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Understanding coordinated development through spatial structure and network robustness:
A case study of the Beijing-Tianjin-Hebei region

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Abstract: In the context of accelerated globalization, intercity factor flows are becoming increasingly dependent on a reasonable and orderly spatial structure. Therefore, an in-depth study of the optimization and adjustment of spatial structure is essential for coordinated development. This study quantitatively evaluated urban development levels and introduced network analysis methods to analyse the spatial structure and robustness of development. The results indicated the following: (1) The urban development level in the Beijing-Tianjin-Hebei (BTH) region increased in all dimensions, and the transmission efficiency significantly improved. (2) The spatial structure of the BTH region has been relatively stable, as illustrated by the main pattern of the spatial distribution of central cities, with a trend towards contiguous development. (3) The ranking of network robustness is environment>society>economy, and the core network and key nodes are primarily located within the radiation of the three central cities of Beijing, Tianjin, and Shijiazhuang. (4) The coordinated development of the BTH region is effective but still needs to be optimized and adjusted, and the strategic significance of edge cities has not been completely exploited. This study aims to provide an emerging analytical perspective for optimizing regional spatial structure and promoting regional coordinated development.

Keywords: urban network; spatial structure; network robustness; coordinated development; Beijing-Tianjin-Hebei (BTH) region

1 Introduction

The rapid economic, technological, and information changes under the impact of globalization have led to the global urbanization of cities at an unprecedented scale and speed (Antrop, 2004). Under this rapid urbanization process, the intersection of economy, demography,

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labour market, and transportation facilities (Zou *et al.*, 2019; Huang *et al.*, 2020; Zhu *et al.*, 2022) has given rise to the spatial polarization effect of urban development. Human-land conflicts (Adam *et al.*, 2015; Ma *et al.*, 2020), uneven economic development (Xu and Jiao, 2021) and ecological degradation (McDonald *et al.*, 2011) occur frequently, and regional development inequalities are exacerbated by differences in development levels between regions (Hao and Wei, 2010; Liao and Wei, 2012; Li *et al.*, 2022). As the process of globalization and the development of regional integration continue to advance, transportation infrastructure and information technology have reinforced intercity connections, which have become more complicated and diverse. Cooperative intraregional development is more vital than ever to counteract the disadvantages of globalization and achieve sustainable development (Hirschi, 2010). Revisiting the relationships and linkages among regional cities to promote integrated development by regulating and guiding the relationships of urban spatial interactions (Frank and Hua, 1981; Shen, 2002) is crucial for promoting current urban and regional development (Liu *et al.*, 2020).

Coordinated development is in line with the current development trend and concept of regional integration and mainly emphasizes the relationships and degrees of connections between cities. It has become the prominent manifestation of regional development by promoting the joint development of multiple elements and valuing subsystems' cooperation and mutually beneficial coexistence. Unlike the harmonious development proposed for addressing intraregional differences and achieving regional averages, coordinated development is proposed to solve the problems of regional connectivity and cooperation mechanisms, such as market fragmentation, and block the free flow of factors to achieve overall regional connectivity, synergy, and competitiveness. Therefore, many countries and regions have identified coordinated development as the basis for achieving sustainable social development.

The transformation from a disorderly structure to an ordered structure within a region constitutes one of the fundamental elements of collaborative development. Thus, the primary mission of overcoming the imbalance of regional development is to optimize the spatial layout structure of the region. The continual optimization of regional spatial structure is conducive to the best allocation of resources and the mutual benefit of cities in a region, so spatial structure has become an essential characteristic and premise for supporting coordinated development.

As economic globalization and information technology continue to advance, the space of flows gradually replaces the space of places as the dominant paradigm and vital structure of urban systems (Castells, 1996), modern society is deeply integrated with cyberspace (Xie and Wang, 2023). The definition of "region" has transitioned from "territorial scope" to "borderless and relational" (Amin, 2004), which has resulted in greater attention being given to intercity connectivity and mobility. In this context, the openness and networked character of regions have been gradually emerging, and the complex network of intercity connections and factor flows has become an essential aspect of the regional spatial structure (Parr, 2004; Wang *et al.*, 2022); this coincides with the concept of coordinated development, which emphasizes intercity spatial connections.

Rapid urbanization in the BTH region has also contributed to an imbalance in intraregional development (Hu *et al.*, 2017; Han *et al.*, 2021). The high concentration of factors within the region has led to an imbalance in the scale system of urban agglomeration, and the number and scale of internal large and medium-sized cities remain small (Wang *et al.*, 2019). The polarization effect of Beijing and Tianjin has led to a continuous outflow of population, resources, and capital from Hebei Province, and the development goals and directions of small cities are unclear (Zhen *et al.*, 2019). Cities anticipate resolving common issues via synergistic development and establishing a close synergistic cooperation mechanism to achieve mutual benefit and a win–win situation (Fang, 2017). In 2015, the *Outline of Coordinated Development of the Beijing-Tianjin-Hebei Region* was introduced to decongest noncapital core functions, adjust regional economic and spatial structures, and achieve intensive internal development. Nevertheless, the severe polarization of internal development levels and the disparity of comprehensive strength have exerted intolerable pressure on the coordinated development of Beijing, Tianjin, and Hebei, and the problems of imbalance in the structure of the urban system, insufficient flow of factors and resources, and weak policy effects persist. In this scenario, ways in which to improve the collaboration and interaction between cities by optimizing the spatial structure and reasonably allocating factor resources has become the critical breakthrough for advancing coordinated development.

2 Literature review

Coordinated development is characterized by the ability of cities to break through the boundaries of administrative divisions and develop regional competitiveness with complementary advantages to achieve joint regional development (Ye *et al.*, 2019). Currently, the assessment of coordinated development is mainly focused on the coupled and coordinated evaluation of the social, economic, and environmental dimensions of cities in a region and explores the issue of development discrepancies at varying development levels (Cui *et al.*, 2019; Li and Yi, 2020; Fang *et al.*, 2021; Han *et al.*, 2021; Wang, 2022). This approach can be used to identify and solve the problems and deficiencies in the existing regional development process but is relatively weak in exploring the factors that hinder the further advancement of synergistic development at a deeper level. Thus, this approach cannot meet the urgent needs of the current coordinated development situation.

Spatial structure refers to the spatial form that is generated by the interaction of numerous elements within a regional space. A logical and orderly urban spatial structure can serve as the platform and carrier for optimizing regional resources, spatial allocation, and high-quality, coordinated economic development. As a direct representation of internal urban spatial connections, this structure depicts how cities are organized in terms of scale, function, and location inside a specific region (Anas *et al.*, 1998; Bertaud, 2004) and can be used to gauge regional stability and development levels. Examining regional spatial structure is tremendously valuable for effectively constraining dominant functions, promoting the proper and orderly flow of factors, and achieving coordinated development.

Following the principle that "understanding urban space implies knowing flows and networks" (Batty, 2013), people have steadily transformed their perspectives to address spatial structure-related issues in coordinated development. The positive interaction of economic, transportation, and information elements among cities has spawned the regional network coordinated development model, which has shifted the study of urban spatial structure to a networked, dynamic, and polycentric urban system and gradually replaced the hierarchy of central places as the primary form of intercity linkage (Castells, 2010). The urban network approach begins with a search for intercity linkages to reveal the spatial configuration of urban networks (Zhang *et al.*, 2021), emphasizing the importance of the structural dominance of cities in contemporary global and regional systems (Meijers, 2005; Meijers, 2007), and can clearly and accurately reflect the complicated relationships of subsystems within regions.

As horizontal, non-hierarchical systems composed of cities with either complementary/vertical or synergistic/cooperative interrelationships (Camagni *et al.*, 1994), urban networks always have a structure that determines their function (Strogatz, 2001). For many years, scholars have researched urban functions (Zhen *et al.*, 2019; Fang *et al.*, 2020; Feng *et al.*, 2022; Wei *et al.*, 2022), spatial structures (Zhang *et al.*, 2020; Liu *et al.*, 2021; Yang *et al.*, 2022; Song *et al.*, 2023), and network evolution mechanisms (Li *et al.*, 2019; Li *et al.*, 2020; Zhang *et al.*, 2022a; He *et al.*, 2023) based on intercity linkages from various perspectives (Wall and Van der Knaap, 2011; Lao *et al.*, 2016; Chong and Pan, 2020; Zhang *et al.*, 2021; Ma *et al.*, 2023) but have neglected to investigate the robustness of network structures within a region. Although cities in the same region share similarities, subjective and objective factors, such as geographic location and policy guidance, cause disparities in the development level and scale of cities within the region. Due to their comprehensive strength and development scale, central cities play a radiation-driven role in guiding the development of neighbouring cities. However, the massive disparity in development levels causes small and medium-sized cities to both assume the "siphoning effect" of central cities and passively accept the factor resources they cannot fully utilize, which makes the overall network inclined towards centralization. The "pathological" expansion of the overall network threatens the stability of intercity connections. To promote the stable and coordinated development of a region, it is essential to evaluate the robustness of the urban network structure, diagnose structural weaknesses, adjust the network structure, and optimize regional resource allocation.

Furthermore, from the perspective of network theory, cities are nodes and hubs that are nested in hierarchical networks in which information, capital, and people flow continuously to reconstruct the hierarchy (Castells, 1996; Castells and Cardoso, 2006), and cities occupy distinct positions in various networks (Sigler and Martinus, 2017; Wei *et al.*, 2022). Previous studies have primarily focused on central cities and stressed their preeminent role in coordinated development. However, cities with lower population and economic scales also have essential positions in a region's coordinated development due to some notable urban functions. In the coordinated development process, the imbalance caused by the polarization effect of central cities should be avoided as much as possible. The timely decentralization of some of their functions facilitates the development of noncentral cities. Therefore, clarifying the location and function of noncentral cities in overall regional development is theoretically important. In addition, as a complex system, multidimensional network linkage measurement can be used to avoid the subjectivity and variability of a single dimension, and the geographic scope and spatial structure of city networks differ under various linkages (Wang *et al.*, 2020). Thus, using different types of relational data to examine intercity network linkages has profound implications for exploring regional spatial structure (Neal, 2013).

