



ARTICLE



<https://doi.org/10.1057/s41599-025-05828-2>

OPEN

# Spatial correlation networks characteristics and influence mechanisms of the resilience of Beijing-Tianjin-Hebei urban agglomeration: a complex network perspective

Peixing Zhang<sup>1,2</sup>✉, Tianlu Jin<sup>1,2</sup>, Min Zhang<sup>1</sup> & Aijun Zhu<sup>1</sup>

Urban resilience forms a multi-level, multi-node spatial correlation network in terms of risk complexity and regional collaboration. However, few studies have explored urban agglomeration resilience in terms of the spatial network. Therefore, a resilience evaluation index system for the Beijing-Tianjin-Hebei urban agglomeration (BTHUA) is constructed in this study based on the driving force-pressure-state-response (DPSR) framework. To this end, the resilience and change characteristics from 2014 to 2022 are analysed using an entropy weight-TOPSIS method and kernel density estimation. Further, the correlation strength and structure of the resilience spatial correlation network in BTHUA are explored using a modified gravity model and social network analysis method, and a quadratic assignment procedure model is used to explain the correlation and mechanism of the influencing factors of the resilience spatial correlation network. The following results were observed: (1) A “core-periphery” pattern in the BTHUA resilience spatial correlation network, with Beijing and Tianjin as pivotal nodes, Shijiazhuang and Tangshan as intermediary connectors, and Zhangjiakou, Xingtai, and Hengshui as weak nodes. (2) Variations in the closeness of the resilience spatial correlation network of BTHUA, with the network exhibiting strong connectivity. However, network centrality shows non-equilibrium characteristics, indicating obvious hierarchical differentiation. (3) Geographic distance, openness to the outside world, economic development level, technological innovation, and urbanisation are identified as influencing factors affecting the resilience spatial correlation network, which show both temporal and spatial heterogeneity. This study provides insights into the collaborative governance of urban agglomerations from the perspective of spatial correlation networks.

<sup>1</sup>School of Management Sciences and Information Engineering, Hebei University of Economics and Business, Shijiazhuang, China. <sup>2</sup>Geographic Information Big Data Platform for Economic and Social Development of Hebei Province, Shijiazhuang, China. ✉email: [zhangpx@hueb.edu.cn](mailto:zhangpx@hueb.edu.cn)

## Introduction

The urbanisation rate of China has approached 64% and is projected to exceed 70% by 2035. This trend is anticipated to result in urban populations comprising 70% of the global population, and urban carbon emissions and urban energy consumptions comprising 75% of the global total (Shi and Li, 2024). Urbanisation and digitalisation have accelerated the agglomeration of people, information and resources, while promoting interdependence and interaction between cities. While such connectivity can improve system efficiency, unmanaged centralisation, particularly where institutions are dispersed or infrastructure is under-redundant, may result in more complexity and diversity of risks (Chen et al. 2024a; Chen et al. 2024b; Haque et al. 2024). Against this backdrop, the risks often exhibit characteristics of high management difficulty, strong destructiveness, and transcendence of spatial and temporal boundaries, severely impacting and affecting the normal functioning of cities (Wang et al. 2024). Consider the public health crises as an example: the population concentration and development of transportation networks accelerated the spread of the COVID-19 virus among cities, affecting not only the stable operation of individual cities but also the sustainable development of surrounding adjacent cities (Guo et al. 2025).

Urban agglomerations emphasise that cities are no longer individual entities in the trend of regional collaborative development and have multiple types of connections, including geographical and functional linkages, because of their geographical contiguity and their economic and ecological spillover effects (Ding et al. 2024). Infrastructure systems of cities develop complex interdependences over the course of urban development. Under this strongly interconnected structure, the failure of any key node in the existence of material or information interactions can affect the operational efficiency and stability of other cities through the correlation network (Zhao et al. 2024). At present, China's urban agglomerations mainly include the Yangtze River Delta urban agglomeration, the Pearl River Delta urban agglomeration, and the Beijing–Tianjin–Hebei urban agglomeration (BTHUA). As the third largest urban agglomeration in China, BTHUA's development pattern is significantly different from that of Yangtze River Delta and Pearl River Delta. Beijing, as the core city of the BTHUA, has been undertaking too many non-capital functions for a long time, which has led to “big city diseases” such as over-concentration of population, traffic congestion, environmental pollution. Tianjin and Hebei, on the other hand, have the capacity to take over the functions of Beijing–Tianjin–Hebei. Tianjin and Hebei, on the other hand, have insufficient capacity to take over functions, and the gap between Hebei's level of economic development and that of Beijing and Tianjin, in particular, limits the overall synergistic effect. The lack of megacities in the region as a “bridge”, Shijiazhuang, Tangshan and other cities in Hebei are insufficient in scale and economic strength, making it difficult to form an effective sub-growth pole.

Improving urban resilience is widely acknowledged as an effective approach to adapt to uncertain events (Almulhim and Cobbinah, 2025; Du et al. 2020). Urban resilience is a concept in sustainable urban planning that emphasises the ability of cities to maintain or quickly restore their basic functions under external pressures and adapt to changes for sustainable development (Jabareen, 2013). The concept of urban resilience is no longer spatially limited to individual cities under the development trend of risk complexity and regional synergy, and instead, it gradually forms a multi-centre, multi-level, and multi-node resilience correlation network structure. Cities interact and synergise with each other through the network structure, enhancing the overall risk resilience of urban agglomerations (Fu et al. 2016). Therefore, in

the current context of highly uncertain, frequent, and coupled occurrence of global economic, social, and natural disaster risks, exploring the characteristics of urban agglomeration resilience correlation and its influencing factors from a spatial network perspective is crucial to identify the weak nodes of urban agglomeration considering risky events and resilience building.

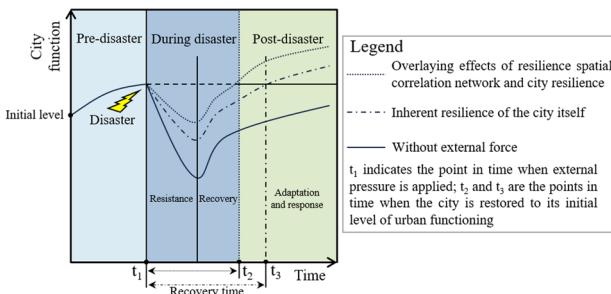
This study constructed the evaluation index system of urban resilience based on a DPSR framework and calculated the level of urban resilience in the BTHUA from 2012 to 2021 and comprehensively applied the entropy weight and technique for order preference by similarity to ideal solution (TOPSIS) method to measure urban resilience in the BTHUA from 2012 to 2021. Subsequently, the strength of the spatial correlation of urban agglomeration resilience and structural characteristics of the spatial correlation network were explored using a modified gravity model and social network analysis. In addition, a quadratic assignment procedure (QAP) model was applied to explain the mechanisms of the influencing factors on the resilience spatial correlation network of the BTHUA.

The remainder of this manuscript is organised as follows: Section 2 provides a comprehensive literature review and summarises the concepts of resilience and its spatial correlation network. Section 3 introduces the relevant methods used, selection of indicators, and data sources. Section 4 presents the results of the case study. Section 5 discusses the results and proposes future work. We conclude the work and provide policy implications in Section 6.

## Literature review

**Concept of urban resilience and its spatial correlation network.** Defining urban resilience forms the basis for rationally constructing the evaluation indicator system. Resilience first appeared in engineering and was defined as the ability of a material to absorb energy during plastic deformation and fracture (Wied et al. 2020). In the 1970s, Holling introduced the concept of resilience into ecology, describing it as the ability of a system to recover after an external disturbance (Holling, 1973). Although the definition of ecological resilience is more comprehensive than that of engineering resilience, it is still affected by the equilibrium perspective, which views system development as a transition from one equilibrium state to another. However, socio-economic systems are in a constant state of evolution and development, which limits the applicability of the equilibrium theory to such systems. Therefore, Alberti defined resilience as the ability of a city to maintain its original structure and function after changes in internal and external driving forces (Alberti, 2005). Wilbanks posited that resilience was the capacity of a city to minimise harm to public safety and socio-economic impacts in the face of multiple crises (Wilbanks and Sathaye, 2007). The Rockefeller Foundation defined resilience as the ability of individuals, communities, institutions, and systems within a city to survive, adapt, and develop under pressure (Cutter et al. 2008). Based on the definitions of urban resilience from the aforementioned studies, this study contends that urban resilience represents the ability of a city to maintain normal operation and development by relying on its dynamic equilibrium, redundancy buffer, and self-repair characteristics under various societal and environmental pressures. This emphasises the ability of the cities to resist, recover, adapt, and learn in the face of disasters.

Urban resilience is not only a property of a single city but is also affected by interactions between cities (Eldesoky and Abdeldayem, 2023). This characteristic indicates that the study of urban resilience needs to expand from the perspective of a single city to that of city agglomeration to consider spatial



**Fig. 1** Effects of resilience spatial correlation network.

interconnections between cities (Liu et al. 2025). As a core unit of regional development, the optimisation of the spatial structure of urban agglomerations is crucial to enhance the overall competitiveness of the region (Zhao et al. 2025). A polycentric and networked perspective emphasises synergy and cooperation among cities and promotes resource sharing and complementarity of advantages by constructing an efficient urban network to achieve sustainable regional development (Cucuzzella et al. 2022). Therefore, the study of spatial structure characteristics has evolved from a single-centre approach to a multi-centre and networked perspective, and the research perspective has changed from individual cities to the exploration of the evolutionary characteristics of the overall network of urban agglomeration (Liu et al. 2024a; Yang and Su, 2024). Further, the study of urban resilience needs to change from the measurement of single-city resilience to the analysis of the spatial network structure characteristics of urban agglomeration resilience. An urban resilience spatial correlation network is essentially the spatial extension and expansion of regional resilience, and it can be defined as the ability of an urban network system to prevent, resist, respond, and adapt to the effects of external shocks and recover or transform from them with the help of inter-city collaborative and complementary relationships across social, economic, engineering, and organisational domains (Wu et al. 2024). The effects of urban resilience and the network of spatial correlation of urban resilience on urban functions is illustrated in Fig. 1. Compared to the inherent resilience effect of a city, cities within the urban resilience spatial correlation network are affected by the resilience spillover effects from other cities. Consequently, under this superimposed effect, the loss of urban functions during disasters is smaller, the recovery speed after disasters is faster, and urban functions are more improved after full adaptation.

