

Spatio-temporal evolution and dynamic simulation of the urban resilience of Beijing-Tianjin-Hebei urban agglomeration

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Abstract: The continuous growth of urban agglomerations in China has increased their complexity as well as vulnerability. In this context, urban resilience is critical for the healthy and sustainable development of urban agglomerations. Focusing on the Beijing-Tianjin-Hebei (BTH) urban agglomeration, this study constructs an urban resilience evaluation system based on four subsystems: economy, society, infrastructure, and ecology. It uses the entropy method to measure the urban resilience of the BTH urban agglomeration from 2000 to 2018. Theil index, standard deviation ellipse, and gray prediction model GM (1,1) methods are used to examine the spatio-temporal evolution and dynamic simulation of urban resilience in this urban agglomeration. Our results show that the comprehensive evaluation index for urban resilience in the BTH urban agglomeration followed a steady upward trend from 2000 to 2018, with an average annual growth rate of 6.72%. There are significant differences in each subsystem's contribution to urban resilience; overall, economic resilience is the main factor affecting urban resilience, with an average annual growth rate of 8.06%. Spatial differences in urban resilience in the BTH urban agglomeration have decreased from 2000 to 2018, showing the typical characteristic of being greater in the central core area and lower in the surrounding non-core areas. The level of urban resilience in the BTH urban agglomeration is forecast to continue increasing over the next ten years. However, there are still considerable differences between the cities. Policy factors will play a positive role in promoting the resilience level. Based on the evaluation results, corresponding policy recommendations are put forward to provide scientific data support and a theoretical basis for the resilience construction of the BTH urban agglomeration.

Keywords: urban agglomeration; urban resilience; Beijing-Tianjin-Hebei (BTH); evaluation system; gray prediction model

1 Introduction

The complexity and vulnerability of urban systems are becoming more aggregated against

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the background of accelerating globalization and rampant urbanization. Cities are faced with various risks and problems, including natural disasters, climate change, public health emergencies, financial crises, food security, terrorist attacks, aging populations, etc.; these are bound to make it difficult for cities to achieve their sustainable development goals. The critical issue for all cities across the globe is to find a way to enhance urban resilience toward a paradigm of sustainable development (Sun *et al.*, 2017). China's urbanization is in a critical transition period between a low-quality development stage of rapid growth and a high-quality development stage (Fang, 2019). The country's current focus is on constructing resilient cities to manage the conflicting demands of high-quality urban development and urban safety problems produced by high-speed urbanization. China's 14th Five-Year Plan (2021–2025) put forth the idea of “building resilient cities, improving the level of urban governance, and strengthening risk prevention and control in the governance of mega-cities”, which brought the construction of resilient cities into the national strategic planning system. The construction of urban agglomerations resilience plays a significant role in promoting China's social and economic development; it is the strategic core of China's economic development and urbanization policies (Fang, 2020). As the development of urban agglomerations in China matures, exchanges between cities in the urban agglomerations become more efficient and convenient. However, correspondingly, when impacted, the effects of a disaster on urban agglomerations are often greater because of urban densities, frequent personnel turnover, and interconnected urban lifeline systems (Elmqvist *et al.*, 2019). In this context, the risk response capacity of a single city is insufficient. There is an urgent need to manage the various risks and impacts through linkages and cooperation between cities within an urban agglomeration. The concept of a resilient city can be further expanded to an agglomeration of resilient cities, which can be created by establishing strong ties between cities, integrating various resources, building a stable, solid network, and improving the level of collaborative governance, risk prevention, and control capabilities (Wang, 2020), to create a resilient urban agglomeration. Hence, constructing an assessment system to scientifically assess the resilience level of cities within the urban agglomerations is an indispensable part of building resilient cities. Exploring strategies to enhance the resilience of urban agglomerations based on the evaluation system and improving the urban agglomerations resilience is an important guarantee to enhance the economic and social stability of the country.

Urban resilience refers to a complex coupled system comprising human and environment systems, such as the urban economy, society, ecology, infrastructure, and institutions, that possess the adaptation, recovery, and learning capacity when a range of sudden and cumulative disturbances (Zhao *et al.*, 2020). With the increasing global focus on urban resilience, numerous studies have been conducted from the perspectives of conceptual connotation, characteristics, evaluation methods, impact mechanisms of urban resilience, etc.

The measurement of urban resilience as a bridge between theory and practice has always been the field's focus. Currently, domestic and foreign researchers focus primarily on two aspects of measuring urban resilience. First, measuring and analyzing the resilience level of urban subsystems using a single dimension: urban economic resilience (Hill *et al.*, 2008; Martin, 2012; Briguglio, 2016; Li *et al.*, 2019; Tan *et al.*, 2020), social resilience (Allenby and Fink, 2005; Dong *et al.*, 2021), ecological resilience (Chen and Li, 2019; Wang *et al.*, 2020; Wang *et al.*, 2021), and engineering resilience (Bruneau *et al.*, 2003; Li *et al.*, 2016). Some researchers have measured urban resilience combined with public health emergencies

(Wang and Tang, 2020), earthquakes (Yang, 2016), typhoons (Xiong *et al.*, 2019), floods (Sun *et al.*, 2016), and other risk disasters. Second, measuring urban resilience by integrating multi-dimensional subsystems. The Rockefeller Foundation proposed a research framework for resilient cities based on four dimensions: leadership strategy, health and well-being, social economy, and facility environment (Silva and Morera, 2014). The Resilience Capacity Index (RCI) constructed by the Regional Research Institute of the State University of New York at Buffalo, evaluates American cities' resilience of regional economic capacity, community population, and community connectivity. Cutter *et al.* (2014) constructed an evaluation index system for regional disaster resilience based on six aspects: society, economy, community competitiveness, organization, infrastructure, and ecological environment. To evaluate the urban system resilience in Japan, Osman (2021) identified more than 130 indicators from the three aspects of city, citizen, and administration.

Researchers in China have similarly tried to construct an evaluation index system for urban resilience at different scales based on economy, society, institution, ecology, infrastructure, and other dimensions. At the city level, based on the complex adaptive system theory, Shi *et al.* (2021) proposed a complex urban system framework from three aspects: system environment, elements, and structure; they further constructed an evaluation method of urban system resilience from the subsystems of ecological environment, social economy, infrastructure, natural resources, and infrastructure. Li *et al.* (2021) used a system dynamics model to measure and dynamically simulate the urban resilience of Beijing considering four dimensions: urban governance, socio-economy, infrastructure, and material and energy. Bai *et al.* (2019) quantitatively evaluated the resilience of cities above the prefecture-level in China, based on a comprehensive measurement index system of urban resilience constructed from the four dimensions of economy, society, ecology, and infrastructure. At the regional level, based on the evaluation framework of ecology, economy, society, and engineering, Chen *et al.* (2020) comprehensively measured the urban resilience of the Harbin-Changchun urban agglomeration. Xie *et al.* (2020) evaluated the network structure resilience of the Harbin-Changchun urban agglomeration from an engineering, economy, society, and innovation perspective. At the community level, to evaluate the community resilience of Guangzhou, Yang *et al.* (2019) constructed an evaluation model based on five dimensions: natural environment, built environment, social capital, economic capital, and government system. As is apparent, the scale of current research, perspectives, and methods to assess the urban resilience are becoming diverse. Specifically, the research scale can be divided into four levels: national, regional, urban, and community; research perspectives mainly include ecology, economy, society, institution, infrastructure, and other dimensions; research methods include comprehensive index methods, GIS spatial analysis methods, function models, social network models, and system dynamics models.