In this study, an urban development level evaluation indicator system was constructed to measure the social, economic, and environmental development level of each district and county in the Beijing-Tianjin-Hebei (BTH) region. This addresses the shortcomings of existing research, such as the inadequate understanding of the multidimensional development level and spatial structure of cities, the absence of network structure robustness analysis, and the lack of core development nodes and network exploration. We constructed different dimensional networks based on the measurement results and evaluated the spatial structure characteristics and spatial and temporal patterns of these networks. This study aims to specify regional resource allocation and spatial linkage intensity and evaluate the efficacy of coordinated development from a network perspective by analysing structural evolution characteristics and robustness. Thus, this study provides a scientific foundation and emerging views for optimizing regional spatial structure and promoting coordinated development.

3 Study area and data sources

3.1 Study area

The BTH region (36°01′–42°37′N, 113°04′–119°53′E) is located in northern China (Figure 1) and includes two municipalities of Beijing and Tianjin that are under the jurisdiction of the central government and 11 prefecture-level cities in Hebei province, with a total of 200 districts and counties in the region. As of 2019, the gross domestic product (GDP) of the BTH region reached 8.5 trillion yuan, accounting for approximately 8.62% of the national GDP. The cities in the BTH region have a clear division of labour and have Progressively formed a "one core, two cities, three axes, four districts, and many nodes" structure, with Beijing as the

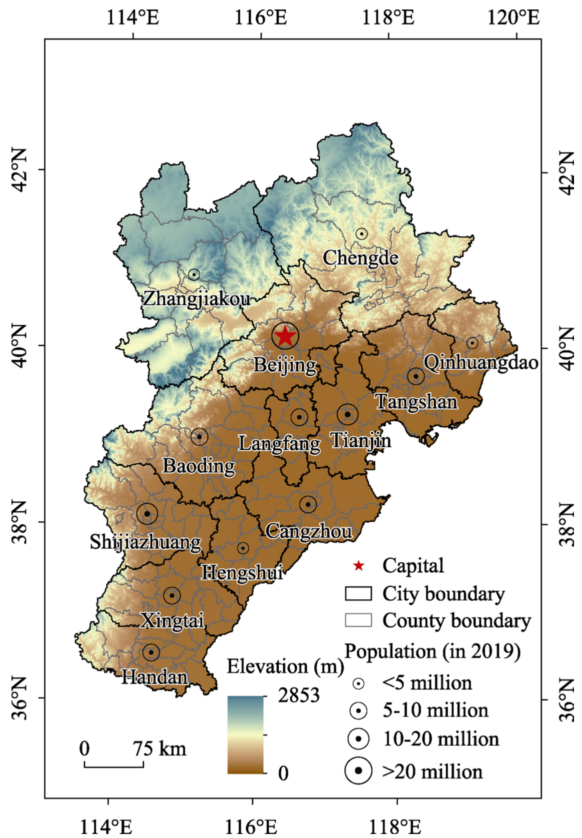

Figure 1 Location of the study area (Beijing-Tianjin-Hebei region)

core city; Tianjin, Shijiazhuang, Tangshan, Baoding, and Handan as the regional centre cities; and Langfang, Cangzhou, Hengshui, Xingtai, Qinhuangdao, Zhangjiakou, and Chengde as the node cities.

3.2 Data source and preprocessing

Regarding data validity and applicability, we selected the following data (Table 1) for our study:

Table 1 Research data sources and description

Name	Data source	Resolution	Brief description
Land use data	Geographic Condition Monitoring Data	2 m/yearly	Reflection of the actual development and construction of the urban area
Road network data	Geographic Condition Monitoring Data, OpenStreetMap dataset (https://www.openstreetmap.org/)	2 m/yearly	Quantification of the urban transportation development level
POI data	Geographic Condition Monitoring Data, POI data (https://www.amap.com/)	2 m/yearly	Indication of people's living standards
Social and economic data	Beijing Regional Statistics Yearbook, Tianjin Statistical Yearbook, and Hebei Statistical Yearbook		Quantitative measurement of quality in all aspects of the city
PM2.5 data	ChinaHighPM2.5 (https://doi.org/10.5281/zenodo.6398971)	1 km/yearly	Characterization of the regional environmental conditions
Nighttime light data	EOG Group, Colorado School of Mines, USA (https://eogdata.mines.edu/products/vnl/)	500 m/yearly	Characterization of the regional economic development level
Remote sensing image	Landsat8 OLI (https://earthengine.google.com/)	30 m/yearly	Quantification of urban environmental quality
Administrative boundary	National Basic Geographic Information Database (https://www.resdc.cn)	/	Definition of the scope of the study area

(1) Land use data. The Geographic Condition Monitoring Data from the Ministry of Natural Resources were used as the data source for the surface coverage data in this study. The data cover the entire BTH region. Compared with similar land cover datasets, the advantage of this product is that the spatial resolution of the original image is better than 2 m, and the accuracy is guaranteed by field verification and quality inspection (Gao *et al.*, 2020; Mao *et al.*, 2021); therefore, this dataset accurately reflects the real land use situation of the city and enhances the accuracy and credibility of the results.

(2) Traffic road network data. We supplemented the road dataset with OSM road data based on the road dataset in the geographic state data, which mainly contains road network datasets of highways, county roads, residential roads, urban primary and secondary roads, and other elements.

(3) POI data. For this study, we crawled two categories of POI data, education and medical, to evaluate the urban public infrastructure level. Since big data have a finer spatial and temporal scale than conventional data, they have high spatial variability and regional instability (Cai *et al.*, 2017; Lv *et al.*, 2021). Therefore, these data served as a supplementary data source for Geographic Condition Monitoring Data.

(4) Socioeconomic data. To quantitatively measure the multifaceted development level of cities, socioeconomic indicators were selected from the statistical yearbooks of Beijing, Tianjin, and Hebei, as well as the statistical bulletins of prefecture-level cities, districts, and counties in the region, and some missing data were filled in using the interpolation method.

(5) Remote sensing data. In this study, nighttime light data and the ChinaHighPM2.5 dataset were used to reflect urban economic construction (Elvidge *et al.*, 2021) and the atmospheric environment (Wei *et al.*, 2021). Moreover, urban greenness, humidity and heat were calculated using Landsat 8 data to reflect the urban spatial environment.

The study data were all from 2015 and 2019, the spatial data were uniformly projected as CGCS2000_GK_CM_117E, and the remote sensing images were processed, such as by denoising and resampling.

4 Research methods

To clarify the characteristics of the evolution of the spatial structure of urban networks in different dimensions and the problems that exist in their existing development, we utilized the spatial interaction analysis method in geoscience combined with the concept of complex networks to analyse the spatial structure of networks and their robustness in the study area. The detailed procedure is as follows (Figure 2):

(1) Multidimensional urban network construction. Objective data from diverse sources were used to quantify urban development across multiple dimensions. These data were modelled into a network of nodes and edges using a modified gravity model.

(2) Analysis of network characteristics. Network indicators were employed to assess the urban network, pinpointing cities of significance based on both overall and individual characteristics.

(3) Analysis of network structure evolution. The evolution of the urban network structure from 2015 to 2019 was examined using community detection algorithms that were complemented by Sankey diagrams to trace transformations across clusters.

(4) Analysis of network robustness. The network's spatial structural robustness was tested through simulated node attacks. Core networks and key nodes were identified to explore patterns of coordinated development.

4.1 Construction of the urban network

4.1.1 Theoretical foundation

Economic, social, and environmental aspects should be balanced in regional development (Sun *et al.*, 2017; Feleki *et al.*, 2018; Gonzalez-Garcia *et al.*, 2018; Jing and Wang, 2020), as demonstrated by various studies (Li and Yi, 2020; Wang *et al.*, 2021). We analysed the interconnections of these aspects in urban areas at the county level, transforming city subsystem development levels into a network to understand coordinated development and synergy. The economic subsystem is the resource backbone, the environmental subsystem sustains growth, and the social subsystem uses these resources to boost the economy and improve living standards. Together, these subsystems collectively promote regional development, as shown in Figure 3.