**Construction of an urban resilience evaluation index system.** Both domestic and global researchers have defined and measured the resilience of urban subsystems including economic resilience (Shang and Liu, 2024), social resilience (Ruggiero et al. 2024), ecological resilience (Feng et al. 2024a), and territorial resilience (Assumma et al. 2021). The resilience evaluation of a city requires a comprehensive assessment from a multi-dimensional perspective. Current research on the construction of an urban resilience evaluation index system falls into three categories: (1) Key factors affecting urban resilience were identified based on the four characteristics of resistance to disturbance, redundancy, wisdom, and rapidity, and an evaluation indicator system for urban resilience was constructed (Wang and Shen, 2025). (2) From the perspective of recovery and learning, infrastructure, economy, community, and organisation were evaluated comprehensively as four dimensions for assessing the resilience and adaptability of a city in the face of shocks (Liu, 2021). (3) Based on the perspectives of ecology, economy, society, and infrastructure services, the indicators of sewage treatment rate, gross domestic product

(GDP), and number of beds in healthcare institutions reflected the basic service capacity and economic development level of the city (Datola, 2023; Sun and You, 2021).

However, these assessment perspectives do not adequately reveal the dynamic process of urban resilience in terms of resistance, recovery, adaptation, and enhancement in the face of disasters, which limits the comprehensive understanding and systematic identification of factors that affect urban resilience. In contrast to traditional frameworks for assessing urban resilience, the driving force-pressure-state-response (DPSR) framework provides a dynamic perspective that is closely aligned with the increasing complexity and diversity of urban risks. The framework helps to provide a holistic view of urban resilience to risk by dividing the process of urban response into three phases: first, responding to immediate disruptions; second, adapting to long-term changing conditions; and third, enhancing the city's ability to withstand and recover from future challenges. By integrating these stages, the DPSR framework provides valuable insights for urban planners and policymakers.

**Quantitative methods for urban resilience correlation and influence mechanisms.** Quantifying the resilience of individual cities is a prerequisite to assess the spatial correlation of resilience in urban agglomerations. Various multi-criteria decision analysis and decision-making methods are employed to assess urban resilience. We classify these methods into three categories: (1) Model-driven methods: System dynamics and STIRPAT models for simulating changes in resilience dynamics and analysing complex interactions (Tian et al. 2024; Li et al. 2020). (2) Data-driven approaches: Entropy weight-TOPSIS and data envelopment analysis for toughness assessment based on empirical data (Xia and Zhai, 2022; Li et al. 2024a). (3) The GANPSort II genetic algorithm and hybrid entropy weight-DEMATEL method, which combines simulation capabilities with empirical validation to deliver comprehensive evaluations (Assumma et al. 2024; Jiao et al. 2024). Among these methodological paradigms, the entropy weight-TOPSIS approach has gained prominence in multi-criteria resilience evaluations because it can objectively determine indicator weights through entropy calculations while systematically ranking alternatives via the TOPSIS technique. This contrasts with purely model-driven methods that suffer from subjective parameterisation and hybrid approaches that require more complex implementation frameworks.

For exploring the influencing mechanism of the spatial network of resilience, decision-making trial and evaluation laboratory-interpretative structural modelling has been applied to identify key factors affecting resilience, clarify pathways and hierarchical structures among these factors, and construct multi-level cascading structure models that can visually present the key factors and their pathways (Chen et al. 2021). Huang et al. (2022) used social network analysis, Spearman's correlation coefficient, and a cubic model to explore factors that affect the ecological resilience system of the Shandong Peninsula urban agglomeration and their action mechanisms. They suggested that the resilience of the urban agglomeration ecosystem was enhanced by optimising the ecological network structure. Further, some researchers explored the spatial network structure of economic resilience and found that economic resilience among Chinese provinces forms a multi-level network structure that is more compact in urban agglomerations wherein geographic distance and human capital are key factors affecting the spatial network of economic resilience (Wang and Ge, 2023).

**Research gaps and main contribution.** Although some progress has been achieved in the research on urban resilience, the

following shortcomings remain: (1) The construction of an indicator system lacks comprehensiveness, systematicity, and dynamism, and thus, it fails to consider the entire process through which urban resilience operates, thereby leading to the omission of key factors when building indicator systems. (2) Most studies focus on measuring the resilience levels of individual cities, while ignoring the spatial correlation network of urban agglomeration resilience in the context of globalisation and regional integration. This limitation in research perspective restricts our understanding of the role of interdependence and synergy in improving the resilience of urban agglomeration. (3) Although many studies have conducted comprehensive analyses of the factors influencing urban resilience and their mechanisms, research on factors and mechanisms affecting the spatial correlation network of urban agglomeration resilience is relatively scarce.

This work aims to fill the knowledge gaps and contribute to the existing urban resilience discourse by establishing a resilience evaluation index system based on the DPSR framework that can provide a structured approach to evaluating urban resilience. Further, the structural characteristics of the BTHUA resilience spatial correlation network are investigated using the modified gravity model and social network analysis, and the results help identify the key nodes and connections in urban agglomerations, enhancing the resilience and recovery of urban agglomerations in the face of natural disasters, economic crises, and other shocks. The factors influencing the resilience spatial correlation network are investigated based on the QAP model. This approach enables the study to identify key factors affecting the correlation and heterogeneity of the resilience spatial correlation network at the scale of urban agglomeration, thereby providing a scientific basis for enhancing the resilience correlation between cities and improving resilience. The research framework is presented in Fig. 2.

## Material and methods

**Study area.** The BTHUA, as a core component of China's capital economic, includes two municipalities directly under the central government of Beijing and Tianjin, as well as the cities of Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, and Hengshui in Hebei Province. The geographical location of the BTHUA is illustrated in Fig. 3. However, the BTHUA has long been facing development problems such as the obvious phenomenon of "mono-core polarisation" and urban hierarchical faults, which have seriously hindered the reasonable distribution of resources within the urban agglomerations, and are not conducive to the construction of the overall resilience network. Therefore, it is necessary to explore the structural characteristics and influence mechanisms of the resilient spatial correlation network of the BTHUA, to reveal the weak nodes of the resilient spatial correlation network of the BTHUA under the "single-core" driving mode, and to provide a reference paradigm for the balanced security and development of similar urban agglomerations around the world.

**Construction of the indicator system.** As one of the logical frameworks for constructing an evaluation system, the DPSR framework has been widely used in different fields such as urban human settlement resilience assessment, water environment carrying capacity assessment, and ecological security assessment (Wu et al. 2022). This study employs the DPSR framework to establish a causal chain encompassing driving forces, pressures, states, and responses and conduct a comprehensive analysis of the intricate process through which a resilience of a city is activated in the aftermath of various disturbances. The constructed index system

and the logical relationship are shown in Fig. 4. As the evaluation framework covers indicators of urban infrastructure, healthcare conditions, and the environment, it can be applied to assess the resilience of cities in the face of risks such as natural disasters, public health crises, and pressure on ecological resources.

**Data sources.** The socio-economic, demographic, and environmental statistics of the Beijing–Tianjin–Hebei region from 2014 to 2022 were obtained from the China Urban, Hebei, Beijing, and Tianjin Statistical Yearbooks. Geographic distances between cities were calculated using ArcGIS software. Individual missing data were supplemented using interpolation and autoregressive fitting methods, and by querying the statistical yearbooks of cities with missing data.

**Entropy weight-TOPSIS method.** The entropy weight method determines the weights by calculating the information entropy of each indicator, reducing the effect of subjective judgement and making the evaluation process more objective. Based on the weights of indicators determined by the entropy method, the TOPSIS method evaluates the merits and demerits of each object by calculating the distance between the evaluation objects and the best and worst schemes. The combined use of entropy weight-TOPSIS method provides a more scientific and objective evaluation for urban resilience measurement, which improves the reliability of the evaluation results by comprehensively considering the objective weights of the indicators and proximity of the evaluation objects to the ideal solution. In urban resilience measurement, this method comprehensively considers indicators from multiple dimensions (e.g. social, ecological, infrastructure, and economic) and provides a dynamic and multi-dimensional evaluation tool for urban planners and decision makers (Szpotowicz and Tóth, 2020). The calculation steps are as follows:

- (1) Use the min-max standardisation method to standardise positive and negative indicators in the resilience evaluation index system. Indicators besides the construction land area are treated with positive normalisation.

For positive indicators,

$$y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

For negative indicators,

$$y_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

In Eqs. (1) and (2),  $y_{ij}$ ,  $x_{ij}$ , and  $\min(x_j)$  and  $\max(x_j)$  represent the standardised indicator value, value of indicator  $j$  ( $j = 1, 2, \dots, m$ ) in evaluation unit  $i$  ( $i = 1, 2, \dots, n$ ), and the minimum and maximum values of indicator  $j$ , respectively.

- (2) Calculate proportion  $P_{ij}$  occupied by the  $i$ -th evaluation unit in the  $j$ -th indicator using