Domestic and foreign researchers have studied urban resilience from different perspectives, scales, and measurement methods, making significant contributions toward the advancement of the construction of resilient cities and accumulating a rich resource of theoretical and empirical material for studying this topic. However, existing research needs further improvements. Although the measurement of urban resilience is vital in the construction of resilient cities, a set of recognized measurement index systems is yet to be established. Additionally, the current research scale primarily focuses on the national, provincial, or indi-

vidual city level; research on the meso-level of urban agglomeration has been limited. Moreover, the research perspective mainly focuses on a static evaluation of urban resilience, rendering the research on the dynamic change process of long time series and the dynamic simulation of urban resilience is insufficient. Accordingly, in this study, we construct an evaluation index system of urban resilience to reveal the spatio-temporal evolution law of urban comprehensive resilience and sub-system resilience for the Beijing-Tianjin-Hebei (BTH) urban agglomeration. We also perform a dynamic simulation of future evolution trends. Through this study, we expect to identify potential shortcomings and promote the regional urban resilience of the BTH urban agglomeration. Furthermore, we hope to provide scientific and accurate support for decision-making related to the implementation of the BTH coordinated development.

2 Data sources and methodology

2.1 Study area and data sources

The BTH urban agglomeration comprises 13 cities—Beijing, Tianjin, Shijiazhuang, Zhangjiakou, Qinhuangdao, Tangshan, Baoding, Langfang, Xingtai, Handan, Hengshui, Cangzhou, and Chengde—and covers an area of 216,800 km² (Fang, 2020). As of 2019, BTH had a population of 113 million, with a gross domestic product (GDP) of 84,580.08 million yuan. BTH urban agglomeration is among China's most dynamic, open, innovative, and populous (Fang, 2017). However, its rapid development has resulted in numerous ecological, environmental, and social problems. Although coordinated development has been remarkable in recent years, BTH urban agglomeration still experiences severe water shortages, heavy pollution, and traffic congestion; it also has high ecological sensitivity and is vulnerable to various risks and disasters. It poses a significant challenge to building urban resilience and promoting healthy and sustainable development in the BTH urban agglomeration.

The Urban Master Planning of Beijing (2016–2035) divides the BTH urban agglomeration by administrative units into core and non-core areas. The former include Beijing, Tianjin, Langfang, Tangshan, Cangzhou, and Qinhuangdao; and the latter include Shijiazhuang, Chengde, Zhangjiakou, Baoding, Hengshui, Xingtai, and Handan. To reveal the dynamic changes in the urban resilience of the BTH urban agglomeration, this study obtained statistical data for each year from 2000 to 2018 from the China Statistical Yearbook, China Urban Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, and Hebei Economic Yearbook. Missing data were added by interpolation.

2.2 Index system construction

Urban agglomeration refers to a highly-integrated city group in terms of infrastructure construction, environmental protection, ecological conservation, and social well-being, facilitated by advanced transportation, communication networks, and a scientifically efficient institutional system. Cities in urban agglomerations are linked together through the flow of people, products, transportation, information, expertise, capital, etc. The construction of urban agglomeration is inseparable from cities, urban networks, and organizational systems (Fang, 2020). Consequently, the urban agglomeration resilience is determined by urban, ur-

ban network, and organizational resilience (Figure 1). The city is the basic unit of urban agglomeration. The resilience level of a single city in the agglomeration is the basis for the resilience of the agglomeration; when the city’s resilience level reaches a certain level, it triggers a spillover effect that plays a leading role in the anti-risk and impact capacity of the other cities in the agglomeration.

The urban network links cities in the urban agglomeration. Cities are interconnected to realize economic, social, and infrastructural cooperation, exchange, and sharing. Improving the resilience of an urban network increases the ability of cities to withstand risk collectively. Urban networks also ensure and promote exchanges and cooperation between cities. They are the internal driving force for the resilient development of urban agglomerations. Additionally, an efficient urban agglomeration organization system is essential in coordinating exchanges and cooperation between cities in an emergency. A resilient organizational system improves the level of cooperative governance, risk prevention, and control capabilities of urban agglomerations, and it is a strong guarantee for building their resilience. Cities, urban networks, and organizational systems are interdependent and indispensable, which jointly affect the resilience of urban agglomerations. They are three dimensions of a complex system, and their resilience influencing factors, mechanisms, and assessment methods differ. This study primarily evaluates and simulates resilience in urban agglomerations from the perspective of urban resilience.

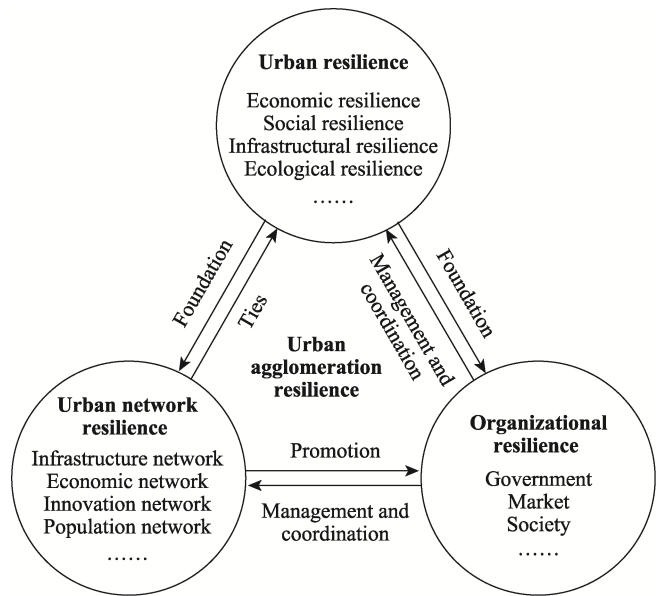


Figure 1 The composition of urban agglomeration resilience

As the basic unit of urban agglomeration, the city is a complex social-economic-natural ecosystem. It has an ecological environment as its fundamental part, human economic activities as the leading part, and the social system and culture as the control center. These three subsystems—ecological, economy, and society—jointly affect the resilience of cities. As an essential carrier of urban social and economic activities, the ecological system not only maintains health, provides water, soil, air, and other resources for the city, but also degrades

urban waste. The deterioration of the ecological environment affects human health and aggravates urban disasters. Therefore, a healthy ecological environment is important for the development of the social economy and increasing competitiveness, and strengthening the resilience of cities. The social system acts as the security system of urban development and includes human resources, social environment, policy, and security. A robust social organization system can mobilize a city's resources, can ensure its normal operation, and improve its ability to deal with risk. The economic system refers to production, circulation, and consumption activities, with human and energy resources as its main drivers. A stable economy is the driving force for maintaining urban development. An efficient economic system plays an essential role in improving urban investment and construction, ecological environment, public safety, and people's living standards. Urban infrastructure is the material guarantee for maintaining the normal operation of urban systems and ensuring the development of the social economy; it plays a vital role in disasters and accidents. The development status of urban infrastructure directly affects the resilience of the urban ecological environment, economy, society, and other subsystems. Therefore, urban resilience can be divided into four subsystems: ecological, economic, social, and infrastructural resilience, which are organically combined through complex interactions (Figure 2).