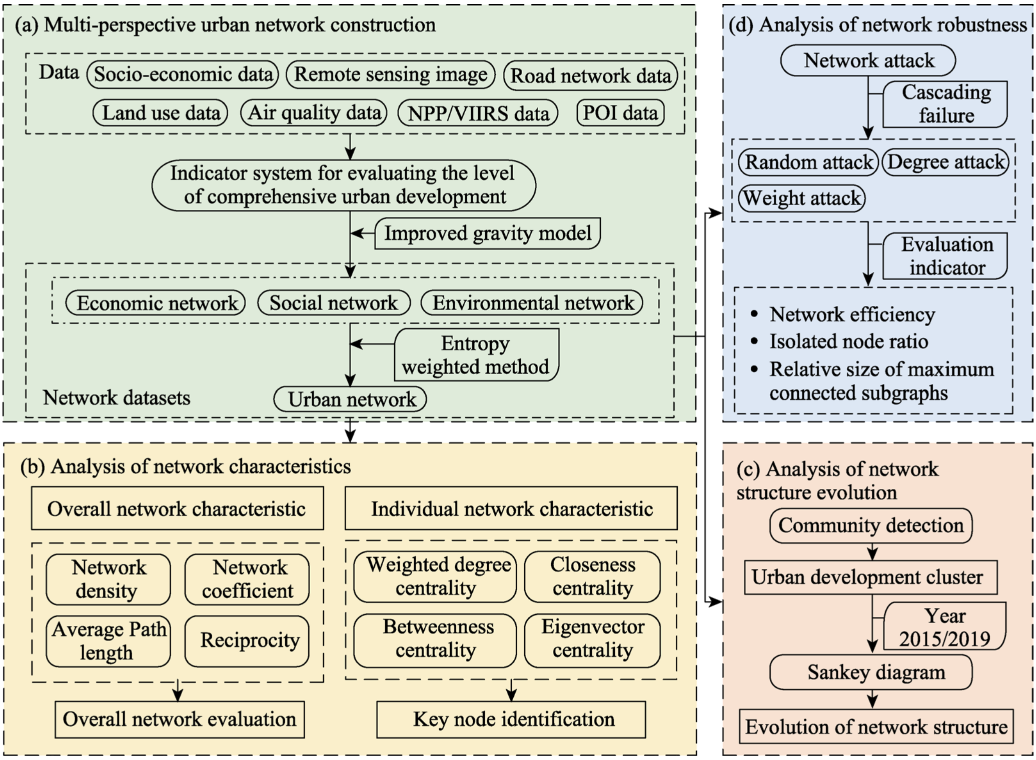

Figure 2 Research framework

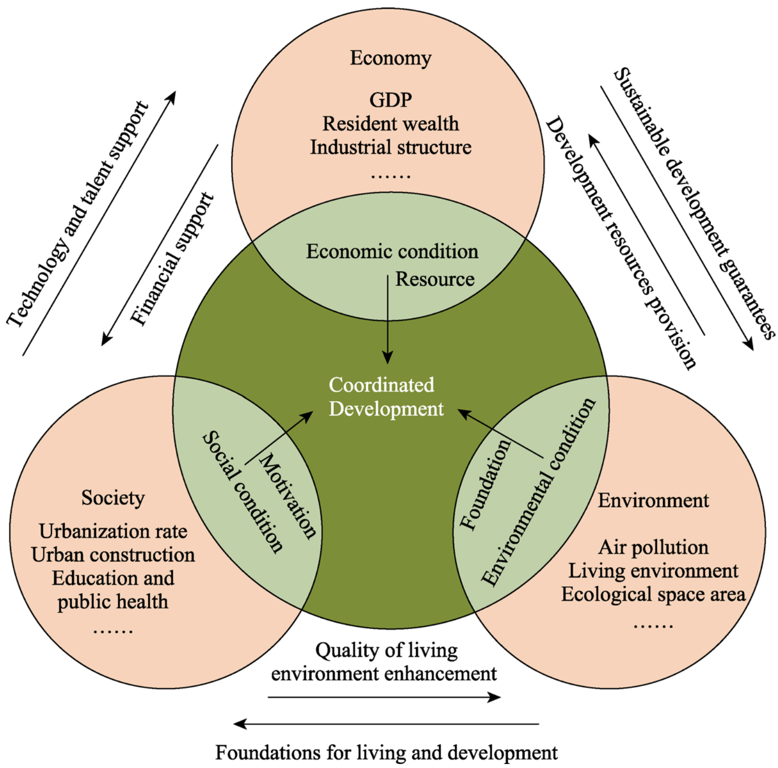

Figure 3 Interaction of the social, economic and environmental subsystems

4.1.2 Evaluation indicator system construction

In this study, we considered the relationships among the social, economic, and environmental subsystems of cities and the existing research foundation (Zhang *et al.*, 2016; Fan *et al.*, 2019; Zhang and Chen, 2021; Mu *et al.*, 2022; Zhang *et al.*, 2022b), referred to the actual development status of cities in the region, and adhered to the principles of representativeness, comparability, and data accessibility to develop a comprehensive urban development evaluation index system (Table 2). The entropy weight method, which determines indicator validity and weight based on the entropy difference of index information, minimizes subjectivity and unpredictability in weight assignment, addressing the issue of redundant indicator information (Luo *et al.*, 2021).

Table 2 The indicator system for evaluating the comprehensive development level of the ESE of cities

Guideline layer	Indicator layer & indicator type	Unit	Indicator meaning	Weight
Economy (ECO)	GDP (+)	10^9 Yuan	Regional economic power	0.2186
	The percentage of added value of the tertiary industry of GDP (+)	%	Industrial and economic structure	0.0341
	per capita GDP (+)	10^4 yuan	Residents' living standards	0.0873
	The averages NTL data (+)	/	Economic development level	0.2282
	General public budget revenues (+)	10^4 yuan	Regional financial strength	0.2354
	General public budget expenditure (+)	10^4 yuan	Regional financial strength	0.1679
	Disposable income per urban resident (+)	yuan	Residents' living standards	0.0285
Society (SCO)	Road network density (+)	km/km²	Infrastructure level	0.1325
	Urbanization rate (+)	%	Urban development potential	0.0202
	Population density (+)	people/km^2	Population growth potential	0.2097
	Length of road per capita (+)	m/people	Convenience of transportation	0.1583
	Percentage of built-up area (+)	%	Land development intensity	0.0548
	Number of health facilities per 10,000 people (+)	Institute/10^4 people	Health services level	0.0344
	Number of schools per 10,000 people (+)	Institute/10^4 people	Education level	0.0455
	Open space area per capita (+)	people/km²	Population's standard of living	0.3446
Environment (ENT)	PM2.5 concentration in the air (–)	μg/m^3	Air quality levels	0.1837
	Percentage of Ecological space area (+)	%	Environmental quality levels	0.5204
	NDVI (+)	/	Urban greenness	0.1050
	LST (–)	/	Urban heat	0.0312
	WET (+)	/	Urban humidity	0.1597

Cities, as hubs of interactions and networks (Batty, 2013), use their development level to shape external connections. To simulate these spatial interactions, we applied an enhanced gravity model to construct economic, social, and environmental networks. This model, which is frequently used for quantifying intercity linkages, has been adapted for specific needs in recent studies (Kabir *et al.*, 2017; Cao *et al.*, 2018; Thompson *et al.*, 2019; Li and Lu, 2021). By incorporating spatial interaction theory (Ullman, 1957), we measured intercity development as directed, using the Baidu Maps API to calculate the shortest driving distance and time between districts and counties, and defined time-cost distance as the product of these two factors.

$$CDI_{ij} = \frac{Q_i}{Q_i + Q_j} \times \frac{Q_i Q_j}{\left(T_{ij} \times R_{ij}\right)^2} \tag{1}$$

where CDI_{ij} is the intensity of the development between two cities i and j under spatial interaction; Q_i. Q_j is the level of urban development between two cities i and j; T_{ij} is the shortest driving time between the two cities; and R_{ij} is the shortest driving distance between the two cities.

Moreover, we synthesized the city development levels under the three social, economic, and environmental dimensions to construct a network of comprehensive urban development levels. The formula is as follows:

$$CDI_{sum} = 3\frac{\left(CDI_{ECO} \times CDI_{ENT} \times CDI_{SCO}\right)^{\frac{1}{3}}}{CDI_{ECO} + CDI_{ENT} + CDI_{SCO}} \tag{2}$$

where CDI_{ECO}, CDI_{ENT}, CDI_{SCO}, and CDI_{SUM} represent the city's economic, environmental, social, and comprehensive development levels, respectively.

Notably, we omitted the network edge data for the last 25% of the range of values for each network, considering that the interconnection of cities in the region is affected by geographic distance and differences in development level.

4.2 Analysis of network characteristics

Our study combined overall and individual network analyses to understand urban networks morphologically and functionally. Overall characteristics such as scale, density, and node interaction were examined through a city's linkage strength, highlighting the importance of nodes and edges (Watts and Strogatz, 1998). Functional aspects such as linkage strength and directional balance were emphasized for individual characteristics (Burger and Meijers, 2012; Liu *et al.*, 2016). Central to this is node centrality indicators, which aid in assessing node significance over time. This dual approach was helpful for identifying key cities and informing strategies for urban development and regional management (Table 3).

Table 3 Overall and individual network indicators

Indicator name	Description	Equation
Network density (D)	Refers to the degree of correlation between network nodes, i.e., the probability of connection between nodes.	$D = \frac{l}{n(n-1)}$ (3)
Average path length (L)	Measures the level of network reachability and the average distance between nodes.	$L = \frac{2}{n(n-1)}\sum_{i \neq j} d_{ij}$ (4)
Average clustering coefficient (C)	Indicates the degree of node aggregation in the network and enables the calculation of the probability that two neighbours of a node may be connected to each other.	$C = \frac{1}{n}\sum_{i \in n}\frac{2m_i}{k_i(k_i - 1)}$ (5)
Reciprocity (R)	The ratio of bidirectionally connected edges to all edges in a directed weighted network (Garlaschelli and Loffredo, 2004) and is able to measure the closeness of the interaction between two nodes.	$R = \frac{L_{bi}}{L_{bi} + L_{uni}}$ (6)
Degree centrality (DC)	Measures a node's connectivity and influence, differentiating between its ability to receive and exert influence in directed networks.	$DC_i = \sum_{j=1}^{n} a_{ji} w_{ji} + \sum_{j=1}^{n} a_{ij} w_{ij}$ (7)
Closeness centrality (CC)	Characterizes the correlation between a city's development and that of other cities, demonstrates superior efficiency of external interactions in regional development networks.	$CC_i = \frac{n-1}{\sum_{j \neq i}^{n} d^w(i,j)}$ (8)
Betweenness centrality (BC)	Reflects the ability of cities to play a communicative and coordinating role in regional development, and to control or influence the flow of resources and information.	$BC_i = \frac{2}{(n-1)(n-2)}\sum_{j<k}^{n}\frac{N_{jk}(i)}{N_{jk}}$ (9)

Table 3 Overall and individual network indicators (continued)

Indicator name	Description	Equation
Eigenvector centrality (EC)	Reflects the degree to which the urban entity itself is connected to key nodes in the vicinity (Li *et al*., 2016), demonstrating the centrality of the nodes	$EC_i = \lambda^{-1}\sum_{j=1}^{n} a_{ij}x_{ij}$ (10)

4.3 Analysis of network structure evolution

City development levels vary due to factors such as location, infrastructure, resources, the external environment, and policies, leading to distinct urban clusters. Understanding these clusters is key for planning spatial development. The Infomap algorithm (Rosvall and Bergstrom, 2008), which is based on information entropy and flow (Girvan and Newman, 2002; Lancichinetti *et al*., 2008), was used to analyse the evolution of network clusters in the BTH region from 2015–2019. This algorithm efficiently partitions network communities by compressing information flow paths and considering node interactions, making it effective for real network community analysis (Rosvall *et al*., 2010; Zhong *et al*., 2014). The formula is as follows:

$$L(M) = qH(Q) + \sum_{1}^{m} p_i H(P_i) \tag{11}$$

where $L(M)$ denotes the average coding length expectation of the paths along which random wanderings occur within and between communities; q and p_i denote the probability of random wanderings occurring between and within communities, respectively; m denotes the number of communities; and $H(Q)$ and $H(P_i)$ denote the entropy of the probability of random wanderings moving between and within communities, respectively.