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^n y_{ij}} \quad (3)$$

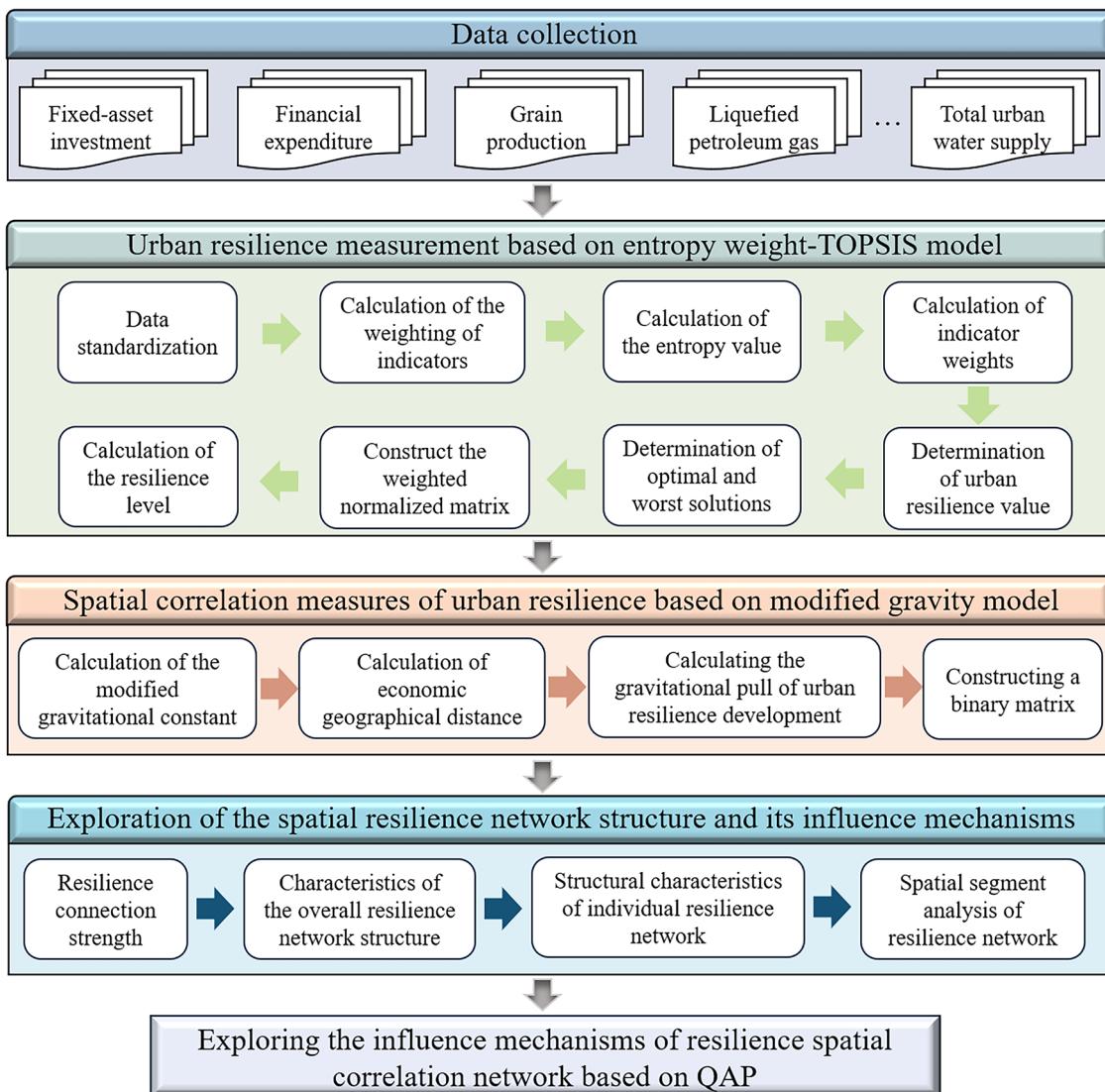
- (3) Calculate the entropy value  $e_j$  of the  $j$ -th indicator using

$$e_j = -\frac{1}{\ln n \sum_{i=1}^n P_{ij} \ln(P_{ij})}, 0 \leq e_j \leq 1 \quad (4)$$

- (4) Determine weights  $w_j$  of the indicators using

$$w_j = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \quad (5)$$

- (5) Construct the weighted normalisation matrix  $z$ , where  $w_j$  represents the weight of each indicator determined using



**Fig. 2** Methodological framework of this research.

the entropy value method, as shown in

$$Z = (z_{ij})_{m \times n} = (w_j y_{ij})_{m \times n} \quad (6)$$

- (6) Calculate the optimal distance  $D_i^+$  and worst distance  $D_i^-$  from the ideal scheme for the object of evaluation using

$$D_i^+ = \sqrt{\sum_{(i=1)}^n (Z_j^+ - z_{ij})^2} \quad (7)$$

$$D_i^- = \sqrt{\sum_{(i=1)}^n (Z_j^- - z_{ij})^2}$$

$$Z^+ = (Z_1^+, Z_2^+, \dots, Z_m^+), Z^- = (Z_1^-, Z_2^-, \dots, Z_m^-)$$

where  $Z_j^+$  and  $Z_j^-$  represent the maximum and minimum values of the  $j$ -th indicator, respectively.

- (7) Obtain the resilience of the evaluation object using

$$R = \frac{D_i^-}{D_i^+ + D_i^-} \quad (8)$$

**Modified gravity model.** The gravity model represents the mutual forces of interaction between different spatial units, not only measuring the spatial connectivity of a region but also the

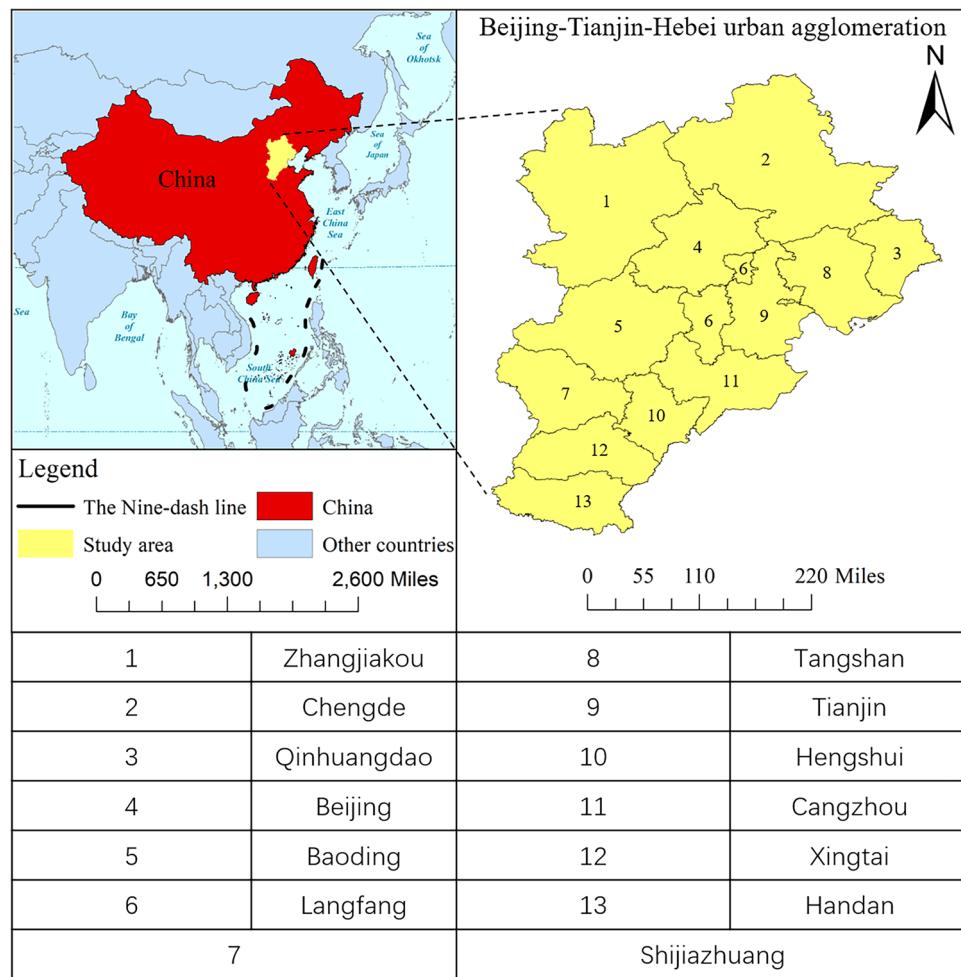
internal spatial flow paths between individuals (Feng et al. 2024b). Given the limitations of the traditional gravity model in dealing with the regional connectivity of resilience levels and issues of fluidity and asymmetry, this study improved the model based on the asymmetry of economic element flow. The modified gravity model is expressed as

$$G_{ab} = k \frac{R_a R_b}{D_{ab}^2} \quad (9)$$

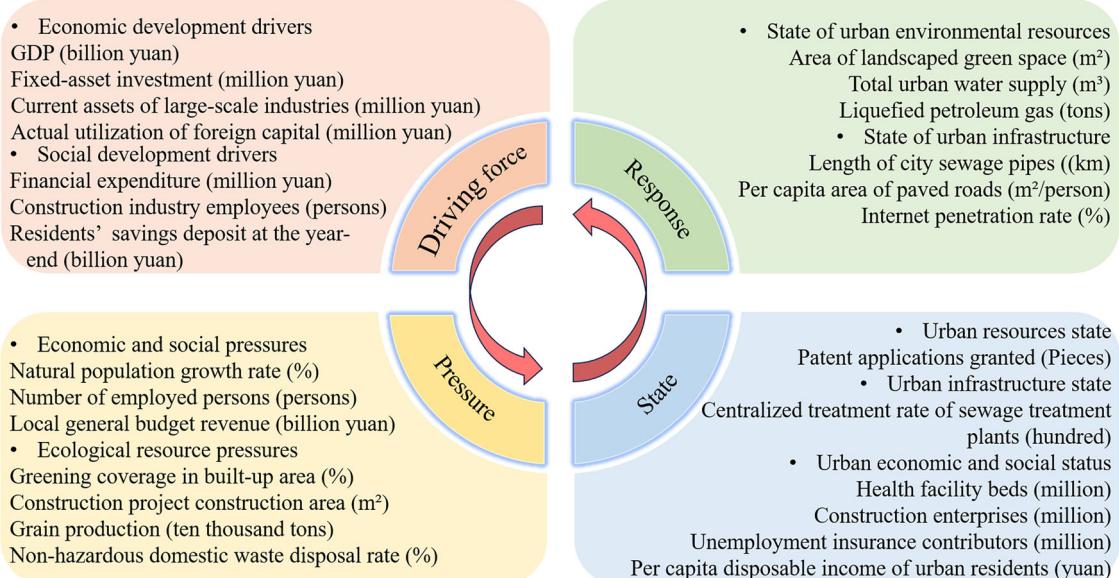
$$k = \frac{R_a}{R_a + R_b} \quad (10)$$

$$D_{ab} = \frac{d_{ab}}{g_a - g_b} \quad (11)$$

where  $G_{ab}$  represents the strength of the correlation of resilience between city  $a$  and city  $b$ ; the gravitational constant  $k$  describes the correction factor for the resilience;  $R_a$  and  $R_b$  represent the level of resilience of cities  $a$  and  $b$ , respectively;  $g_a$  and  $g_b$  represent the GDP of cities  $a$  and  $b$ , respectively;  $d_{ab}$  represent the distance between cities  $a$  and  $b$ ; and  $D_{ab}$  represent the economic-geographical distance of the city.



**Fig. 3** Geographical location of the BTHUA.



**Fig. 4** Evaluation index system of urban resilience.

**Social network analysis.** Compared to other methods, social network analysis can effectively reflect the overall characteristics of a network structure and position of individuals in the network. It is often used to explore the spatial correlation network of regional carbon emissions, spatial correlation network of water resources, environmental and ecological efficiency, and spatial correlation network of green innovation efficiency, thereby providing a powerful tool to understand and optimise these complex networks (Liu et al. 2024b; Li et al. 2024b). Social network analysis is grounded in social network theory, which posits that individuals or entities (nodes) are interconnected through the various types of relationships (edges). These relationships form a network structure that can significantly affect the behaviour and outcomes of the nodes within it.