Based on the existing studies and the available data, an urban resilience evaluation index system is established (Table 1) to reflect the development and evolution of urban resilience in the BTH urban agglomeration (Ma *et al.*, 2020; Zhao *et al.*, 2020; Zhu and Sun, 2020). The first-level index system includes four indicators—urban economic, social, infrastructural, and ecological resilience; the second-level index system includes 24 sub-indicators from the different systems' perspectives to measure urban resilience. Among them, the city's economic resilience comprises six indicators: the economic foundation, the economic opera-

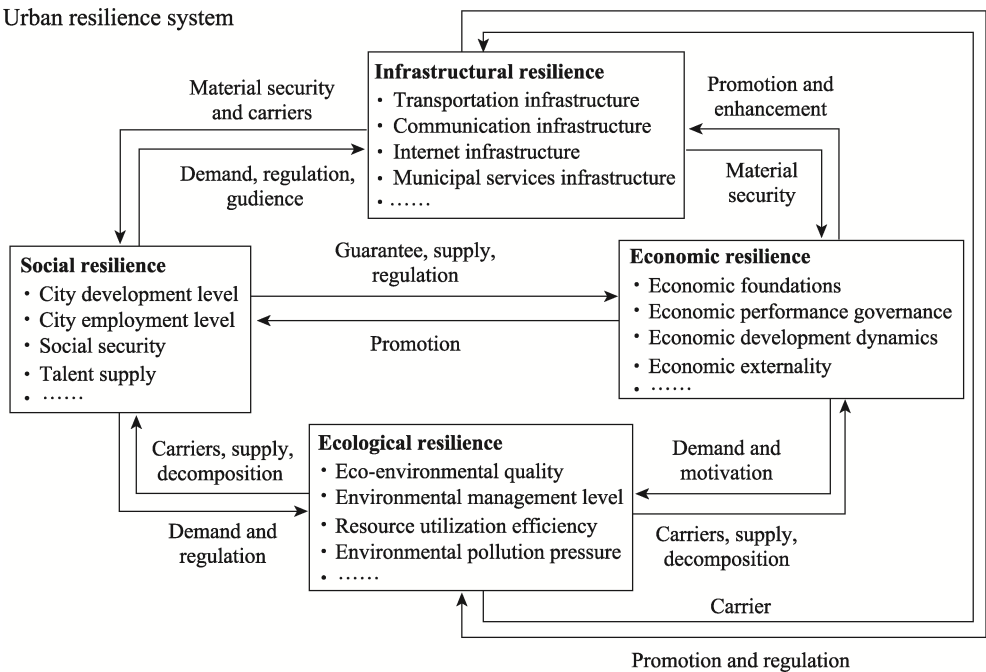


Figure 2 Composition and interaction of urban resilience system

Table 1 Evaluation index system for urban resilience in the Beijing-Tianjin-Hebei urban agglomeration

First-level indicators	Weight	Secondary indicators	Weight	Indicator meaning and attribute
Urban economic resilience	0.4422	Per capita GDP (yuan)	0.0518	Macroeconomic fundamental (+)
		Proportion of total fiscal revenue to GDP (%)	0.0138	economic operation quality (+)
		Amount of foreign capital actually utilized (billion USD)	0.2023	Economic openness (+)
		Fixed assets investment per capita (yuan)	0.0625	Power of economic development (+)
		Proportion of tertiary industry to GDP (%)	0.0299	Rationality of economic structure (+)
		Proportion of R&D expenditure to GDP (%)	0.0818	Innovation capacity (+)
Urban social resilience	0.2426	Proportion of employees in the tertiary industry (%)	0.0390	Social employment level (+)
		Number of beds in health institutions per 1000 people (PCs.)	0.0114	Population health security capacity (+)
		Number of college students per 12,000 people (person)	0.0696	Talent supply and reserve capacity (+)
		Percentage of urban population (%)	0.0302	Urban development level (+)
		Urban per capita disposable income (yuan)	0.0485	Living standard (+)
		Registered urban unemployment rate (%)	0.0438	Impact of unemployment on social system (−)
Urban infrastructural resilience	0.2473	Mobile subscription (%)	0.0430	Perfection of social communication system (+)
		Internet penetration rate (%)	0.0504	Perfection of social network system (+)
		Road network density (km/km ²)	0.0236	Traffic accessibility (+)
		Per capita domestic water consumption (L/day/person)	0.0071	Pressure of water consumption on water supply facilities (−)
		Number of public buses per 10,000 people (vehicles)	0.0302	Development level of urban public transport (+)
		Length of drainage pipe per capita (m)	0.2473	Perfection of water supply and drainage system (+)
Urban ecological resilience	0.0680	Green coverage rate of built area (%)	0.0093	Greening level of public environment (+)
		Comprehensive utilization rate of general industrial solid waste (%)	0.0117	Solid waste pollution control level (+)
		Centralized sewage treatment rate (%)	0.0133	Urban water use efficiency and water environment governance level (+)
		Harmless treatment ratio for house refuse (%)	0.0068	Environmental protection and resource reuse level (+)
		Sulfur dioxide emission per 10,000 yuan GDP (ton/10,000 yuan)	0.0025	Environmental pollution pressure (−)
		Per capita public green space area (m ² /person)	0.0243	Urban human settlement environment quality (+)

Note: “+” stands for positive indicator and “−” stands for negative indicator in the table.

tion quality, the power of economic development, the economic extroversion, and the innovation ability. The city’s social resilience consists of six indicators: the city’s development level, employment level, health security, living standard, education, and talent supply and reserve. The city’s infrastructural resilience includes six indicators, including the communication system, internet, transportation, and municipal service facilities. Finally, the city’s ecological resilience consists of six indicators, including quality of the city’s living envi-

ronment, environmental protection, and resource reuse.

2.3 Research methods

2.3.1 Entropy method

This study used the entropy method to determine the weight of the urban resilience assessment index system to ensure the objectivity and accuracy of the assessment. As it involves comparing different cities and years, a time variable was added, based on the traditional entropy method, to make the analysis results more robust. The improved entropy method model is as follows:

(1) Standardization

Because different indicators have different units and dimensions, it is necessary to standardize the data. If there are m years, n cities, and α indexes, then x_{ijk} is the k -th index value of city j in the i -th year.

Positive indicator:

$$x'_{ijk} = \frac{(x_{ijk} - x_{kmin})}{(x_{kmax} - x_{kmin})} \quad (1)$$

Negative indicator:

$$x'_{ijk} = \frac{(x_{kmax} - x_{ijk})}{(x_{kmax} - x_{kmin})} \quad (2)$$

where x'_{ijk} is the standardized value of the k -th index of city j in the i -th year, x_{kmax} is the maximum value of the k -th index, and x_{kmin} is the minimum value of the k index.

(2) Determination of the index weight

$$P_{ijk} = \frac{x'_{ijk}}{\sum_{i=1}^m \sum_{j=1}^n x'_{ijk}} \quad (3)$$

where P_{ijk} is the weight of the k -th index of city j in year i .

(3) Entropy value of the k -th index

$$E_k = -a \sum_{i=1}^m \sum_{j=1}^n P_{ijk} \ln(P_{ijk}) \quad (4)$$

where $a > 0$, $a = 1/\ln(m \times n)$, $E_k \geq 0$.

(4) Redundancy of the k -th index

$$D_k = 1 - E_k \quad (5)$$

The larger the value of redundancy D_k , the more important the index in the comprehensive evaluation index system.

(5) Weights of the secondary indicators of the city:

$$W_k = \frac{D_k}{\sum_{k=1}^{\alpha} D_k} \quad (6)$$

(6) Comprehensive evaluation value of urban resilience:

$$R_{ij} = \sum_{k=1}^{\alpha} W_k x'_{ijk} \quad (7)$$

where R_{ij} is the comprehensive evaluation value of urban resilience of city j in year i .