4.4 Analysis of network robustness

Central cities are key to regional development but have limited capacity. Excessive development can hinder their growth and affect neighbouring cities, potentially causing a cascading network failure in which one node's failure leads to others', possibly resulting in large-scale network collapse. This concept, which is known as cascade failure (Motter and Lai, 2002), is increasingly relevant in real network analysis (Dong *et al*., 2020; Dui *et al*., 2020).

Regional development depends on the robustness of its spatial structure to shocks. Changes in network nodes affect the overall structure, which is evident in the BTH region's development and is marked by significant disparities. Understanding node capacity and network robustness is essential for future planning. In this study, we used the cascade failure model to simulate attacks on urban networks from 2015 to 2019 using three methods. Random Attack (a random attack on network nodes, RA) was used to simulate random failures or disruptions that may occur in a network, such as accidents, natural disasters, or random acts of violence that disrupt the normal operation of network nodes. Degree Attack (a sequential attack based on node degree size, DA) was used to simulate the chain reactions triggered by the collapse of a central city that is unable to assume a leadership role in an uncontrolled development model. Edge Weight Attack (a sequential attack based on edge weight size, WA) was used to simulate the impact of the reduction and disappearance of cooperative communications such as population flows, trade, and environmental resource sharing if the central city maintained the status quo development level with other cities. We assessed network robustness using specific indices (Table 4) and analyse the results to identify core networks and key nodes.

Table 4 Network robustness evaluation indicator system

Indicator name	Description	Equation
Network efficiency	Reflects the ease of network operation, the more efficient the network, the better the network connectivity	$E=\frac{1}{n(n-1)}\sum_{i=1}^{n}\sum_{j=1(i\neq j)}^{n}H_{ij}$ (12)
Isolated node ratio	Reflects the proportion of nodes that have no edges connected to them when the network is under attack	$\Delta N=\left(1-\frac{n^*}{n}\right)*100\%$ (13)
Relative size of maximum connected subgraphs	Reflects the size of the largest subgraph during network fragmentation in the event of an attack, providing a visual representation of the extent of network disruption	$G=\frac{P^*}{P}$ (14)

5 Results

5.1 Network development evaluation

Spatial linkage calculations in the BTH region from 2015 to 2019 revealed varying network linkage strengths across multiple dimensions, categorized into six levels using logarithmic grading (Figure 4). The region's network grew rapidly during this period, with an increase in high-grade connections within cities, improved communication with neighbours, and overall developmental progress. Central cities such as Beijing, Tianjin, Tangshan, and Shijiazhuang expanded their network connections, creating a significant "connection corridor" that drove regional development and benefited peripheral cities. While the regional network structure strengthened, disparities and gaps in development persisted, especially in the northern higher elevation areas, due to natural and other factors.

The primary goal of BTH coordinated development was to minimize disparities among districts and counties. In 2015, central cities such as Beijing (including Beijing-Zhangjiakou, Beijing-Baoding-Shijiazhuang, and Xingtai-Handan) had strong internal linkages, but economic disparities between cities remained by 2019. The regional network was mainly concentrated in Beijing and Tianjin, with weaker networks in Zhangjiakou, Chengde, and Hengshui. Social networks developed rapidly, improving connections region-wide. Environmental development was stable, with potential for enhancement through ecological policies. Zhangjiakou and Chengde emerged as key players in environmental linkages. Overall, since the implementation of the coordinated development policy, the network in the BTH region has improved, especially in southern counties, with an increase in high-grade links and a reduction in cross-municipal linkage imbalances, although regional development imbalances still exist.

5.2 Analysis of network characteristics

5.2.1 Overall network characteristics analysis of the BTH region

We measured the overall network characteristics to elucidate the spatial structure of the different

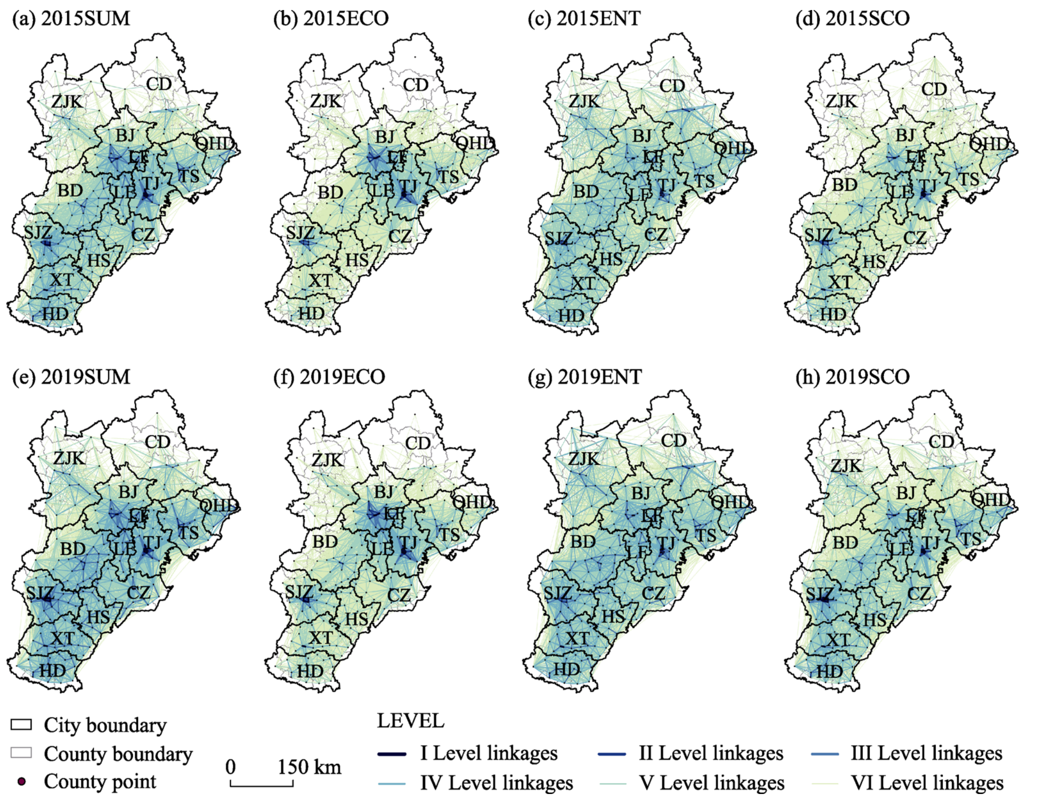

Figure 4 Evolution of various networks in the Beijing-Tianjin-Hebei region from 2015–2019

dimensional networks (Table 5). The development of different-dimensional networks from 2015–2019 resulted in network density, network efficiency, and reciprocity, all of which showed an increasing trend, while the decrease in the average path length revealed the network's rich internal network paths and hierarchical network space structure.

In 2015, the density of the BTH network, an indicator of overall connectivity, was close to 0.5, revealing both high intercity connections and significant economic inequalities within the network. This loose spatial structure provided opportunities for enhancing intraregional connections. By 2019, network connections stabilized with an increase greater than 10%, and social network density improved, indicating a narrowing of social development gaps. Transmission efficiency, measured by the average path length, improved across all networks, with social networks demonstrating the highest interaction capacity and forming more functionally complementary regional clusters than economic and environmental networks. The clustering coefficients from 2015 to 2019 suggested dense intercity connections and fewer isolated nodes, enhancing the network's robustness, particularly with the active participation of central cities in regional development. Despite this progress, the reciprocity index revealed that nearly 30% of nodes were still economically passive and struggled to form effective two-way connections, which highlights the need for continued focus on economic development within the network.

5.2.2 Individual network characteristics analysis of the BTH region

To quantify the impact of coordinated development strategies on urban nodes in the regional

Table 5 Overall network structure characteristics

Name	2015ENT	2019ENT	2015ECO	2019ECO	2015SCO	2019SCO	2015SUM	2019SUM
D	0.503	0.609	0.416	0.562	0.483	0.719	0.514	0.642
L	1.558	1.416	1.686	1.467	1.582	1.283	1.548	1.373
C	0.765	0.801	0.719	0.778	0.754	0.844	0.777	0.826
R	0.830	0.861	0.598	0.693	0.692	0.804	0.839	0.902

network, we evaluated the difference in node centrality results from 2015–2019. We depicted the spatialized results hierarchically using natural breaks (Jenks) (Figure 5). By evaluating the variations in the centrality of various nodes horizontally and comparing the dynamics of node centrality vertically, we could discover the crucial nodes and regions involved in regional synergy.