In the context of urban resilience, social network analysis enables us to examine how cities within a region are interconnected and how these connections affect their resilience. Therefore, we used the indicators of network density, network connectedness, network hierarchy, network efficiency, and centrality to explore the overall characteristics and individual differences of the resilience spatial correlation network of the BTHUA. The methods of calculating the indicators and their meanings are listed in Table 1.

**Quadratic assignment procedure model.** The resilience spatial correlation network of urban agglomerations results in the interplay among various factors. If traditional econometric models are employed for empirical testing, the results could be biased because of multi-collinearity among factors. QAP is a non-parametric testing method for examining regression relationships between multiple matrices and a single matrix. Compared to traditional multivariate regression statistical testing methods, the QAP model can overcome the issue of multi-collinearity among independent variables (Bai and Lin, 2024).

The formation of the resilience spatial correlation network is a manifestation of the multi-dimensional interaction and

collaboration among cities in geographical space, with individual differences between cities being the main cause of the asymmetric phenomenon in the flow of elements. Thus, the difference matrix of geographical distance, level of economic development, degree of openness to the outside world, government macro-control, ecological resources and environment, and level of infrastructural services are selected as explanatory variables. These socio-economic factors can reflect the situation of the flow of factors of production, industrial synergy and infrastructure connectivity between cities in the event of external shocks such as natural disasters and economic crises. The specific descriptions provided in Table 2. The constructed model is expressed as:

$$UR = f(GD, ED, OOW, TN, UD, ISL). \quad (12)$$

## Results

**Measurement of urban resilience.** Equations (1)–(8) are used to calculate the resilience of individual cities, and the results are summarised in Table 3. Urban resilience increased between 2014 and 2018, which was closely associated with urban development, policy support, and infrastructure construction. However, a decline in resilience was observed in 2022 for these cities, which can be potentially attributed to the COVID-19 pandemic and economic fluctuations. Beijing and Tianjin, as two direct-controlled municipality cities within the region, maintained a high level of resilience during this period, reflecting their advantages in resource allocation, policy formulation, and emergency response capabilities.

Kernel density estimation can reveal spatial distribution characteristics, patterns, and polarisation levels of urban resilience. In this study, we applied this method to explore the trends in the BTHUA resilience across different years, as illustrated in Fig. 5. In 2014, the urban resilience of BTHUA exhibited a significant polarisation characteristic. From 2014 to 2018, the distribution of resilience within urban agglomeration became more concentrated, with the peak shifting to the right. This trend indicates that, during this period, the overall resilience level of BTHUA was enhanced, and the polarisation

**Table 1 Indicators for evaluating the structure characteristics of spatial correlation network.**

Indicators	Equation	Symbolic significance	Function
Network density	$\rho = \frac{2M}{N(N-1)}$	$M$ and $N$ represent the number of edges and nodes in the network, respectively.	Describes the density of node distribution.
Network connectedness	$C = 1 - N \times (N-1)/2V$	$C$ and $V$ represent the connectedness and logarithm of unreachable points in the network, respectively.	Measure the tightness of connections between nodes in the network.
Network efficiency	$E = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{D_{ij}}$	$E$ , $D_{ij}$ , and $G$ represent the efficiency, shortest distance of all from city $i$ to city $j$ , and set of remaining nodes in the network after removing the nodes, respectively	Used to measure the information transfer efficiency in the network.
Network hierarchy	$G_H = 1 - \frac{V}{\text{MAX}(V)}$	$G_H$ , $V$ , and $\text{MAX}(V)$ represent the network hierarchy, number of point pairs of mutually symmetrically reachable regions in the correlation network, and maximum number of pairs of points in the network that are mutually reachable by two points, respectively.	Evaluate the stability and complexity of the network.
Degree centrality	Out-degree $C_{od}(i) = \sum_{j=1}^n X_{ij}/(n-1)$ In-degree $C_{id}(i) = \sum_{j=1}^n X_{ji}/(n-1)$	$X$ indicates whether there is a direct link between cities, with 1 for a direct link and 0, otherwise.	Measures the number of connections a city has to or by other cities.
Closeness centrality	Out-closeness centrality $C_{oc}(i) = (n-1)/ \sum_{i \neq j, j=1}^n d(i,j)$ In-closeness centrality $C_{ic}(i) = (n-1)/ \sum_{i \neq j, j=1}^n d(j,i)$	$d(i,j)$ represent the shortest distance from a city $i$ to other city $j$ .	Measure the average distance from a node to all other nodes.
Betweenness centrality	$C_b(i) = \sum_{j \neq i \neq k} \frac{g_{jk}}{g_{jk}}$	$g_{jk}$ and $g_{jk}(i)$ represent the total number of shortest paths between city $j$ and $k$ that generate links and number of shortest paths through city $i$ that generate links from $j$ to $k$ , respectively.	Measure the intermediary role of a node.

**Table 2 Selection of variables.**

	<b>Indicator</b>	<b>Abbreviation</b>	<b>Measurement</b>
Dependent variable	Resilience spatial correlation network	UR	BTHUA resilience spatial correlation matrix
Independent variable	Geographic distance	GD	Euclidean distance between cities based on ArcGIS software
	Level of economic development	ED	Per capita GDP
	Degree of openness to the outside world	OOW	Actual amount of foreign capital utilised
	Technological innovation capability	TN	Number of patent applications authorised
	Urbanisation degree	UD	Construction area of building projects
	Infrastructure service level	ISL	Total urban water supply volume

**Table 3 Urban resilience of BTHUA.**

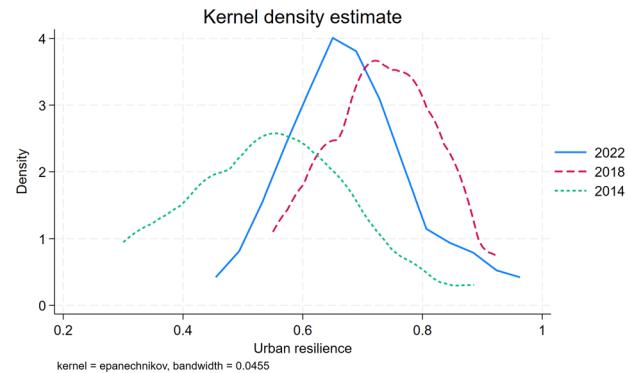
<b>City</b>	<b>2014</b>	<b>2018</b>	<b>2022</b>
Shijiazhuang	0.642	0.852	0.821
Chengde	0.442	0.631	0.604
Zhangjiakou	0.468	0.692	0.652
Qinhuangdao	0.589	0.791	0.711
Tangshan	0.676	0.783	0.763
Langfang	0.548	0.774	0.720
Baoding	0.570	0.719	0.661
Cangzhou	0.402	0.550	0.500
Hengshui	0.303	0.646	0.566
Xingtai	0.300	0.629	0.593
Handan	0.524	0.776	0.635
Beijing	0.886	0.924	0.917
Tianjin	0.654	0.718	0.700

phenomenon was mitigated. However, from 2018 to 2022, the distribution of urban agglomeration resilience in this region became dispersed again, with the peak shifting to the left, influenced by the pandemic and economic conditions. This change reflects differences in resilience among various cities. Cities with higher resilience levels can adapt and respond effectively when faced with external shocks, which can reduce the impact of the shock. In contrast, cities with lower resilience levels are more severely affected because of their relatively weaker adaptability and response capabilities.

### Structural characteristics of the resilience spatial correlation network

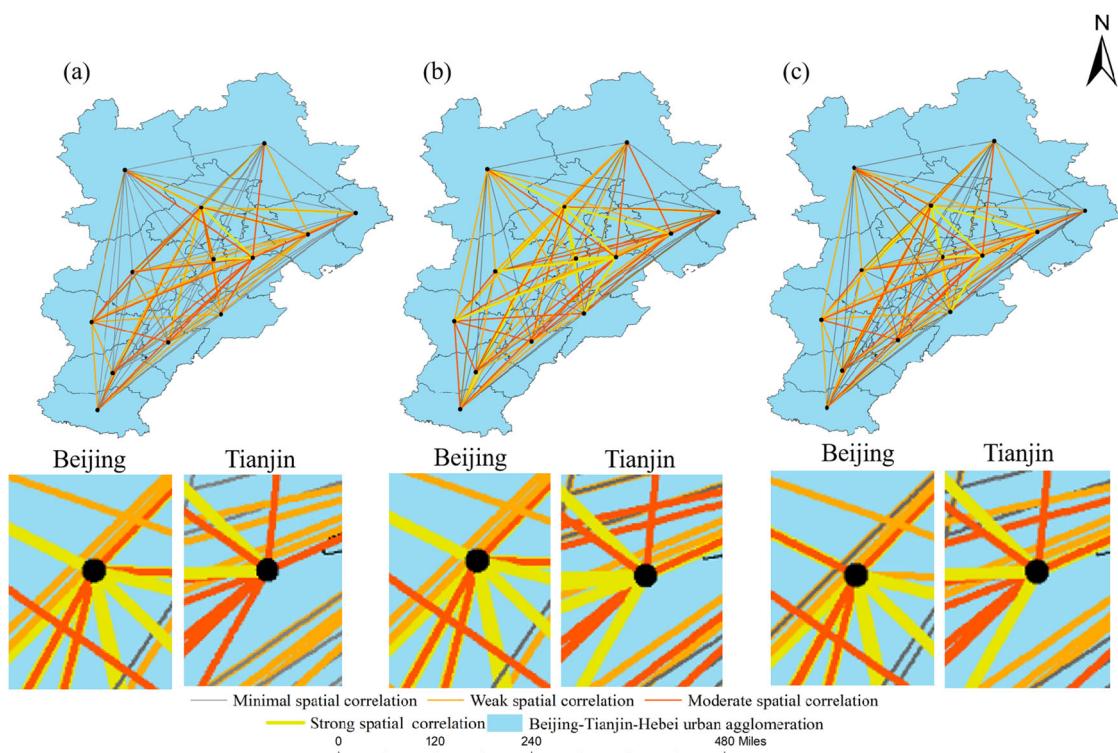
*Analysis of the strength of resilience correlation in urban agglomerations.* Based on the modified gravity model, the resilience correlation strength between cities was determined using Eqs. (9)–(11) to calculate the gravity matrix of resilience in the BTHUA from 2014 to 2022. The natural breaks method was applied to categorise the correlation strength into four levels for clearly illustrating the internal resilience correlation strength. Further, the ArcGIS software was utilised to visualise the spatial correlation network, as shown in Fig. 6.