2.3.2 Theil Index

We used the Theil index to measure regional differences in resilience within the BTH urban agglomeration based on the urban resilience evaluation index system. The Theil index can reflect the overall level of regional differences and decompose them to reflect the sources of regional differences (Sun *et al.*, 2018). The specific calculation formula is as follows:

$$Theil = \frac{1}{n} \sum_{i=1}^n \frac{R_i}{\bar{R}} \ln \left(\frac{R_i}{\bar{R}} \right) \quad (8)$$

where *Theil* is the Theil index reflecting the overall difference in urban resilience, R_i is the resilience value of the i -th city, \bar{R} is the average resilience value of all cities, and n is the number of cities. The larger the *Theil* value, the more obvious the regional differences. Based on the total Theil index, the overall difference can be further decomposed into the intra-group difference T_w and the inter-group difference T_b . The specific formula is as follows:

$$Theil = T_w + T_b \quad (9)$$

$$T_w = \sum_{p=1}^m \left(\frac{n_p}{n} \frac{\bar{e}_p}{\bar{e}} \right) T_p \quad (10)$$

$$T_b = \sum_{p=1}^m \left(\frac{n_p}{n} \frac{e_p}{\bar{e}} \right) \ln \left(\frac{e_p}{\bar{e}} \right) \quad (11)$$

where T_w is the intra-group difference, T_b is the inter-group difference, m is the number of groups, n_p represents the number of cities included in the p -th group, \bar{e}_p represents the average index value of the p -th group, \bar{e} represents the average value of all city indexes, and T_p represents a Theil index of the index difference of the p -th group.

2.3.3 Standard deviation ellipse

This study adopted the standard ellipse method to investigate further the whole characteristics of urban resilience in the BTH urban agglomeration, such as the direction of development and spatio-temporal distributions. The standard deviation ellipse of urban resilience was generated using the directional distribution (standard deviation ellipse) tool in ArcGIS software with urban resilience values as weights. Then, we calculated the coordinates of the center of the standard deviation ellipse, the rotation angle, the distance between the major and the minor axis, and the flattening. The center represents the central position of the whole data; the rotation angle and the long axis represent the direction of the data distribution. The short axis represents the area of the data distribution—the shorter the short axis, the more obvious the centripetal force. The flattening represents the directivity of the data—the larger the flattening, the more obvious the directivity (He *et al.*, 2016).

2.3.4 Gray prediction model GM (1,1)

The gray prediction model GM (1,1) constructs a continuous differential equation with time as the variable by accumulating or subtracting the data scattered on the time axis to predict future data (He *et al.*, 2016; Feng and Li, 2020). Since the GM (1,1) has the advantages of simple calculation principle and high calculation accuracy, it is widely used for simulations and predictions in economic, social, and technical fields, among others. In this study, the

urban resilience of the BTH urban agglomeration from 2020 to 2030 was dynamically simulated using the GM (1,1) in a Matlab R2018b environment to use as a reference for building the future resilience of the BTH urban agglomeration. The method is as follows:

First, let the time series of the original variable R_0 be:

$$R_0 = \left[r_0^1 - \frac{\mu}{\beta} \right] e^{-\beta k}, k = 1, 2, \dots, n \quad (12)$$

The sequence is generated by accumulating R_0 :

$$R_1 = [r_1^1, r_1^2, \dots, r_1^n] \quad (13)$$

The corresponding differential equation of GM (1,1) model is:

$$\frac{dR_1}{dt} + \beta R_1 = \mu \quad (14)$$

The final prediction model can be obtained by solving the differential equation:

$$R_1(k+1) = \left[r_0^1 - \frac{\mu}{\beta} \right] e^{-\beta k} + \frac{\mu}{\beta}, k = 1, 2, \dots, n \quad (15)$$

where β is the developing gray scale, μ is the gray action, and k is the time.

Finally, the accuracy of the prediction model was tested, and the established model used to predict urban resilience.

3 Spatio-temporal evolution characteristics of urban resilience in Beijing-Tianjin-Hebei urban agglomeration

3.1 Overall evaluation

Based on the comprehensive urban resilience assessment results of the BTH urban agglomeration, the Jenks natural discontinuity classification method was used to classify the resilience assessment scores of the 13 cities from 2000 to 2018. The scores were divided into five levels of areas: the lowest resilience areas (0.064742–0.146171), low resilience areas (0.146172–0.224678), medium resilience areas (0.224679–0.323060), high resilience areas (0.323061–0.506108), and the highest resilience areas (0.506109–0.781137). Accordingly, the characteristics of urban resilience of the BTH urban agglomeration were analyzed on the temporal and spatial scales.

From the temporal scale (Figure 3 and Table 2), the overall resilience of the BTH urban agglomeration showed a steady upward trend from 2000 to 2018, with an average annual growth rate of 6.27%. It transitioned from low resilience areas (0.1301) to high resilience areas (0.3891). Resilience trends were similar for each city; however, there were significant differences in resilience improvements between cities. For instance, Xingtai and Chengde's level of resilience increased by 328.4% and 323.4%, respectively, which allowed them to transition from the lowest resilience areas to medium resilience areas. It is mainly due to the rapid development of infrastructure and economic growth. By contrast, Beijing and Tianjin saw the smallest increase in reliance, at 107.6% and 155.8%. The growth rate was between 160% and 305% for most other cities. Beijing moved up from high resilience areas to the highest resilience areas. Similarly, Tianjin transitioned from medium resilience areas to the

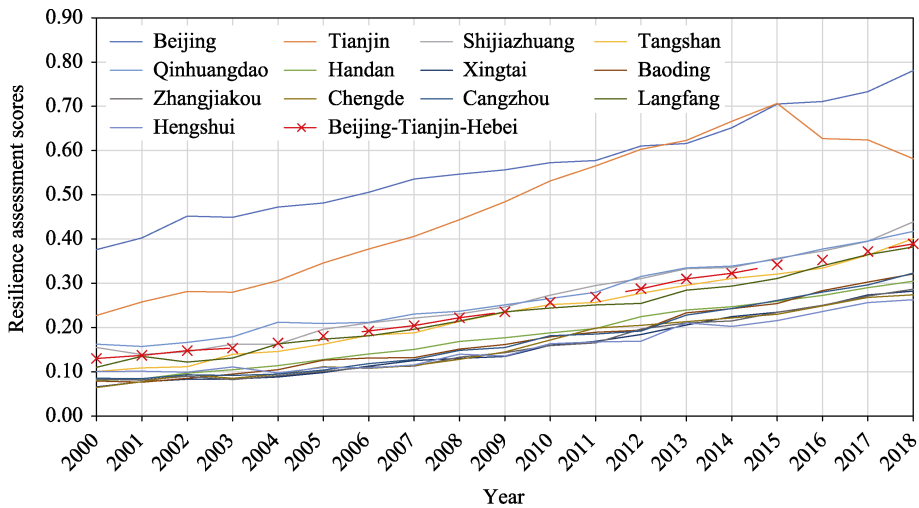


Figure 3 The development trend of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

highest resilience areas. However, although Tianjin's overall resilience increased, it is the only city that experienced a significant decrease in resilience since 2015, with a fall of 17.68% from 2015 to 2018. Due to the impact of policies and industrial transformation, Tianjin's economy had been weak, showing a downward trend in recent years.