From 2015 to 2019, the network city nodes in the BTH region maintained stable weighted degree centrality, with emerging economic synergy and polycentric development in cities such as Shijiazhuang, Baoding, and Cangzhou. The environmental quality initially declined due to rapid urbanization. Overall network analysis indicated that Beijing had a strengthening core position, with significant growth in Cangzhou and Shijiazhuang. Closeness centrality increased across most cities, suggesting more efficient intercity cooperation and a shift from Beijing and Tianjin’s single-core dominance to more distributed regional development. Betweenness centrality showed that central cities still controlled the region’s development, but peripheral cities faced locational constraints. Eigenvector centrality revealed enhanced city standing due to urban expansion, forming significant clusters such as Beijing-Tianjin and Xingtai-Handan, although central regions, particularly around Shijiazhuang and Hengshui, still faced development challenges. This highlights the need for targeted development aid, especially in central areas such as Shijiazhuang, to address social and environmental disparities.

5.3 Analysis of network structure evolution

Based on the variance in the intensity of spatial interactions, the region is divided into distinct clusters. We delineated urban development clusters from the perspective of spatial aggregation and intercity node linkages for different dimensional networks. We named the clusters with central cities to represent the spatial structure of BTH region in the context of coordinated development.

From 2015 to 2019, the economic network in the BTH region was stable, with core cities such as Beijing and Tianjin maintaining their clusters, as shown in Figure 6a. Minor changes included Chengde joining the Beijing-Tianjin cluster and significant shifts in southern clusters such as Baoding, leading to the formation of a new Hengshui-centred cluster. The environmental network, as shown in Figure 6b, saw the Beijing-Tianjin cluster divide, with parts merging into the Baoding cluster and enhanced cohesion in the Shijiazhuang and Xingtai-Handan clusters. The social network, as shown in Figure 6c, indicated a trend towards regional integration, especially in border areas. Overall, the region’s community structure, consistent with administrative boundaries, as shown in Figure 6d, saw cities focusing on their central areas and the formation of a few peripheral joint clusters.

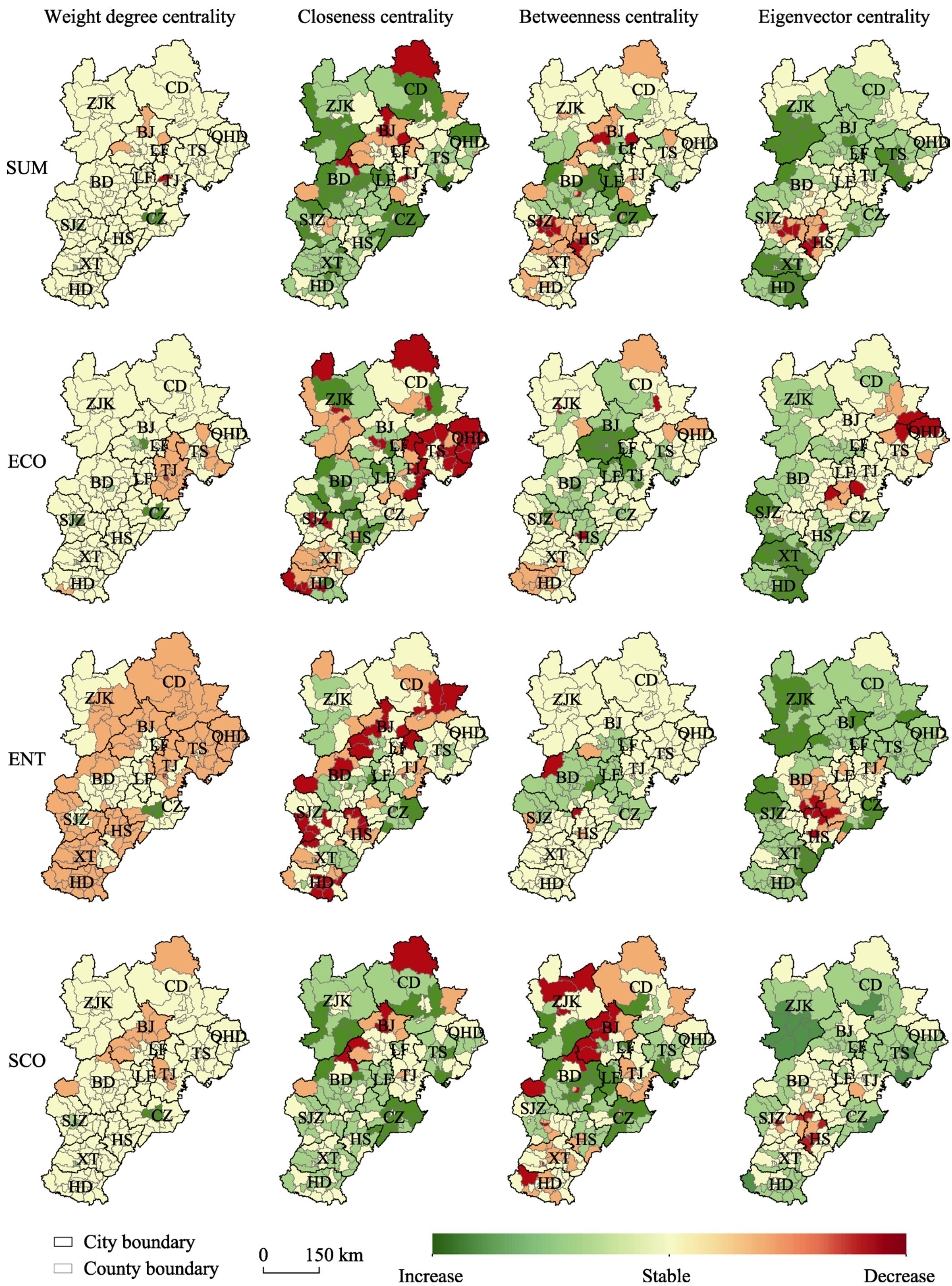

Figure 5 Network centrality differences among different subsystems in the Beijing-Tianjin-Hebei region from 2015 to 2019

To further elucidate the spatial pattern of the network following intercommunity urban transfer, we spatialized the three-dimensional network clusters' spatial structure (Figure 7). The economic cooperation in the BTH region is defined by the strong link between Beijing

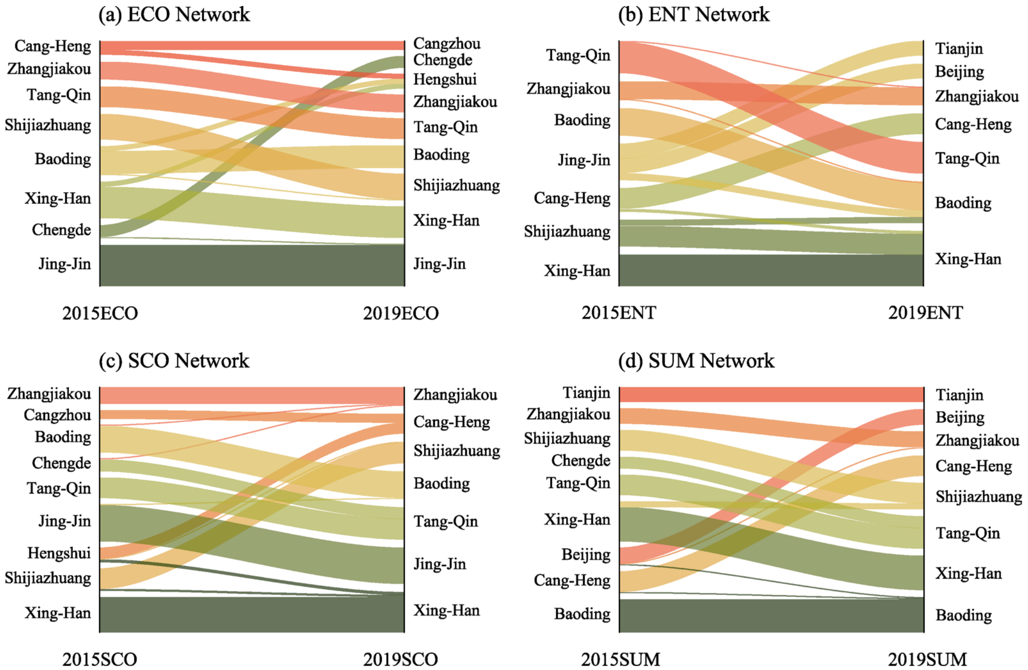

Figure 6 Evolution of various networks in the Beijing-Tianjin-Hebei region from 2015–2019 (Note: Different colours represent different clusters, and the width size represents the number of city transfers.)