From 2014 to 2018, the correlation strength of the BTHUA resilience exhibited an increasing trend, which implied a growing frequency of economic and ecological resource transfers. Higher resilience connection strengths were observed among core cities within the urban agglomeration, forming a spatial development pattern centred around ‘Beijing–Tianjin–Shijiazhuang–Tangshan’, which generated a radiating and driving effect on the surrounding cities. In addition, the number of weakly and moderately correlated cities increased significantly, further enriching the levels and structure of internal resilience correlation within BTHUA. From 2018 to 2022, the resilience correlation strength between cities showed a reduction. During this period, only a strong correlation was maintained among core cities such as Beijing, Tianjin, Tangshan, and Shijiazhuang, whereas the resilience correlation strength between core and peripheral cities weakened.

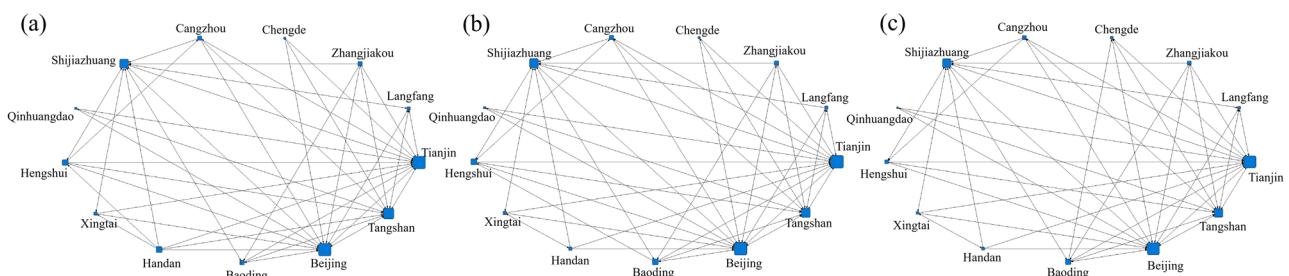
**Fig. 5** Results of kernel density estimation.

*Social network analysis of resilience spatial correlation network structure.* The resilience spatial correlation network in 2014, 2018 and 2022 are shown as Fig. 7. The UCINET software is used to analyse the network structure characteristics from 2014 to 2022, and the results are presented in Table 4. A clear trend of increasing resilience spatial correlation network density within BTHUA from 2014 to 2018 was evident, rising from 0.359 to 0.394. This upward trajectory signified a growing intensity of inter-city connections and interactions, suggesting an enhancement in the connectivity of the network. However, the COVID-19 outbreak in 2019 had a severe impact on BTHUA, which resulted in a sharp drop in network density to 0.353. This could be attributed to the lockdown measures, transport restrictions, and reduced economic activity of the city during the pandemic, which weakened physical and economic correlation between cities and affected the resilience correlation between them. From 2020 to 2022, the resilience spatial correlation network density showed an upward trend again, rising to 0.372. This reflected the positive regulatory role of the government and the self-adjustment and resilience of urban agglomerations in the face of external shocks.

The network connectedness remaining at 1 from 2014 to 2022 indicated that all cities within BTHUA were connected to at least one other city, with no cities developing in isolation. The network efficiency increased from 0.546 in 2014 to 0.515 in 2019, suggesting an enhancement in the efficiency of information transfer. The network efficiency exhibited a fluctuating upward trend, increasing from 0.546 in 2014 to 0.561 in 2022, with network efficiency dropping to its lowest point of 0.455 in 2019 and 2021. This phenomenon not only reflected the overall improvement in the efficiency of resource factor flow but also highlighted the significant adaptive and rapid recovery capabilities of BTHUA in the face of external shocks. The network centrality increased from 0.4 in 2014 to 0.572 in 2018, reflecting a strengthening of intercity connections. It subsequently declined to 0.286 in 2020, and then recovered to 0.561 in 2021 and 0.574 in 2022. The recent ceiling increased from 0.955 in 2014 to 1 in 2022. The network centrality and recent ceiling results demonstrated an increasing asymmetry within the BTHUA resilience



**Fig. 6 Correlation strength of resilience spatial network in BTHUA. a 2014, b 2018, c 2022.**



**Fig. 7 Resilience spatial correlation network in BTHUA from 2014 to 2022. a 2014, b 2018, c 2022.**

**Table 4 Density and correlation analysis of resilience spatial correlation network.**

Year	Network density	Correlation analysis			
		Network connectedness	Network efficiency	Network hierarchy	Recent ceiling
2014	0.359	1	0.546	0.4	0.955
2015	0.372	1	0.561	0.4	1
2016	0.372	1	0.546	0.435	1
2017	0.376	1	0.545	0.546	1
2018	0.385	1	0.515	0.572	1
2019	0.394	1	0.455	0.286	0.985
2020	0.353	1	0.546	0.286	0.985
2021	0.361	1	0.455	0.561	0.985
2022	0.372	1	0.561	0.574	1

spatial correlation network, with significant differences in node accessibility. This trend can be attributed to the fact that certain cities hold more strategic positions within the network, possessing greater resources and influence compared to those of the others.

*Characteristics of nodes in the resilience spatial correlation network.* In the context of the resilience spatial correlation network of the BTHUA in 2022, the results for the degree centrality, closeness centrality, and betweenness centrality of each node in the network are listed in Table 5. The in-degree in both Beijing and Tianjin was 12, which is significantly higher than their out-degree, underscoring their strong attractiveness for resources and capacity to aggregate information. This suggests that these two cities are not only the political, economic, and cultural hubs but also the primary destinations for resource flow in the BTHUA. Shijiazhuang had an out-degree of 7, which is higher than that in the in-degree, indicating that it has the strong capacity for information output and resource radiation. Tangshan had an out-degree of 9, which is greater than that of the in-degree, which is related to its status as an industrial city that exports more resources and information to other cities. Baoding, Cangzhou, and Zhangjiakou had degree centralities of 6, 5, and 5, respectively, which reflects a moderate level of connectivity. Baoding and Cangzhou exhibited a relatively balanced out-degree and in-degree, which suggests a symmetrical pattern of bidirectional communication within the network. In particular, Zhangjiakou showed an out-degree of 5 and an in-degree of 0, thereby indicating a greater dependency on information and resource inflow.

**Table 5 The network centrality of BTHUA.**

City	Degree centrality		Closeness centrality		Betweenness centrality
	Out-degree	In-degree	Out-closeness	In-closeness	
Beijing	4	12	34.286	Beijing	29.667
Handan	4	1	37.5	Handan	4.355
Xingtai	4	2	37.5	Xingtai	11
Hengshui	4	2	37.567	Hengshui	5.879
Shijiazhuang	6	7	40	Shijiazhuang	19.65
Cangzhou	5	2	38.710	Cangzhou	9.5
Baoding	5	3	38.710	Baoding	6.317
Langfang	4	4	37.5	Langfang	9.667
Tianjin	5	12	36.364	Tianjin	22.083
Tangshan	6	9	37.5	Tangshan	13.233
Qinhuangdao	3	1	30.769	Qinhuangdao	10.622
Zhangjiakou	5	0	60	Zhangjiakou	2.833
Chengde	3	3	30.769	Chengde	8.65

from other cities. One of the main reasons for this is Zhangjiakou's weak economy and infrastructure, which limits its ability to attract external resources. Its industrial structure is monolithic, dominated by agriculture and mining, with a low demand for external information and resources. In addition, the city's remote location and poor accessibility also impede the inflow of information and resources. Handan, Xingtai, Hengshui, Langfang, and Chengde cities had a low degree centrality of 4, 4, 5, 4, 3, and 4, respectively, and thus, they were at the periphery of the resilience spatial correlation network of the BTHUA.

Beijing's out-closeness centrality was 34.286, whereas its in-closeness centrality was as high as 100. This not only implies that the average distance between Beijing and other cities is very short but also indicates that Beijing is the core hub in the BTHUA, with extremely high accessibility. Further, Tianjin achieved an in-closeness centrality of 100. Shijiazhuang and Tangshan had relatively high accessibility, second only to Beijing and Tianjin, which demonstrates the significant position of these two cities in the resilient network of the BTHUA. In contrast, regions with lower accessibility, such as Zhangjiakou, Xingtai, and Hengshui, have a weak correlation in the BTHUA resilience spatial correlation network. Further, it is necessary to strengthen their connections with other cities to enhance their accessibility and influence within the regional network, which increases their capacity to withstand sudden risk events.

Beijing exhibited the highest betweenness centrality with a score of 29.667, which underscores its pivotal bridging role within the BTHUA network and highlights its substantial effect on the connectivity and overall efficiency of the network. Tianjin's betweenness centrality was 22.083, ranking second, and its contribution to regional connectivity was second only to Beijing. In addition, Shijiazhuang had a relatively high betweenness centrality of 19.650. Combined with the analysis of degree centrality, it is evident that Shijiazhuang not only has numerous direct connections with other cities but also plays a crucial role in connecting other non-directly connected cities. In contrast, cities such as Handan, Hengshui, and Zhangjiakou have relatively lower betweenness centralities at 4.355, 5.879, and 2.833, respectively.