From a spatial scale perspective (Figure 4), the resilience level of each city in the BTH urban agglomeration is quite different. The standard deviations trend upward before 2015 and fall downward since 2015, indicating that the overall difference first increased and then decreased. As central cities, the resilience of Beijing and Tianjin has consistently been higher than that of other cities. In 2000, Beijing had the highest level of resilience, followed by Tianjin, which had medium resilience. Shijiazhuang and Qinhuangdao are classified as low resilience areas; except these two cities, the other nine cities in Hebei Province are the lowest resilience areas. It means that the spillover effect from Beijing and Tianjin in 2000 is obvious—driven by the two cities, the resilience levels of Tangshan, Langfang, Qinhuangdao, and Cangzhou improved rapidly. Shijiazhuang, the provincial capital city, was always more resilient than the other cities in Hebei Province. In 2018, Beijing and Tianjin were the highest resilience areas; and Shijiazhuang, Langfang, Tangshan, Cangzhou, and Qinhuangdao were high resilience areas. The rest of the cities were all classified as medium resilience areas. Except for Shijiazhuang, high resilience areas were primarily concentrated in the core areas. The non-core areas in the south and northwest had relatively low levels of resilience.

3.2 The characteristics of the spatio-temporal evolution of urban subsystems' resilience

Analyzing the development characteristics of each subsystem's resilience can help us examine each subsystem's impact on the city's overall resilience. Figure 5 shows the resilience level of each subsystem in the BTH urban agglomeration increased continuously from 2000 to 2018, similar to the development trend in the overall resilience. However, there are obvious differences in the growth rates of each subsystem. The average annual growth rate of

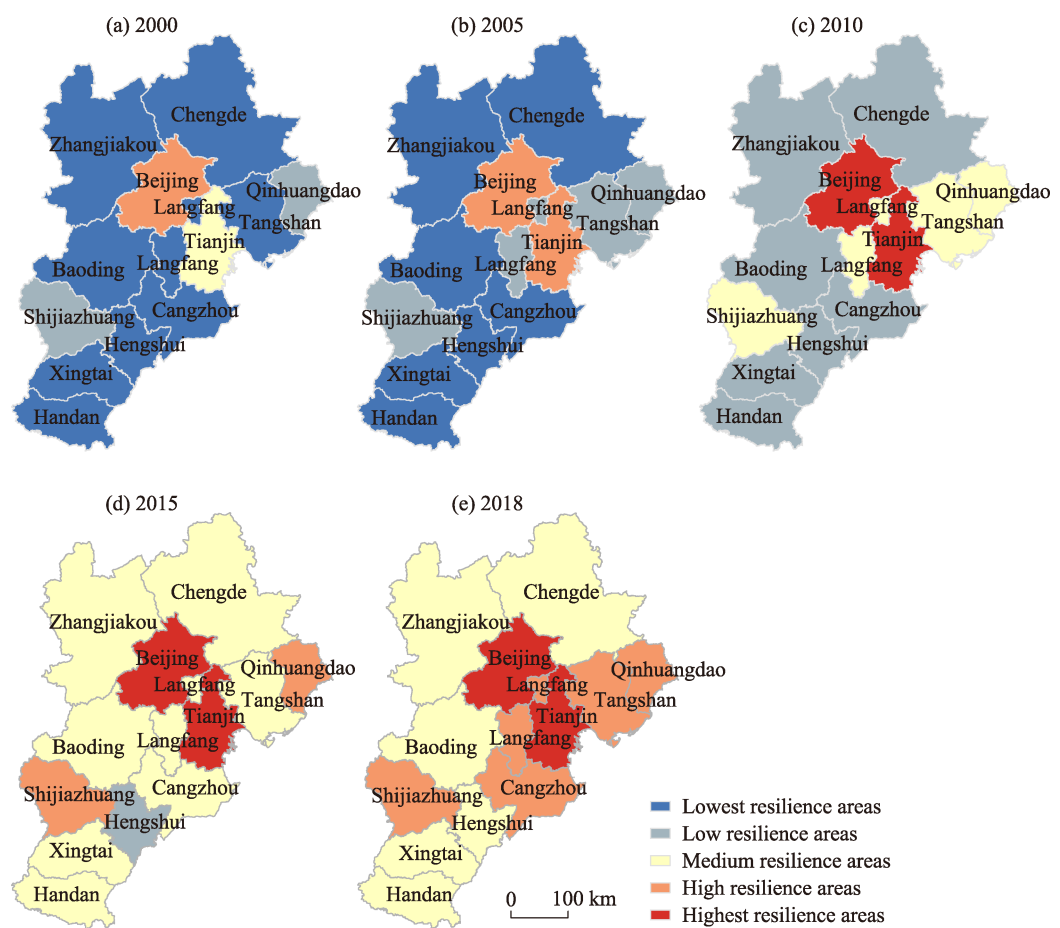


Figure 4 Spatio-temporal evolution of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