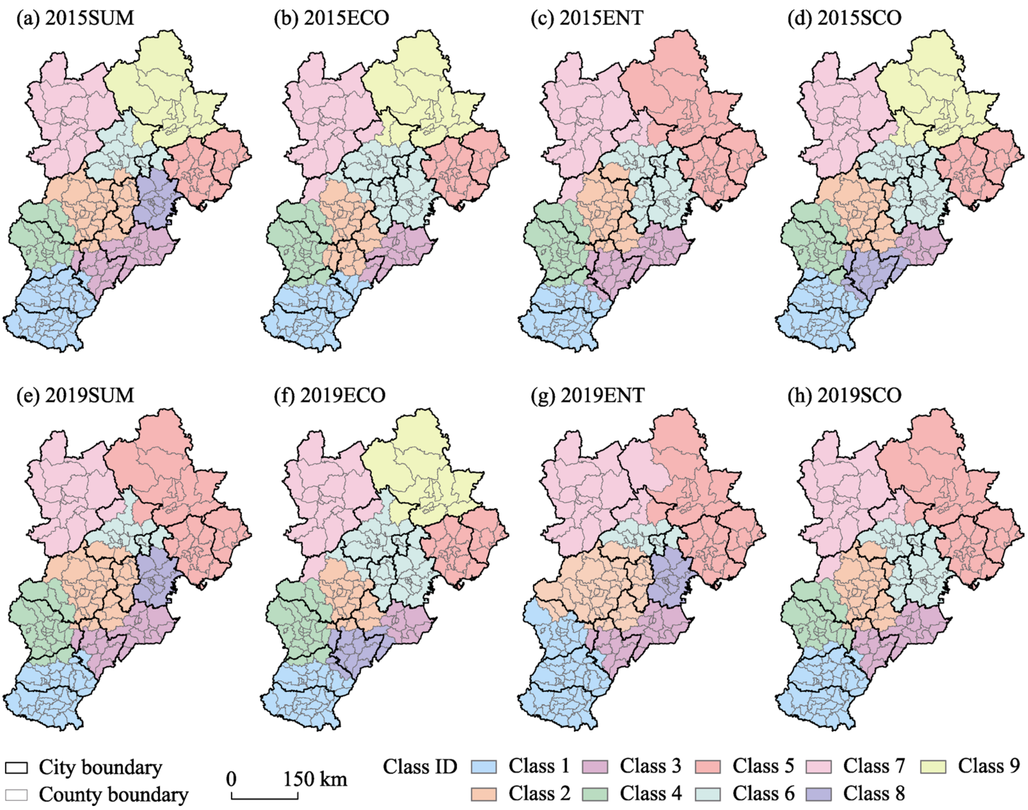

Figure 7 Results of city clustering in different dimensions in the Beijing-Tianjin-Hebei region from 2015–2019 (Note: Different classes represent different urban clusters.)

and Tianjin and the independent growth of other cities, with the only significant change being the contraction of the Baoding cluster due to the development of Hengshui. Social cooperation remains stable, and the linkage of peripheral areas has become a new type of development. Environmental dynamics have significantly evolved, particularly in the Shijiazhuang and Xingtai-Handan areas, splitting into two parts based on their geographical location to the north and south. Furthermore, environmental disparities in the Beijing-Tianjin-Langfang region weakened their previously close ties. Despite industrial policy impacts, Beijing maintains its core position, and areas such as Cangzhou-Hengshui and Tangshan-Chengde are developing a "leading the weak with the strong" approach. City transfers within urban clusters typically follow administrative boundaries and involve cities with similar development but lacking distinct features and strong connections. The coordinated development of the region is challenged by significant disparities in development levels among cities, highlighting the need to accelerate development in certain clusters to advance the goal of contiguous regional development.

5.4 Analysis of network robustness

5.4.1 Robustness of the urban network structure under different attack methods

Using the random attack method, we can examine the evolution of the network's actual robustness and overall coordination capacity; using the deliberate attack method, we can assess the pressure-bearing capacity and influence of the BTH region on the development of different networks (Figure 8).

During random attacks, network efficiency linearly declined, and isolated nodes increased with a decrease in the maximum connectivity subgraph. Overall, each network remained stable, but robustness decreased after significant node attacks in 2015, with economic networks collapsing at 100 nodes and social and environmental networks at 120 nodes. By 2019, this threshold improved by 20 urban nodes, reflecting better functional distribution and enhanced network robustness. Environmental networks were the most robust, followed by social and economic networks, aligning with the BTH region's development.

Deliberate attacks showed varying degrees of network degradation, and there were "critical points" that could hasten the collapse of the whole network. The economic network was most affected, collapsing after 30 nodes due to reliance on central nodes and significant differences in varied city economies. However, the 2019 data indicated a delayed collapse point, suggesting that coordinated development alleviated economy-led imbalances among nodes. Both deliberate and random attacks on the environmental network in the BTH region followed a similar declining pattern due to its extensive core network and balanced node communication. Notably, the network's collapse threshold decreased from 80 to 72 core nodes in 2015, reflecting the impact of rapid urbanization on its robustness. However, the stability against weight attacks indicated that this decline in robustness was temporary. Similarly, the social network exhibited a linear decline before a sharp drop, but its robustness and overall development improved significantly, showing greater consistency. In summary, the robustness of networks in the BTH region has increased, as indicated by the delayed critical points of network failure and a shift from monocentric dominance to multicentric coexistence. The convergence of change curves under various attack methods reinforces this transition. Furthermore, the overall robustness strength suggests that evaluating

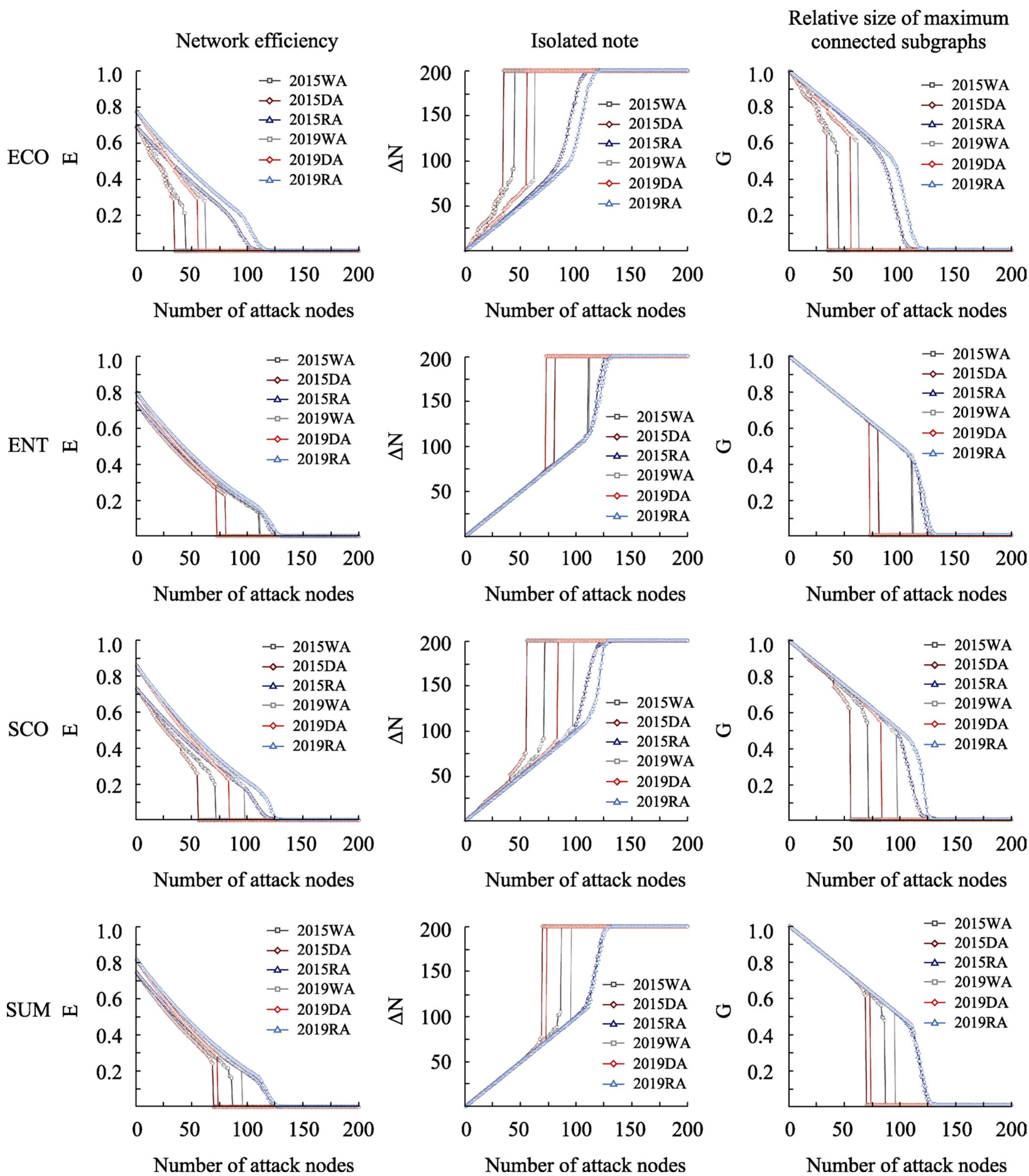

Figure 8 Variations in network robustness characteristic value under different node attack methods

urban network robustness from a single perspective may be limited, and considering multiple flow aspects can bolster network resilience.

5.4.2 Identification of the core network and key nodes

By comparing the changes in the robustness of each network in response to random and deliberate attacks, we discovered that various attacks led to different mutation points for network robustness. However, deliberate attacks are highly focused, resulting in more severe network failure. Thus, we used the mutation points in the degree attack curve to investigate the core network in each dimensional network and the mutation points in the weight attack to determine the core nodes in each network.

The core network of the BTH region was concentrated in the central region and had distinctive characteristics in all dimensions (Figure 9). By 2019, all of the dimensions of the core network of the BTH region, which was initially concentrated in the central area, improved significantly. The economic network evolved from a primarily Beijing-Tianjin focus to include stronger connections with Baoding and Cangzhou and a more developed "Beijing-Baoding-Shijiazhuang" corridor. This network transitioned from a "triangular" to a "funnel" topology. The environmental network was upgraded cohesively, with Shijiazhuang and Baoding emerging as hubs, although Zhangjiakou and Chengde remained outside the network due to geographic constraints. The social network expanded markedly, with Tangshan, Cangzhou, and Hengshui developing robust medium-level connections, demonstrating resilience to network attacks and benefiting significantly from coordinated development efforts. Consequently, the BTH region's core network stabilized, especially the "Beijing-Tianjin-Shijiazhuang-Baoding" network, which matured with close internal links and regular exchanges, extending its influence to peripheral cities.