In summary, Beijing, Tianjin, Shijiazhuang, and Tangshan, leveraging their advantages in technology, economy, and geographical location, assumed central leadership roles in the network, thereby providing solid support for the stability and development of the entire region. In contrast, peripheral cities represented by Handan, Hengshui, Zhangjiakou, and Chengde played the role of 'beneficiaries' within the network, which primarily relies on core cities to enhance their connectivity and resilience. Beijing and Tianjin, as municipalities that are directly

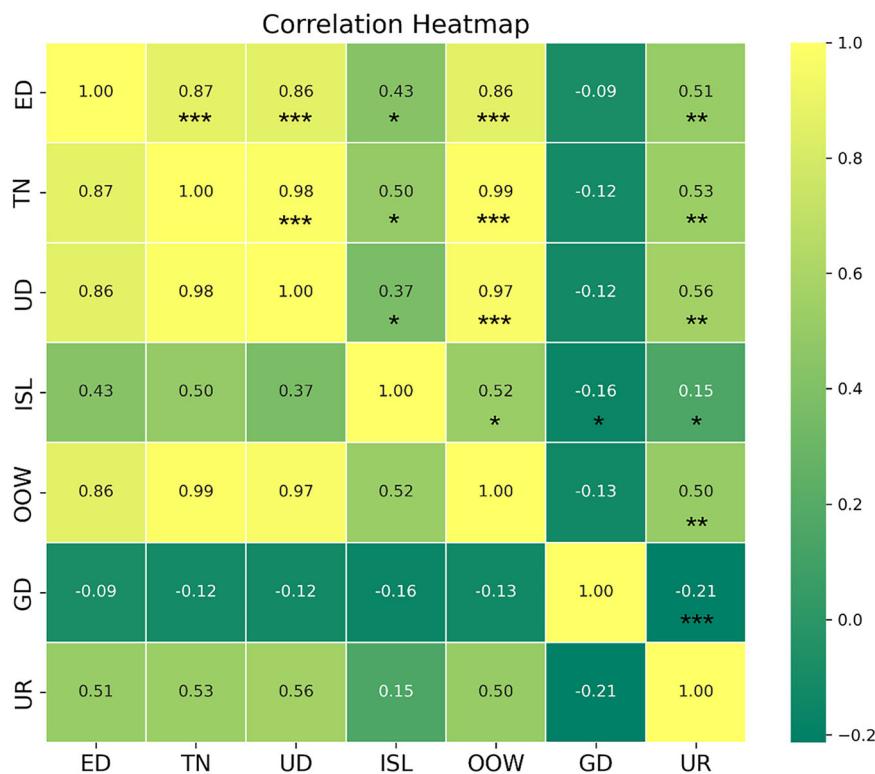
under the central government, occupied a core position in the resilience spatial correlation network; however, their role in resource transfer and resilience spillover within Hebei Province was weaker than that of Shijiazhuang. This is attributed to differences in administrative hierarchy and restrictions in resource allocation mechanisms, which create certain barriers in the transfer of resource elements. Shijiazhuang and Tangshan play a more important role in the synergistic development of resilience among cities in Hebei Province.

#### Influence mechanisms of resilience spatial correlation network

*Correlation and significance analysis of resilience spatial correlation network with other variables.* The correlation and significance coefficients between the resilience spatial correlation network and other variables of the BTHUA, as depicted in Fig. 8. The results indicate that the resilience spatial correlation network exhibits a negative correlation with geographical distance at the 1% significance level, which suggests that the resilience of the spatial correlation network of urban agglomeration may weaken with an increase in geographical distance. This finding can be related to the facilitating role of geographical proximity in inter-city connections. An increase in GD can result in diminished interactions and connectivity among cities, consequently affecting the development of the resilience spatial correlation network. In contrast, ED, OOW, TN, UD, and ISL all showed significant positive correlation with the resilience spatial correlation network. The BTHUA with a higher ED can possess greater resources and capabilities for tackling a range of challenges. A higher OOW can foster increased interactions and collaboration among cities. Enhancements in the TN can introduce novel solutions and strategies to the BTHUA. In addition, a higher UD can bolster interconnectedness between cities, while an improved ISL can lay a more robust material foundation for the development of urban agglomerations. The inter-city resilience correlation in the BTHUA is enhanced through these pathways.

*QAP analysis and heterogeneity analysis.* The results of the QAP regression are presented in Table 6, which indicates the impact coefficients and significance levels of relevant factors on the resilience spatial correlation network. The R<sup>2</sup> for 2014, 2018, and 2022 are 40.1%, 48.8%, and 53.5%, respectively, and they are significant at the 1% level. This implies that independent variables selected in this study have a strong explanatory power for the dependent variable.

Overall, GD was the most significant factor affecting the urban resilience network in 2014 and 2018, while in 2022, ED became



**Fig. 8** Correlation among variables (Note: \* $P < 0.1$ , \*\* $P < 0.05$ , \*\*\* $P < 0.01$ ).

**Table 6 Results of QAP regression.**

Variables	2014	2018	2022
GD	-0.218**	-0.288***	-0.17***
ED	0.013**	0.266**	0.272**
OOW	0.105**	0.0878**	0.139**
TN	0.182*	0.205*	0.231**
UD	0.180**	0.077**	0.162**
ISL	0.084**	0.039**	0.110**
R <sup>2</sup>	0.401***	0.488***	0.535***

\* $P < 0.1$ ; \*\* $P < 0.05$ ; \*\*\* $P < 0.01$ .

the most critical influencing factor. The regression coefficient for *GD* was negative and significant at the 1% level, reflecting that adjacent cities are more likely to form resilience correlations. However, the absolute value of its coefficient shows a decreasing trend, dropping from 0.218 to 0.170, which suggests that the dependence of urban resilience correlation on *GD* is gradually decreasing. In contrast, the improvement of *ED* has a significant positive effect on the urban agglomeration resilience network. The impact coefficient for *ED* increased continuously from 0.013 in 2014 to 0.27 in 2022, which implies that with urban economic development, cities, based on their resource endowments, gradually build specialised industrial chains, thereby enabling resources and information to flow and share rapidly within the urban agglomeration, significantly enhancing the urban agglomeration risk resistance capacity.

The *OOW* played a positive role in the resilience spatial correlation network in 2014, 2018, and 2022, and the impact coefficient increased gradually. This can be attributed to enhancing *OOW* being more attractive foreign investment and outward investment, thereby promoting exchanges and cooperation among cities and the diversified development of the economy, which increases urban economic vitality.

Although the impact coefficient of the level of *TN* fluctuates, it showed an upward trend, which rises from 0.182 in 2014 to 0.231 in 2022, thereby playing a positive role in promoting the development of the BTHUA resilience network. This implies that *TN* can promote the modernisation of urban governance systems and capabilities, which improves the efficiency and level of urban governance.

In the early stages of urbanisation, the effect of *UD* on the urban agglomeration resilience spatial correlation network did not pass the significance test. However, in 2022, the level of urbanisation showed a positive promotion effect on the urban agglomeration resilience spatial correlation network at the 10% significance level. This is because, at the early stage of urbanisation, there were relatively few correlations and interactions within the BTHUA, and resource spillovers and synergies between cities that are yet to be brought into full play. The connections and interactions within the urban agglomeration gradually strengthen with advancements in the process of urbanisation, and the resource spillover and synergy effects between cities begin to emerge.

The regression coefficient of *ISL* changes from 0.084 to 0.11 from 2014 to 2022, revealing that the role in the improvement of the level of infrastructure services in enhancing the resilience spatial correlation network of the BTHUA is gradually strengthening. This indicates that improvements in the efficiency of key services such as transport, energy, and communications increased the efficiency of the internal correlation of urban agglomeration and facilitated economic, social, and cultural exchanges within the BTHUA. Such enhanced exchanges contribute to the formation of a closer and more complex network of resilience spatial correlation in the BTHUA.

## Discussion

Geographical conflicts, ecological degradation, and economic crises, which occur frequently, have extensive negative impacts

within urban agglomerations, challenging their operational efficiency and sustainable development. Therefore, investigating and reinforcing the resilient interconnections between cities from a spatial network perspective is necessary. This perspective emphasises that, in the face of risk events, urban agglomerations should actively coordinate resources, share information, and jointly respond to external shocks to enhance their overall resilience. This study innovatively constructed a resilience evaluation index system throughout the entire process of resilience function. From a social network perspective, it analysed the structural evolution characteristics of the resilience spatial correlation network in the BTHUA, identified weak nodes and development patterns, and further explored the related factors influencing and their spatiotemporal heterogeneity.

**Characteristics of the evolution of resilience in the BTHUA.** Current studies on urban resilience focus on assessing the resilience levels of individual cities. For example, Sun et al. indicated that the resilience of the BTHUA is developing with Beijing and Tianjin as the core (Sun et al. 2024). Mu et al. employed the entropy method to measure the urban resilience of BTHUA from 2000 to 2018, and findings showed an increasing trend in urban resilience over the study period (Mu et al., 2022). All these conclusions show that Beijing and Tianjin exert a radiating and driving effect on surrounding cities, and the capacity of the BTHUA to maintain or restore the normal functioning of urban systems in response to external disturbances and challenges has been progressively strengthening. However, in this study, it is worth noting that Tianjin's resilience remained at a high level in 2014, while its resilience level is no longer in the lead after 2018. The main reason for this is that, as a traditional industrial centre, Tianjin's economy is dependent on traditional industries such as petrochemicals and heavy manufacturing. In 2014, the value added of the petrochemical industry accounted for as much as 30% of the city's total industrial output value. This dependence makes Tianjin less resilient to external shocks, including economic downturns and increasingly stringent environmental regulations. In addition, the devastating port explosion in 2015, coupled with recurring environmental crises such as air and water pollution, led to a decline in its resilience in the post-2018 rankings.

In comparison, although the Yangtze River Delta and Pearl River Delta urban agglomerations possess core cities, their patterns and velocities of resilience development differ. The resilience of the Yangtze River Delta urban agglomeration was on a continuous growth trajectory, while that of the Pearl River Delta urban agglomeration has transitioned from a low to a high-speed phase (Zhu et al. 2020). In contrast, this research focused on the period from 2014 to 2022, considering the process of resilience function and constructed a dynamic resilience evaluation index system. The findings of this study reveal a significant decline in the resilience of the BTHUA after 2019, which can be attributable to the effects of the COVID-19 pandemic. With the inherent resilience of the city and government intervention, there is a clear upward trend in resilience; however, the area is still recovering.

**Characteristics of resilience spatial correlation network in the BTHUA.** Analysing the resilience spatial correlation strength in the BTHUA revealed that higher resilience connections exist between core cities within the urban group, forming a spatial development pattern centred on Beijing–Tianjin–Shijiazhuang. This finding is similar to that reported by Zhao et al., wherein the development quality of cities within the BTHUA and pattern of inter-city connections exhibited a 'belt' structural development in space. Although this 'belt' structure is also reflected in the

Yangtze River Delta and Pearl River Delta urban agglomerations, it differs in specific manifestations (Zhao et al. 2018). For example, the urban resilience in the Yangtze River Delta urban agglomeration showed a positive spatial agglomeration, forming a Z-shaped high-resilience urban zone (Wang and Wang, 2024). In addition, there are significant differences in the growth pole effect between the BTHUA and Yangtze River Delta and Pearl River Delta urban agglomerations. The growth pole effect in the BTHAU is reflected in the two core cities of Beijing and Tianjin, while the Yangtze River Delta and Pearl River Delta urban agglomerations exhibited a more balanced distribution of growth poles (Du et al. 2019; Fang et al. 2024; Fang et al. 2025). This suggests that the BTHUA needs to focus on the balanced development within the region and the supporting role of small and medium-sized cities.