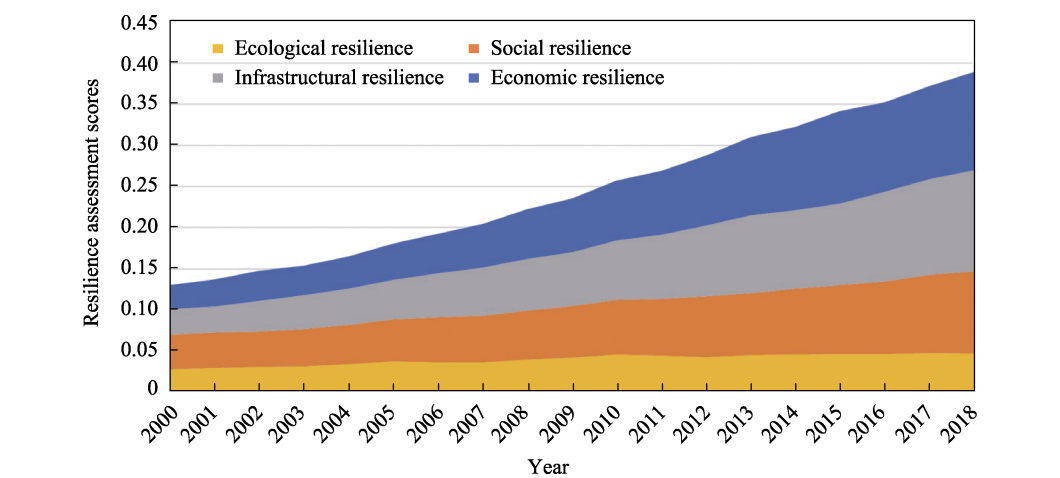
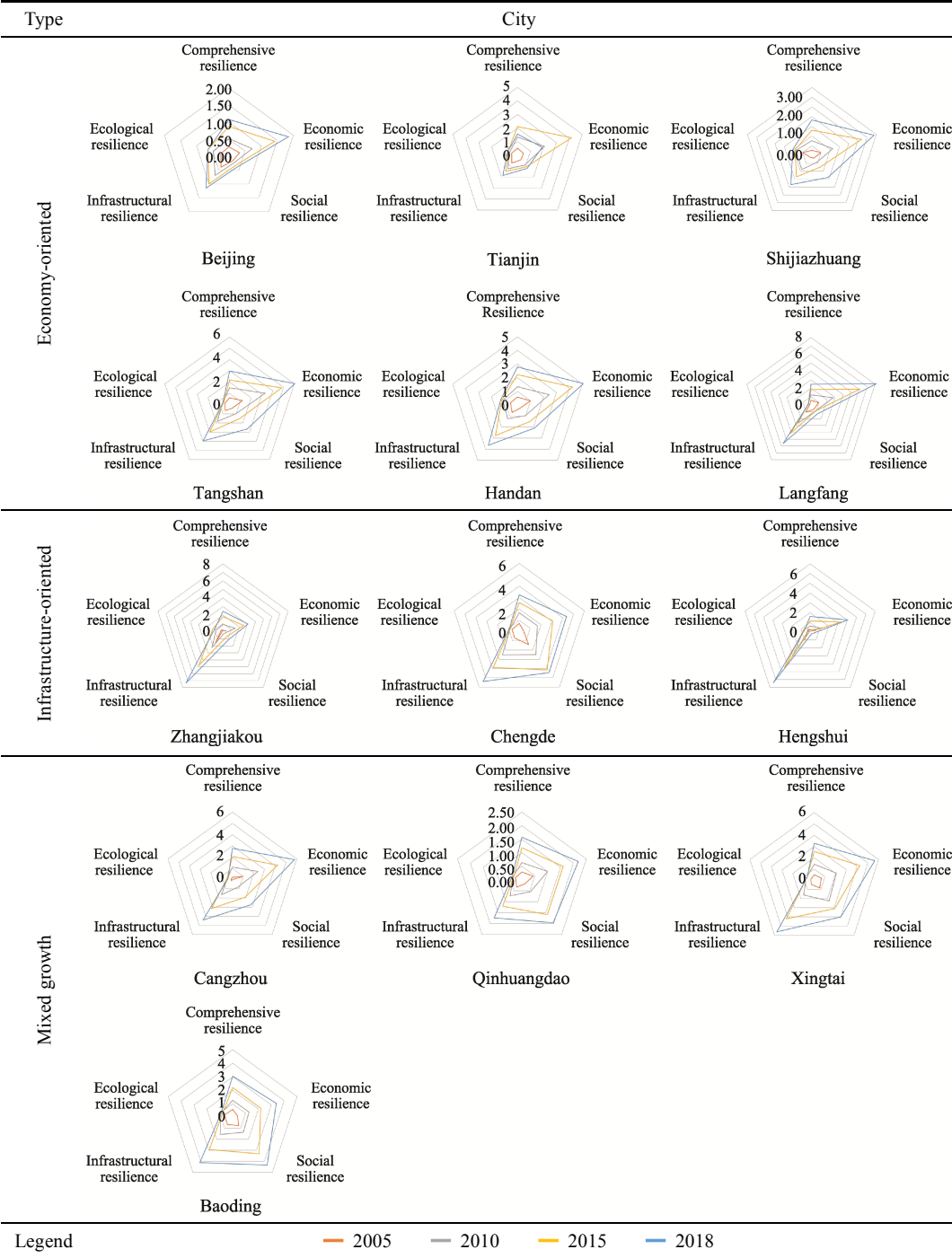


Figure 5 The development trend of resilience of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

economic resilience was the highest at 8.06%, compared to the relatively low growth rate of ecological resilience at 2.98%. Additionally, cities had different dominant resilient growth subsystems, which can broadly be divided into three types: economy-oriented, infrastructure-oriented, and mixed growth (Table 2).

Table 2 The resilience growth rate of each subsystem from 2000 to 2018



(1) Economy-oriented growth. The resilience growth rate of the economic subsystems of Beijing, Tianjin, Shijiazhuang, Tangshan, Handan, and Langfang was significantly higher than that of the other three subsystems from 2000 to 2018. The economic resilience of Langfang increased by 816.31%, in contrast to the ecological resilience, which increased by a mere 32.71%. It demonstrated that Langfang achieved rapid economic development due to the spillover effects of Beijing and Tianjin, but neglected to protect and promote the environment. From 2000 to 2015, Tianjin's economic resilience increased by 417.5%; however, from 2015 to 2018, due to a decline in tax revenue, the actual use of foreign capital, and fixed asset investment, the economic resilience declined sharply, standing at 190.42% in 2018. Beijing, the BTH urban agglomeration's core city, maintained a steady growth trend in economic resilience. However, the cumulative growth rate of economic resilience was only 185.27% because the growth took place from a relatively high base.

(2) Infrastructure-oriented growth. The resilience of the infrastructural subsystems in Zhangjiakou, Chengde, and Hengshui increased by more than 500% from 2000 to 2018, which is much higher than that of the other three subsystems. Zhangjiakou's infrastructure resilience increased by 736.35%, mainly due to the construction of the Beijing Winter Olympics in 2022. Zhangjiakou accelerated its construction program and greatly improved the resilience of its infrastructure since 2015. Although the resilience levels of the three subsystems of economy, society, and ecology also show an increasing trend, the growth rate is relatively low, and there is considerable room for improvement.

(3) Mixed growth. Cangzhou, Qinhuangdao, Xingtai, and Baoding had two or more resilience subsystems that increased considerably. Cangzhou and Xingtai's economic and infrastructural subsystems showed the largest increase, whereas Qinhuangdao's economic and social system had the largest increase in resilience. Baoding's infrastructural and social resilience also increased.

On the spatial scale (Figure 6), the resilience levels of each subsystem showed different spatial distribution characteristics. The spatial distribution of each subsystem's resilience in 2018 shows that the distribution characteristics of the three subsystems of economy, society, and infrastructure were consistent with overall resilience: with a relatively high resilience level in the core areas and a relatively low resilience level in the non-core areas. Ecological resilience was higher in the north and south, and low in the center. It is evident that the development of the cities influenced their ecologies.

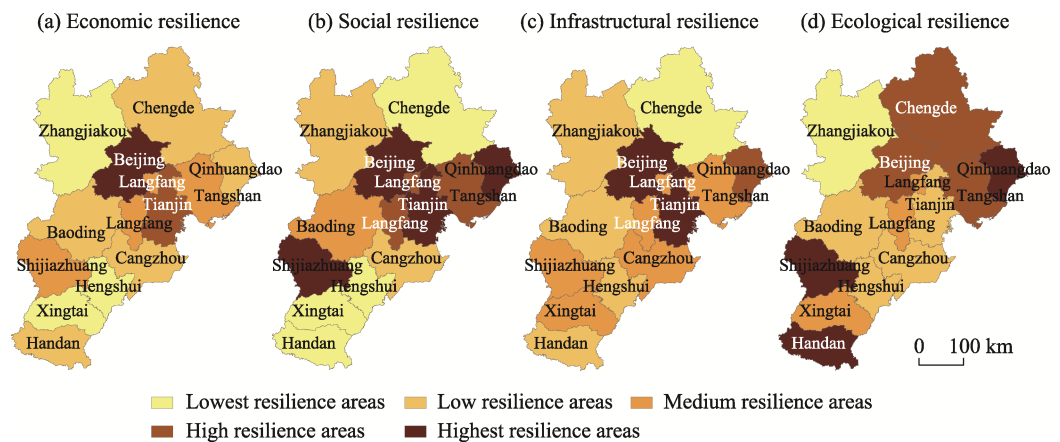


Figure 6 Spatial distribution pattern of subsystem resilience in the Beijing-Tianjin-Hebei urban agglomeration in 2018

3.3 Spatial difference and spatial form evolution of urban resilience

3.3.1 Spatial difference analysis

To analyze the spatial differences of the urban resilience level in the BTH urban agglomeration, this study calculated the total Theil index as well as the inter- and intra-group differences between core and non-core areas from 2000 to 2018. The following was observed from the calculation results (Table 3 and Figure 7).