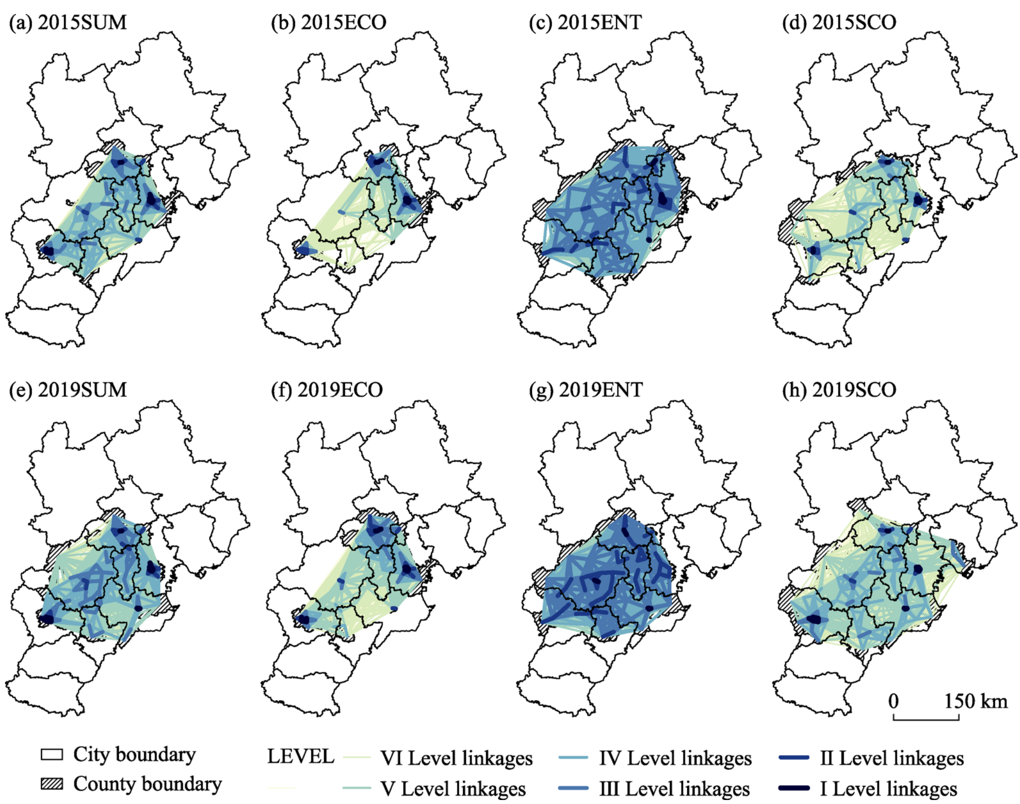

Figure 9 Multidimensional core network in the Beijing-Tianjin-Hebei region (Note: Different levels represent the contact strength, where the first level is the highest; the grading criteria are the same as those in Figure 4.)

According to the results of identifying core nodes (Figure 10), the whole region's core nodes consisted of each city's centre and adjacent counties. From 2015 to 2019, the number of core nodes in the BTH region, encompassing city centres and adjacent counties, increased, with significant spatial overlap; however, the central role of some city nodes in coordinated development decreased. The economic network (Figure 10(b)) initially had the most core

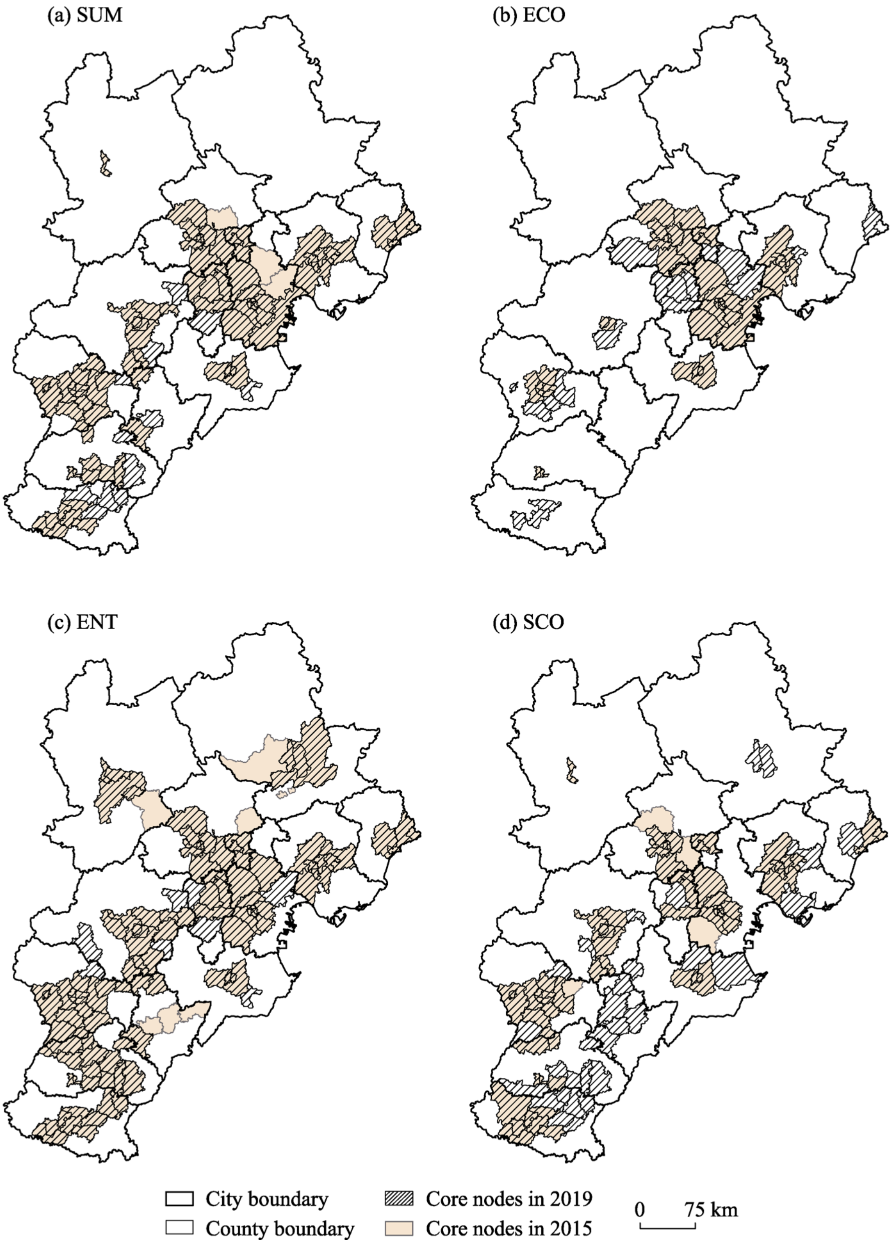

Figure 10 Core nodes of the multidimensional network in the Beijing-Tianjin-Hebei region at county level

nodes in Beijing, Tianjin, Tangshan, and Shijiazhuang, with fewer in the less robust southern region. By 2019, these nodes had expanded to include neighbouring nodes, forming large clusters in Beijing and Tianjin. The southern region, led by Handan, started integrating into the main network, replacing Xingtai's central role, while the northern mountainous region remained isolated. The environmental network, with its numerous core nodes and small clusters in all cities, showed balanced environmental progress, except for significant changes within Hengshui. The social network evolved from independent core areas to contiguous regional cooperation, with Shijiazhuang, Baoding, Hengshui, and others drawing closer together, while the range of Beijing and Tianjin's core nodes contracted. Overall, future network robustness improvements should focus on the northern region and connection enhancement.

6 Discussion

6.1 Effectiveness of the BTH coordinated development

City cooperation within the BTH region is becoming more frequent, and the central city has continuous but unstable external communication. From 2015 to 2019, city cooperation within the BTH region increased, with central cities such as Beijing, Tianjin, and Shijiazhuang at the heart of regional growth but experiencing a decline in their dominant positions. The economic network, initially led by the Beijing-Tianjin core, expanded to include frequent communications with Shijiazhuang and the integration of Cangzhou and Handan, resulting in a richer and more diverse network. This led to the development of new network branches, such as the "Beijing-Tianjin-Cangzhou-Hengshui" route, enhancing the overall network structure. The region's linkage strength has transitioned from primary to intermediate, with high-grade linkages still concentrated around the four core areas of Beijing, Tianjin, Tangshan, and Shijiazhuang. However, their dominant position decreased, while Cangzhou's role as an intermediary within the southeastern BTH region increased. In the urban network system, cities no longer develop separately but instead extend their interactions to other regional urban nodes (Xia *et al.*, 2019). By inspecting the spatial network linkages between the cities in the BTH region, we found that the overall linkage strength of the region has been in transition from primary to intermediate. The high-grade linkages across administrative boundaries were still concentrated in Beijing-Tianjin-Tangshan-Shijiazhuang's four core development areas. There are "core-core" and "core-edge" linkages within the region. The "agglomeration effect" produced by nodal cities brings together mobile network resources to achieve scale effects, and as node functions are strengthened, the region becomes more unequal (Meijers *et al.*, 2018).

The spatial structure will continue to improve and be upgraded, affecting not only the intraregional factor of resource flow but also the hierarchical and coupling relationships of intercity spatial interaction and exchange and intracity activities. Thus, a network structure can be used to reflect the current situation and issues of regional coordinated development. Although the overall network appears dense, it exhibits hierarchical inequalities. Cities such as Hengshui, as weaker elements in the core network, struggle to gain attention and support from major cities such as Beijing, Tianjin, and Shijiazhuang, highlighting their vulnerability in the development process. Peripheral cities, while close to core cities, often do not benefit from their advantages, leading to a significant "siphoning effect" (Liu *et al.*, 2017) in which economic and social ties are predominantly concentrated around Beijing and Tianjin. This has exacerbated regional competition and amplified the "Matthew effect," in which stronger regions continue to grow while weaker regions lag behind. Additionally, the impact of industrial downsizing, particularly in traditional sectors in Hebei and Tianjin, has become apparent, with the economic network showing little change over the past five years and even a decline in areas such as the Binhai New Area.

