Rim Region through the number and size of the headquarter-branches of listed enterprises. We explored the economic network resilience evolution characteristics of the Bohai Rim by integrating the resilience assessment system of the economic network and network node cities. Further, at the level of overall network resilience, We also evaluated the overall resilience characteristics and evolution law of the regional economic network at the levels of overall network resilience and economic resilience of the network node cities from five attributes. We selected 12 indicator characteristics of the cities in three different dimensions, corresponding to the resilience of the city's economic level. We use the K-means clustering algorithm to classify the economic resilience of cities and analyze the overall resilience network characteristics of the region and the change characteristics of each node in depth.

At the level of overall network economic resilience, this study finds that the structural resilience of the economic network in the Bohai Rim Region is stronger, forming a spatial pattern of double-core and multiple points around Beijing and Tianjin, and the level of economic resilience is constantly rising. However, the level of resilience evolution in different dimensions also vary. The following features are specifically listed: (1) The hierarchy of the network is significant, and the heterogeneity of the economic network and the radiation effect of core cities are obvious. (2) The network is linked by "core-core" links, and the assortativity is gradually weakening. (3) The transmission path has good efficiency and the importance of nodes in the information flow is strong. (4) Fault tolerance of the transmission path is enhanced, and stability is improved. (5) The clustering effect is obvious around the three core clusters of Beijing, Shenyang-Dalian, and Qingdao, which form a dense cluster of links but with significant local differences.

At the level of economic resilience of network node cities, this study finds that (1) The economic resilience network of the Bohai Rim Region city cluster presents the characteristics of dual-core and multi-point, with the Beijing-Tianjin–dual-core grouping forming a strong core form. The provincial capitals and sub-provincial cities supplement it as an important node in the region. (2) The overall presentation of the center city's economic resilience grade is high; the grade of the surrounding region is insufficient to supplement. Hence, the spatial matching still needs to improve the development of the situation. (3) Over time, the overall resilience grade of the region first improves and then decreases. The overall economic resilience grade of Liaoning cities is lower, and the ability to resist blows is weaker. Shandong, part of the city's node regional resilience level, has increased, and the city's economic resilience around the Jinan metropolitan area has increased. (4) The city's economic resilience level is affected by the economic environment and regional development policies.

This study still has the following limitations. When measuring cities, only the resident population of the city is used as an indicator to measure city size, and the impact of intra-regional population mobility on urban resilience is not considered. When selecting the data of listed enterprises, no weighted division of different types of listed enterprises was performed. Thus, in future research, the precision of the study can be further improved, the time axis of the study can be shortened, and the impact of population mobility on urban resilience can be investigated. Different network resilience capabilities can also be divided according to the types of enterprises so as to enhance the scientificity and accuracy of the study.

This study helps to identify regional economic linkage networks, improve regional resilience in a targeted manner, alleviate regional development imbalance, promote the in-depth combination of theoretical methods and practical applications of planning decision support, and facilitate the development of quantitative research on national territorial spatial planning.

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