(1) The total Theil index of urban resilience of the BTH urban agglomeration showed a downward trend, from 0.165 in 2000 to 0.058 in 2018, a decrease of 64.8%. It implied that the urban resilience of the BTH urban agglomeration has a “core-periphery” spatial structure, with the overall difference decreasing from 2000 to 2018.

(2) The inter-group difference in BTH urban agglomeration also showed a downward trend, from 0.056 in 2000 to 0.024 in 2018. Nevertheless, the contribution of inter-group difference showed an upward trend, increasing by 21.7% in 18 years; the contribution rate to the total Theil index was 41.23% in 2018. Inter- and intra-group differences were the critical factors of spatial differences in urban resilience in the BTH urban agglomeration.

(3) The disparities within the BTH urban agglomeration also showed a downward trend. However, the disparities within the core and non-core areas were significantly different. The intra-group difference of the core area was significantly larger than those of the non-core

Table 3 Urban resilience Theil index and its decomposition in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

Year	Theil index	Inter-group difference	Intra-group difference	Intra-group difference of core area	Intra-group difference of non-core area	Contribution of inter-group	Contribution of intra-group in core area	Contribution of intra-group in non-core area
2000	0.165	0.056	0.109	0.146	0.046	0.339	0.558	0.103
2001	0.170	0.066	0.104	0.148	0.024	0.388	0.560	0.051
2002	0.179	0.063	0.116	0.172	0.018	0.353	0.611	0.036
2003	0.167	0.062	0.105	0.148	0.029	0.372	0.565	0.063
2004	0.167	0.071	0.096	0.136	0.022	0.426	0.528	0.046
2005	0.148	0.056	0.091	0.128	0.028	0.382	0.547	0.071
2006	0.147	0.058	0.089	0.123	0.030	0.395	0.529	0.076
2007	0.148	0.060	0.088	0.121	0.030	0.405	0.521	0.074
2008	0.129	0.054	0.075	0.107	0.022	0.418	0.519	0.064
2009	0.126	0.055	0.072	0.101	0.023	0.432	0.500	0.068
2010	0.111	0.046	0.065	0.094	0.018	0.414	0.521	0.064
2011	0.107	0.041	0.066	0.095	0.021	0.386	0.538	0.076
2012	0.105	0.040	0.065	0.096	0.019	0.381	0.547	0.072
2013	0.086	0.034	0.052	0.078	0.014	0.394	0.538	0.068
2014	0.091	0.037	0.054	0.082	0.013	0.405	0.536	0.059
2015	0.094	0.038	0.056	0.085	0.014	0.401	0.541	0.058
2016	0.071	0.029	0.042	0.063	0.012	0.412	0.520	0.068
2017	0.062	0.026	0.036	0.056	0.010	0.413	0.516	0.070
2018	0.058	0.024	0.034	0.049	0.015	0.412	0.478	0.109

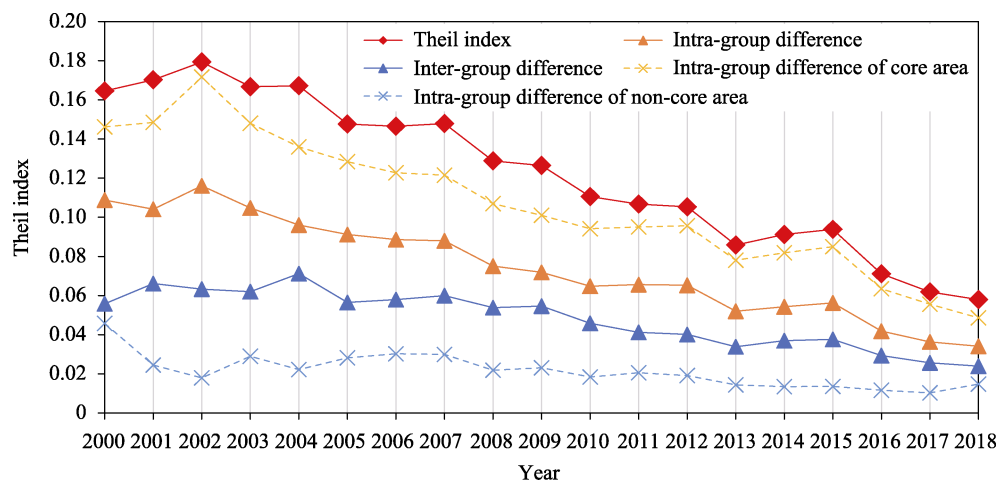


Figure 7 Theil index of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

area, and the contribution of the intra-group in the core area was 7.8 times that of the non-core area. It means the resilience level of intra-group difference of non-core area in BTH urban agglomeration had a smaller difference, while there was a larger difference in the core area.

In general, the spatial difference of urban resilience in the BTH urban agglomeration decreased from 2000 to 2018. The main spatial difference was the resilience between cities in the core area. Because the urban positioning, urban construction base, and development level of Beijing and Tianjin are higher than those of cities in Hebei province, their resilience level would also be higher than those of cities in Hebei province. However, the development trend of the Theil index revealed that Beijing and Tianjin promoted the development of surrounding cities, under the integration policy between Beijing, Tianjin, and Hebei; consequently, the gap between the cities in terms of resilience is narrowing.

3.3.2 Spatial morphology evolution

The standard deviation ellipse and spatial center of gravity of urban resilience of the BTH urban agglomeration from 2000 to 2018 were calculated using ArcGIS 10.6, and the spatial distribution direction, center of gravity, and distribution range of resilience of the BTH urban agglomeration in different periods were analyzed. The variation in the center of gravity and the parameters are shown in Figure 8 and Table 4.

Regarding the perspective of the direction of the spatial distribution, the long semi-axis of the level of urban resilience in the BTH urban agglomeration always remained in the north-east-southwest direction. The angle of the standard deviation ellipse only rotated counter-clockwise by 1.6 degrees from 2000 to 2018, indicating that the overall direction of the spatial distribution of the urban resilience level of the BTH urban agglomeration remained relatively stable. It was also roughly in line with the general spatial arrangement of the BTH urban agglomeration.

From 2000 to 2005, the center of gravity of the spatial distribution of resilience shifted 2.30 km to the northeast. The level of resilience of Tianjin, Langfang, and Tangshan increased rapidly during this period. From 2005 to 2018, the center of gravity shifted 12.60 km

Table 4 The parameters of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2018

Year	Central longitude	Central latitude	Direction angle	Long axis distance (km)	Short axis distance (km)	Flattening
2000	116.4855	39.2813	41.214	220.720	118.252	0.4642
2001	116.5154	39.2991	39.892	218.449	116.022	0.4689
2002	116.5092	39.3185	39.033	220.123	116.731	0.4697
2003	116.5156	39.2828	40.564	222.340	115.307	0.4814
2004	116.5564	39.3132	41.327	221.773	115.978	0.4770
2005	116.5122	39.2824	40.924	223.412	115.389	0.4835
2006	116.4989	39.2603	40.861	223.539	115.435	0.4836
2007	116.5053	39.2526	40.842	224.396	114.796	0.4884
2008	116.4980	39.2399	40.252	224.078	115.860	0.4829
2009	116.5133	39.2515	40.542	223.889	116.061	0.4816
2010	116.4992	39.2332	40.061	225.264	116.216	0.4841
2011	116.4982	39.2360	39.984	227.008	116.089	0.4886
2012	116.4994	39.2388	40.080	229.090	118.261	0.4838
2013	116.4764	39.2042	40.012	229.167	117.978	0.4852
2014	116.4817	39.2074	39.872	228.378	117.470	0.4856
2015	116.4748	39.2104	39.682	227.355	117.902	0.4814
2016	116.4505	39.2020	39.478	230.057	118.949	0.4830
2017	116.4386	39.1948	39.306	231.430	119.430	0.4839
2018	116.4242	39.1918	39.578	232.278	120.064	0.4831