Most noncentral city locations and regional functions within the region are not well utilized. Intercity collaboration and involvement constitute network advantages, and the existence of intercity functional networks can provide synergies and complementarities (Capello, 2000) and further serve as an intrinsic motivation for network development (Meijers *et al.*, 2008). The rising regional core position of Cangzhou reflects the cohesion of its central city in terms of spatial structural clustering and centrality, hence contributing to the progressive establishment of a closed-loop structure in the central BTH regional network. Among the centrality results, implementing the BTH coordinated development policy has more significant results, with the initial single-centre development model gradually evolving into a multicentre coordinated development model. The three major central cities of Beijing, Tianjin, and Shijiazhuang remain at the regional development centre. The rapid increase in development in Cangzhou has made it a key conduit for Beijing and Tianjin to communicate with the southern region, which is centred on Shijiazhuang. In contrast, the majority of noncentral cities have potential for improvement.

During the present period of the coordinated development of the BTH, the greatest obstacle is that many cities need distinct positioning, which makes it challenging for them to utilize their respective development advantages. As the absolute core and radiating centre of the region, Beijing should retain the integrity of its spatial structure; nevertheless, the outlying districts and counties of Yanqing, Miyun, and Fangshan have been detached from each other in various aspects of development. The central city's self-development has gradually increased internal differences, which have now spread to Zhangjiakou and Chengde, where internal and external communication capacities are severely limited due to geography and functional positioning. Similarly, the smaller changes in the development clusters demonstrate the absence of resource circulation and communication within the region, and the disparities between the development levels of the cities persist. Beijing, Tianjin, and Hebei have distinct resource endowments and development stages, and their respective interest goals and demands do not conflict. The results of the urban network indicated that the BTH region has formed prominent connection corridors and is "branching out" incrementally. In the future, coordinated development of the BTH should strengthen the multilevel linkages between cities and take advantage of the spatial structure of "one core, two cities, three axes, four districts, and multiple nodes."

With the support of network robustness evaluation, we discovered that several aspects of network features and expression are distinct, which echoed the existing research (Mu *et al.*, 2022). For instance, there are apparent central nodes and "channel" networks in economic and social networks, which is conducive to optimizing regional resource allocation. The channel network can facilitate the flow of factors from highlands to other locations, whereas the "trickle-down effect" of mobile factors moving from high to low levels limits polarization and uneven regional development (Van Nuffel and Saey, 2005). The results of the degree attack and the edge attack have demonstrated that the absolute dominance of the central city in the region hinders the development of the region. At the same time, with industrial transfer, cities that traditionally rely on manufacturing and other forms of single industries will decline, which may even lead to the disruption of cooperation chains with the central city, reducing population and capital flows, which weakens the efficiency of integrated linkages. Similarly, we discovered that low-cost network nodes have some benefits. Low-cost nodes refer mainly to core or edge nodes in the core network that have geographical benefits but are not outstanding in their development (e.g., Hengshui and Langfang). From the perspective of network robustness, these nodes help to distribute the development pressure of core nodes and prevent the collapse of the core nodes, which paralyzes the overall network. To achieve balanced and sustainable development, it is necessary to fulfil morphological and functional polycentricity, prevent the negative externalities of agglomeration, and enhance regional competitiveness (Wei *et al.*, 2020).

6.2 Coordinated development policy suggestions

Therefore, based on the results of this study and the current situation of development in the BTH region, we propose the following specific recommendations:

(1) Developmental pressure from central cities to surrounding cities based on local factors should be alleviated to prevent homogenous rivalry. Resource-rich cities should share their internal development resources with adjacent cities, fully consider regional characteristics and related implications based on existing development relationships, and maximize the benefits to surrounding cities. For example, Beijing needs to pay attention to the growth of Yanqing, Huairou, and other districts while decentralizing its functions to progressively realize outwards expansion and lessen internal fragmentation caused by its imbalance through "point to area" development. Industrial transfer is more feasible in the BTH region, which has an entirely distinct industrial structure. The ideal strategy is to utilize industrial synergy to propel the growth of interregional economic transportation and other aspects of coordinated development.

(2) City functional positioning should be defined. The BTH region has a lengthy history and complicated and diverse city positions. Most resource-depleted cities are confronted with transformation challenges and stagnated development, so strategic options for coordinated development are needed as an impetus. Moreover, from the perspective of the characteristics of network nodes, increasing the importance of noncentral cities can support the regular operation of the network and facilitate the movement of elements and resources within the network. Each city in the BTH region should actively utilize its unique assets and avoid disadvantages to achieve the same purpose and mutual benefits.

(3) The spatial structure of the coordinated development of BTH should be continuously optimized. The spatial structure of the BTH region is typically complex, with local communities dominating, but administrative boundaries must be more strictly adhered to. Diverse clusters make internal functional positioning unclear and muddled, so the government-led establishment of regional spatial units, such as urban agglomerations and metropolitan areas, is needed to coordinate inter-cluster development and prevent the existence of isolated core structural clusters that disrupt regional coordination. Future coordinated development of the Beijing, Tianjin, and Hebei regions should rely on locally appropriate policy planning, consider the development of small- and medium-ranking districts and counties, establish a proven mechanism for the division of labour and cooperation, and break the current trend of a gradual widening development gap between two cities and one province.

(4) Communication and collaboration with peripheral regions should be enhanced to foster regional coordinated development with differentiation. The network robustness evaluation results clearly reveal the weak points in the BTH region, and the lack of attention given to peripheral areas causes the overall network to concentrate on the development of the cen-

tral region. However, there are still vulnerable areas in the core network. The radiation function of the central city is fully utilized, while the central city's load is reduced to prevent network cascade failure due to excessive pressure. Simultaneously, coordinated development cannot rely solely on Beijing's radiation drive for the whole region or particular localities. Leveraging regional subcentres has an equivalent investment value for urban development. The Tongzhou subcentre and Xiong'an New Area serve as transition hubs for regional development resources and enhance the regional development network.

6.3 Limitations

This study still has the following limitations:

(1) There is a lack of measurement of the development level of science and technology, innovation, etc. An information-oriented society makes science and technology innovation a vital engine of urban development in the new era. However, the limited availability of county-level data makes it difficult for our indicator system to reflect the innovation level of each district and county. Moreover, quantifying policy impacts is crucial for evaluating development levels. The need for more relevant data and indicators will be one of the most significant challenges for future studies.

(2) Regional development needs more exploration into the principles of spatial structure evolution and influence mechanisms. According to the findings of this study, central cities have a limited ability to drive the surrounding areas, and too many cities impede the advancement of coordinated development. However, the radiation and driving range of different development phases vary. In other words, the integration of different cluster networks within the region is the linchpin of the coordinated development stage, and determining the spatial scale evolution law and influence mechanism of clusters within the region during the coordinated development process will be a significant focus in the future.

(3) This study lacks in-depth analysis from a multiscale network perspective. Since the degree of development and radiation capacity of each subnetwork within a region varies, there are also disparities in spatial structure and network robustness between networks. Thus, urban networks at various scales should be further considered in the context of globalization and decentralization (Swyngedouw, 2010). In the future, we should analyse the spatial structure characteristics of each cluster network in the region, quantify the contributions of different subnetworks to the overall network evolution process, and comprehend the interrelationship between spatial structure and coordinated development on a finer scale.

7 Conclusions

In the context of globalization and networks, spatial interactions and their spatial patterns impact regional integrated development considerably, and the analysis of spatial interactions can offer policy-makers regional information and guidance (He *et al.*, 2017). In this study, we constructed economic, environmental, and social urban development evaluation indicators for each district and county in the BTH region from 2015 to 2019. We transformed the assessment results into network forms and quantified the characteristics of various dimensional networks using overall network indicators and individual network characteristics. We used the Infomap algorithm to delineate the spatial pattern of regional development, estimated the robustness of different dimensional networks, and identified regional core networks and key nodes by simulating various network attack methods. The main conclusions are as follows:

(1) The development in the BTH region is increasing rapidly. The development level of cities in the BTH region has improved in all dimensions, with basic coverage of high-grade connections, improvement of low-grade connections, and a reduction in the disparity between cross-regions and cities in terms of connection strength. The density of multidimensional networks in the BTH region has increased progressively, and interregional connectivity and transmission efficiency are greatly enhanced. The characteristics of multidimensional networks have gradually evolved from the original single-centre development mode to the multicentre coordinated development mode, although disparities in regional development levels persist.

(2) The spatial structure of the BTH region is relatively stable and tends to be complicated and scalable. The 2015–2019 spatial pattern of regional development shows no significant changes, and the regional spatial clusters have a spatial structure dominated by local clusters supplemented by cross-municipal clusters in peripheral areas (CangHeng, XingHan, and TangQin) and a development trend of contiguity.

(3) The network robustness of cities in the BTH region has continuously increased, and the central clustering of core networks and nodes is prominent. Overall, the robustness of the network in the BTH region is ranked as follows: environment > society > economy, with the robustness of the comprehensive network between the environment and society. Currently, most core nodes are in Beijing, Tianjin, and Shijiazhuang, primarily in the central city and its surroundings, and the core networks are restricted to these three cities.

(4) The coordinated development of the BTH region is effective, but much potential for improvement remains. An increase in the number of core nodes indicates that more cities can contribute to coordinated development. However, the status changes of some core nodes imply that they are not yet stable. In this phase, the BTH region is primarily driven by the radiation of the central node, which exponentially increases the risk of cascade failure, necessitating a re-evaluation of the strategic significance of edge cities.

The in-depth study of urban spatial structure can clarify the potential and scale of urban development, promote the sensible allocation of factor resources, and provide a theoretical foundation for designing regional development planning strategies. This study can be applied to evaluating regional development and problem analysis studies in similar places.

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