The density of the resilience spatial correlation network in the BTHUA increased year-by-year from 2014 to 2018. Economic, social, and infrastructure urban systems were severely affected under the effect of the pandemic, leading to a reduction in the exchange of resources between cities and a decrease in network density in 2020. However, complex networks possess robustness and resilience when facing attacks and disturbances (Lu et al. 2023), and therefore, the network efficiency recovers gradually in 2021 and 2022. In addition, the characteristics of the resilience spatial correlation network in the BTHUA differ from those of other urban agglomerations. The structure of the resilience network in the Chengdu-Chongqing urban agglomeration evolved from a weak connection state to a tight connection state (Shi and Niu, 2024). In contrast, the BTHUA demonstrates a long history of market segmentation and administrative barriers, which result in increasingly asymmetric networks of spatial correlation of resilience and lower levels of network density.

The network centrality of each city in the BTHUA's resilience network shows differentiated characteristics. Core cities like Beijing, Tianjin, and Shijiazhuang play central leadership roles in the resilience network, underpinning regional stability and development. This is because they are the political, economic, and cultural hubs of the BTHUA and thus facilitate resilience spillover (Ren et al. 2024). In contrast, peripheral cities mainly depend on core cities to strengthen their connectivity and resilience.

Notably, Beijing and Tianjin have a relatively weak role in resource transfer and resilience spillover within Hebei Province. This is mainly due to administrative and resource allocation differences. In comparison, Shijiazhuang and Tangshan are better integrated into Hebei's provincial administrative and resource systems. As Hebei's capital, Shijiazhuang is central to policy implementation and resource distribution within the province, making it more effective at promoting resource transfer and resilience spillover among Hebei's cities (Luo et al. 2024).

**Influence mechanisms of the resilience spatial correlation network in the BTHUA.** Differences in *UD*, *ED*, *GD*, *ISL*, *TN*, and *OW* primarily affect the urban resilience spatial correlation network. Increased urbanisation and economic development enhance inter-city connectivity and resource allocation capacity, positively affecting the resilient spatial correlation network, similar to the results of previous studies (Hu et al. 2022). The increase in *GD* has a negative effect on the resilience network. A possible explanation for this can be the higher probability of neighbouring cities to form close connections because of lower communication costs, which is crucial for the formation of the spatial relational network of urban resilience (Zhang et al. 2020). The *ISL* directly affects the connectivity capability of a city (Li et al. 2024c). The *TN* is a key factor in promoting urban

development and an important approach for improving urban resilience because technological innovation can introduce new solutions to help cities better cope with various challenges, such as improving urban management efficiency and disaster response capacity through smart city technology (Wang and Hao, 2024). In addition, the opening-up policy helps promote the diversification of the economic and industrial structure of urban agglomerations, reduce the dependence on a single industry, and enhance the resilience of the economy, thereby improving the resilience of urban agglomerations.

**Policy recommendations.** Based on the results of the study, we put forward the following recommendations to strengthen the resilience network of the Beijing–Tianjin–Hebei coordinated development region and to improve the overall regional resilience in the face of potential risks in order to promote sustainable regional development.

Firstly, for Beijing–Tianjin, as the dual core of the Beijing–Tianjin–Hebei resilience spatial correlation network, there is a need to take advantage of its resources and policies to strengthen its correlation with other cities, promote resource sharing, and bear risks together. The Beijing–Tianjin–Hebei Joint Sovereign Bond Issuance Mechanism can be established, with the Beijing Financial Street and Tianjin Free Trade Zone as the platforms, to pilot the issuance of “Regional Resilience Special Bonds”, which can be directed to support the supply of public goods such as cross-municipal flood control facilities and emergency material storage depots.

Secondly, strengthen the supportive role of sub-core cities such as Shijiazhuang and Tangshan, build a close industrial chain and innovation chain through the interconnection of transport, information and other infrastructures, share the functions of the dual-core cities together, and become a new engine to drive the development of other cities in Hebei Province. The “Policy Enclave” model can be implemented in Shijiazhuang, Baoding, Langfang Science and Technology Innovation Corridor, Beijing–Hebei Caofeidian Cooperative Development Demonstration Zone, and Shijiazhuang Hi-Tech Zone can be allowed to set up a “Special Zone of Industry Chain Resilience” in Handan. “Shijiazhuang Hi-Tech Zone” is allowed to set up a special resilience zone in Handan, sharing carbon emission quotas and emergency capacity indicators.

Thirdly, for the peripheral cities in the resilient spatial network, such as Handan, Xingtai, Chengde, infrastructure investment should be increased to promote the modernisation of transport, energy, communications, to build an efficient, safe and intelligent infrastructure network, and to enhance its position in the urban resilience spatial correlation network.

**Limitations.** Although this study has achieved progress in exploring the characteristics of the resilience spatial correlation network structure and its influencing mechanisms, it suffers from the following limitations. The current research does not fully incorporate simulation under sudden risk events. Future research should develop and apply more refined simulation models to analyse the performance of urban resilience under various risk scenarios. In addition, non-geographic factors, such as institutional coordination agreements and asymmetric “aid-dependency” relationships and boundary effects, may dominate interactions in high resilience nodes. Future research could address this limitation by incorporating more detailed data on inter-city institutional interactions and resource-sharing agreements.

## Conclusions

Exploring the characteristics of urban agglomeration resilience network structure and its influencing factors is of great significance for constructing urban agglomeration resilience networks and enhancing the overall risk resistance capacity of urban agglomerations. This study considered the BTHUA as the research object, and based on the DPSR framework, constructed a dynamic perspective resilience evaluation system from the entire process of resilience action. The entropy weight-TOPSIS method was used to measure the resilience of each city in the region. Further, the resilience correlation between cities was quantitatively analysed using the modified gravity model. Based on the analysis results, a social network analysis and QAP model were used to explore the resilience spatial correlation strength, structural characteristics of the network, and its influencing mechanisms. The main conclusions are as follows:

From 2014 to 2022, the resilience correlation intensity between cities in the BTHUA showed a trend of increasing first and then decreasing, with high resilience contact intensity among the core cities. In contrast, the resilience connection between core cities and peripheral cities was weaker. The resilience correlation between different cities gradually resulted in a complex spatial correlation network. The resilience network of the BTHUA formed during the research period, and the density change trend of the resilience spatial correlation network in the BTHUA was diversified. The connectedness and stability of the network showed signs of improvement; however, they remained at a relatively low level, with pronounced hierarchical disparities evident within the network. The resilience spatial correlation network of the BTHUA showed a multi-level structure characteristic with ‘Beijing and Tianjin as the dual core and Shijiazhuang and Tangshan as the sub-core layer’. Cities such as Handan, Xingtai, Hengshui, Langfang, Qinhuangdao, and Chengde assumed the role of ‘beneficiaries’ and were the weak nodes in the network, urgently requiring further strengthening of the resilience construction of these cities.

The evolution of the BTHUA resilience spatial correlation network is influenced by a multitude of factors, and the influence intensity shows different trends over time. There exists a negative correlation between *GD* and the resilience network. The effect of distance on the urban resilience spatial correlation network development is progressively diminishing, and conversely, factors such as *ED*, *OOW*, *TN*, *ISL*, and *UD* exhibit a positive correlation with the resilience network, with their influence intensifying over time.

## Data availability

The data that support the findings of this study are available from the authors.

Received: 3 January 2025; Accepted: 22 August 2025;

Published online: 30 August 2025

## References

- Alberti M (2005) The effects of urban patterns on ecosystem function. *Int Reg Sci Rev* 28(2):168–192
- Almulhim AI, Cobbina PB (2025) Dammam metropolitan area: advancing the pursuit of urban resilience. *Habitat Int* 163:103499
- Assumma V, Bottero M, De Angelis E, Lourenço JM, Monaco R, Soares AJ (2021) A decision support system for territorial resilience assessment and planning: an application to the Douro Valley (Portugal). *Sci Total Environ* 756:143806
- Assumma V, Bottero M, Ishizaka A (2024) Enhancing territorial resilience assessment with a decision-aiding model in regional planning of Socio-Ecological Systems. *Environ Sci Policy* 154:103691

- Bai R, Lin B (2024) An in-depth analysis of green innovation efficiency: new evidence based on club convergence and spatial correlation network. *Energy Econ* 132:107424
- Chen L, Chang M, Yang H, Xiao Y, Huang H, Wang X (2024a) Comprehensive evaluation and optimal management of extreme disaster risk in Chinese urban agglomerations by integrating resilience risk elements and set pair analysis. *Int J Disaster Risk Reduct* 111:104671
- Chen M, Liu Y, Ye Z, Wang S, Zhang W (2024b) Vivid London: assessing the resilience of urban vibrancy during the COVID-19 pandemic using social media data. *Sustain Cities Soc* 115:105823
- Chen W, Zhang N, Zhang Y, Cheng Z, Zhang Y (2021) Study on influencing factors of urban disaster resilience based on DEMATEL-ISM. *J Catastrophol* 36(1):1–6
- Cucuzzella C, Owen J, Goubran S, Walker T (2022) A TOD index integrating development potential, economic vibrancy, and socio-economic factors for encouraging polycentric cities. *Cities* 131:103980
- Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. *Glob Environ Change* 18(4):598–606
- Datola G (2023) Implementing urban resilience in urban planning: a comprehensive framework for urban resilience evaluation. *Sustain Cities Soc* 98:104821
- Ding C, Gao X, Xie Z (2024) Analysing the differential impact of the COVID-19 pandemic on the resilience of the tourism economy: a case study of the Chengdu-Chongqing urban agglomeration in China. *Int J Disaster Risk Reduct* 102:104255
- Du M, Zhang X, Wang Y, Tao L, Li H (2020) An operationalizing model for measuring urban resilience on land expansion. *Habitat Int* 102:102206
- Du Z, Zhang H, Ye Y, Jin L, Xu Q (2019) Urban shrinkage and growth: Measurement and determinants of economic resilience in the Pearl River Delta. *J Geographical Sci* 29(8):1331–1345
- Eldesoky AH, Abdeldayem WS (2023) Disentangling the relationship between urban form and urban resilience: a systematic literature review. *Urban Sci* 7(3):93
- Fang C, Chen R, Zhou L, Liu X, Ge S (2025) Utilizing complex networks and multi-scale analysis for spatial coordination and regional integration: insight from the Pearl River Delta, China. *Habitat Int* 161:103409
- Fang C, Gu X, Zhou L, Zhang W, Liu X, Liu S, Werner M (2024) Exploring spatial complexity: overlapping communities in South China's megaregion with big geospatial data. *Comput Environ Urban Syst* 112:102143
- Feng X, Zeng F, Loo BP, Zhong Y (2024a) The evolution of urban ecological resilience: an evaluation framework based on vulnerability, sensitivity and self-organization. *Sustain Cities Soc* 116:105933
- Feng X, Lin X, Li Y, Yang J, Yu E, Lei K (2024b) Spatial association network of carbon emission performance: formation mechanism and structural characteristics. *Soc Econ Plan Sci* 91:101792
- Fu G, Wilkinson S, Dawson RJ (2016) A spatial network model for civil infrastructure system development. *Comput Aided Civ Infrastructure Eng* 31(9):661–680
- Guo W, Wang J, Liu X, Pan Z, Zhuang R, Li C, Tang H (2025) Towards resilient communities: evaluating the nonlinear impact of the built environment on COVID-19 transmission risk in residential areas. *Build Environ* 267:112289
- Haque MN, Rahman S, Saroor MM, Sresto MA (2024) Building resilience: insights into ecosystem-based integrated environmental risk reduction approaches for urban environments in coastal Bangladesh. *Int J Disaster Risk Reduct* 111:104660
- Holling CS (1973) Resilience and stability of ecological systems. *Annu Rev Ecol Syst* 4(1):1–23
- Hu X, Li L, Dong K (2022) What matters for regional economic resilience amid COVID-19? Evidence from cities in Northeast China. *Cities* 120:103440
- Huang L, Wang J, Cheng H (2022) Spatiotemporal changes in ecological network resilience in the Shandong Peninsula urban agglomeration. *J Clean Prod* 339:130681
- Jabareen Y (2013) Planning the resilient city: concepts and strategies for coping with climate change and environmental risk. *Cities* 31:220–229
- Jiao L, Han B, Tan Q, Zhang Y, Huo X, Wu L, Wu Y (2024) An improved DPSIR-DEA assessment model for urban resilience: a case study of 105 large cities in China. *Land* 13(8):1133
- Li G, Kou C, Wang Y, Yang H (2020) System dynamics modelling for improving urban resilience in Beijing, China. *Resour Conserv Recycling* 161:104954
- Li H, Wang Y, Zhang H, Yin R, Liu C, Wang Z, Fu F, Zhao J (2024a) The spatial-temporal evolution and driving mechanism of Urban resilience in the Yellow River Basin cities. *J Clean Prod* 447:141614
- Li Z, Yu K, Zhong J, Yang J, Zhang D, Zhu J (2024b) Spatial correlation network characteristics and influencing factors of water environmental efficiency in three major urban agglomerations in the Yangtze River Basin, China. *Sustain Cities Soc* 104:105311
- Li Z, Yu K, Zhong J, Yang J, Zhang D, Zhu J (2024c) Spatial correlation network characteristics and influencing factors of water environmental efficiency in three major urban agglomerations in the Yangtze River Basin, China. *Sustain Cities Soc* 104:105311
- Liu J, Liu B, Lee CC (2024a) Social network analysis of regional transport carbon emissions in China: based on motif analysis and exponential random graph model. *Sci Total Environ* 954:176183
- Liu J, Wang R, Tian Y, Zhang M (2024b) The driving mechanisms of industrial air pollution spatial correlation networks: a case study of 168 Chinese cities. *J Clean Prod* 470:143255
- Liu J, Long F, Chen L, Zheng L, Mi Z (2025) The role of polycentric urban structures in shaping low-carbon lifestyles. *Cities* 157:105616
- Liu Y (2021) Urban resilience system development measurement: based on an empirical study of 288 Chinese cities. *Urban Dev Stud* 28:77–87
- Lu Y, Liu Y, Xing L, Liu Y (2023) Robustness test of multiple protection strategies for ecological networks from the perspective of complex networks: Evidence from Wuhan Metropolitan Area, China. *Land Degrad Dev* 34(1):52–71
- Luo Z, Ji L, Xie Y (2024) Multi-dimensional equilibrium optimal allocation of water resources in Beijing-Tianjin-Hebei region through spatial association network analysis. *J Hydrol* 642:131826
- Mu X, Fang C, Yang Z (2022) Spatio-temporal evolution and dynamic simulation of the urban resilience of Beijing-Tianjin-Hebei urban agglomeration. *J Geographical Sci* 32(9):1766–1790
- Ren X, Xiong R, Ni T (2024) Spatial network characteristics of carbon balance in urban agglomerations—a case study in Beijing-Tianjin-Hebei city agglomeration. *Appl Geogr* 169:103343
- Ruggiero A, Piotrowicz WD, John L (2024) Enhancing societal resilience through the whole-of-society approach to crisis preparedness: complex adaptive systems perspective—The case of Finland. *Int J Disaster Risk Reduct* 114:104944
- Shang X, Liu Q (2024) Digital inclusive finance and regional economic resilience: evidence from China's 283 Cities over 2011–2021. *Financ Res Lett* 69:105953
- Shi W, Li B (2024) Resilience spatial network structure of the three major urban agglomerations in the Yellow River Basin. *Arid Land Geogr* 47(10):1767–1780
- Shi Y, Niu Y (2024) Resilience spatial correlation network and its influencing factors in Guanzhong Plain urban agglomeration. *Arid Land Geogr* 47(2):270–280
- Sun J, Zhai N, Mu H, Miao J, Li W, Li M (2024) Assessment of urban resilience and subsystem coupling coordination in the Beijing-Tianjin-Hebei urban agglomeration. *Sustain Cities Soc* 100:105058
- Sun Y, You X (2021) The measure of urban resilience and its spatio-temporal evolution: a case study of Jiangsu province. *Nanjing J Soc Sci* 7:31–40
- Szpotowicz R, Tóth C (2020) Revision of sustainable road rating systems: selection of the best suited system for Hungarian road construction using TOPSIS method. *Sustainability* 12(21):8844
- Tian R, Zhang Y, Peng L, Wang Y, Wang W, Gu Y (2024) Measurement of flood resilience of metro station based on combination weighting-cloud model. *Int J Disaster Risk Reduct* 114:104950
- Wang C, Shen J (2025) Towards a socially resilient city: healthcare accessibility and rural migrants' identity integration in urban China. *Appl Geogr* 176:103542
- Wang H, Ge Q (2023) Spatial association network of economic resilience and its influencing factors: evidence from 31 Chinese provinces. *Humanit Soc Sci Commun* 10(1):1–14
- Wang H, Wang W (2024) Pattern evolution and spatial spillover effect of urban resilience in the Yangtze River Delta. *Geography and Geo-Information Science* 40(4):57–66
- Wang Y, Shu J, Yuan Y (2024) Navigating urban risks for sustainability: a comprehensive evaluation of urban vulnerability based on a pressure–sensitivity–resilience framework. *Sustain Cities Soc* 117:105961
- Wang Z, Hao Y (2024) Can smart cities improve energy resilience? Evidence from 229 cities in China. *Sustain Cities Soc* 117:105971
- Wied M, Oehmen J, Welo T (2020) Conceptualizing resilience in engineering systems: an analysis of the literature. *Syst Eng* 23(1):3–13
- Wilbanks TJ, Sathaye J (2007) Integrating mitigation and adaptation as responses to climate change: a synthesis. *Mitig Adapt Strateg Glob Change* 12(5):957–962
- Wu S, Tian C, Li B, Wang J, Wang Z (2022) Ecological environment health assessment of lake water ecosystem system based on simulated annealing-projection pursuit: a case study of plateau lake. *Sustain Cities Soc* 86:104131
- Wu W, Wang Z, Wu K, Chen Y, Wang S, Niu X (2024) Urban resilience framework: a network-based model to assess the physical system reaction and disaster prevention. *Environ Impact Assess Rev* 109:107619
- Xia C, Zhai G (2022) The spatiotemporal evolution pattern of urban resilience in the Yangtze River Delta urban agglomeration based on TOPSIS-PSO-ELM. *Sustain Cities Soc* 87:104223
- Yang Y, Su X (2024) Spatial correlation network structure of carbon emission reduction capacity on urban agglomerations and its driving factors: a perspective of Sustainable Development Goals. *Sustain Cities Soc* 113:105646
- Zhang W, Fang C, Zhou L, Zhu J (2020) Measuring megaregional structure in the Pearl River Delta by mobile phone signaling data: a complex network approach. *Cities* 104:102809
- Zhao J, Chen N, Jin Z (2025) The more centralized the spatial structure is, the greater the economic growth? Evidence from urban agglomerations in western China. *Humanit Soc Sci Commun* 12(1):1–16

- Zhao J, Zhang L, Song J (2018) Spatial structure of urban system and its evolution in Jing-Jin-Ji urban agglomeration. *Area Res Dev* 37(2):9–13
- Zhao Z, Zhou X, Zheng Y, Meng T, Fang D (2024) Enhancing infrastructural dynamic responses to critical residents' needs for urban resilience through machine learning and hypernetwork analysis. *Sustain Cities Soc* 106:105366
- Zhu J, Sun H (2020) Research on spatial-temporal evolution and influencing factors of urban resilience of China's three metropolitan agglomerations. *Soft Sci* 34(02):72–79

## Acknowledgements

This work was financially supported by the Natural Science Foundation of Hebei Province (Grant No. D2020207003); Science Research Project of Hebei Education Department (Grant No. QN2022052); Science Research and Development Program of Hebei University of Economics and Business (Grant No. 2023QN16); Hebei Province Higher Education Teaching Reform Research Project (Grant No. 2022GJJG176); Graduate Student Innovation Capability Training Funding Program of Hebei University of Economics and Business (Grant No. XJCX202584). Research Project of Basic Research Operating Costs of Higher Education Institutions in Hebei Province (Grant No. QN25030).

## Author contributions

Peixing Zhang: Writing - review & editing, Writing - original draft, Validation, Software, Resources, Supervision, Conceptualization, Methodology, Investigation, Formal analysis, Conceptualization, Visualization. Tianlu Jin: Writing - review & editing, Writing-original draft, Validation, Software, Conceptualization, Investigation, Formal analysis, Data curation, Methodology, Validation, Visualization. Min Zhang: Investigation, Formal analysis. Aijun Zhu: Validation, Formal analysis.

## Competing interests

The authors declare no competing interests.

## Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

## Informed consent

This article does not contain any studies with human participants performed by any of the authors.

## Additional information

Correspondence and requests for materials should be addressed to Peixing Zhang.

Reprints and permission information is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025