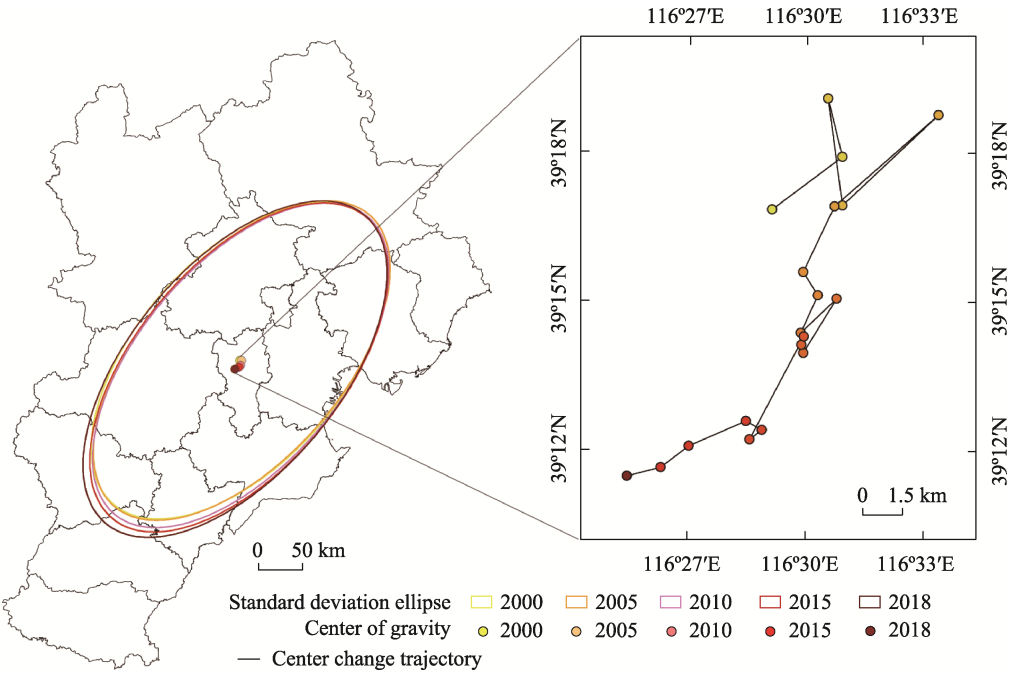


Figure 8 The standard deviation ellipse of urban resilience and the trajectory of gravity center movement from 2000 to 2018

to the southwest, which means a rapid improvement in the resilience of the cities in the southwest. In general, the spatial distribution center of urban resilience in the BTH urban agglomeration tended to shift toward the southwest from 2000 to 2018.

The spatial distribution area of urban resilience in the BTH urban agglomeration was mainly concentrated in the core area, with Langfang as the gravitational center, showing an expanding trend. The area of standard deviation ellipse increased by 6.85% from 2000 to 2018, indicating that the difference in the level of resilience between cities is gradually decreasing. The flattening of the standard deviation ellipse had increased by only 0.02 in 18 years, indicating that the spatial distribution of urban resilience in the BTH urban agglomeration had changed little in direction and degree of distribution.

4 Dynamic simulation of spatio-temporal patterns under different scenarios

4.1 Prediction method

Against the current policy background, the proposal of the BTH coordinated development and the new requirement to promote high-quality development in China has profound implications for the future urban resilience of the BTH urban agglomeration. In this study, two scenarios (1 and 2) for the development of urban resilience in the next ten years were developed.

Scenario 1 was based on the premise that the resilience and economic development will be no significant fluctuations over the next decade. The resilience evaluation value of each city in the BTH urban agglomeration from 2000 to 2018 was used as the basic data, as it can be inserted into the GM (1,1) model to obtain the prediction results of Scenario 1.

Scenario 2 is policy-oriented urban resilience development. Since the BTH coordinated development strategy was proposed in 2014, the BTH urban agglomeration has achieved milestones in industrial, transportation, and ecological integration. Therefore, the prediction parameters of urban resilience development scenarios under political leadership can be calculated based on the resilience assessment value from 2014 to 2018. Taking the information from 2000 to 2013 as the basic data and substituting them into the GM (1,1) model, the resilience level from 2014 to 2018 was predicted and taken as the resilience level without large fluctuations. Then, the parameter values for each year were calculated by dividing the actual value of the resilience score from 2014 to 2018 by the predicted value of the corresponding year. The average value of the parameters from 2014 to 2018 was used as the prediction parameter under the policy guidelines, and the resilience value from 2019 to 2030 obtained from Scenario 1 was multiplied by the prediction parameter to get the resilience prediction value of Scenario 2 for each city in the BTH urban agglomeration.

The average relative error, average extreme ratio deviation, and C-value of the models created by each city were tested. The C-values of the cities were less than 0.35 as well as the average relative error and average extreme ratio deviation were less than 0.1, indicating a reliable accuracy and a robust fit of the model. The model could be used to predict and analyze future development. The prediction frame of this study is 2019–2030.

4.2 Prediction of urban resilience evolution trend

The prediction results of Scenario 1 (Table 5) show that the overall resilience of the BTH

urban agglomeration will continue to increase at an average annual rate of 3.6%. The resilience levels of individual cities will also continue to improve. In 2020, only Chengde, Zhangjiakou, Hengshui, and Xingtai would be medium resilience areas, while other cities would be either high or highest resilience areas. All cities in the BTH urban agglomeration will reach a high resilience level by 2025, with Shijiazhuang, Tangshan, and Qinhuangdao will reach the highest resilience level. In 2030, all the cities except Chengde, Zhangjiakou, Hengshui, Xingtai, and Handan will reach the highest level of resilience. The resilience of the BTH urban agglomeration will improve rapidly in the next ten years. The prediction results for Tianjin ignore, to some extent, the downward trend in resilience in recent years. Therefore, there are some discrepancies between this result and the actual situation. Tianjin should actively adjust its industrial structure, push forward industrial transformation, and promote the city’s development through measures such as talent policy and infrastructure investment and construction. Try to reverse the current situation of weak economic development and improve the level of urban resilience to avoid a further decline.

Table 5 Prediction of future changes of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration based on Scenario 1

Predict unit	Beijing	Tianjin	Shijiazhuang	Tangshan	Qinhuangdao	Handan	Xingtai
2020 Predictive value	0.798	0.775	0.457	0.421	0.441	0.332	0.303
2025 Predictive value	0.916	0.904	0.558	0.519	0.529	0.408	0.377
2030 Predictive value	0.991	0.971	0.667	0.623	0.623	0.487	0.455

Predict unit	Baoding	Zhangjiakou	Chengde	Cangzhou	Langfang	Hengshui	Total
2020 Predictive value	0.338	0.303	0.302	0.337	0.402	0.274	0.422
2025 Predictive value	0.422	0.376	0.373	0.422	0.489	0.332	0.510
2030 Predictive value	0.510	0.453	0.449	0.512	0.581	0.393	0.593

Based on the prediction results of Scenario 2 (Table 6), the overall level of resilience of the BTH urban agglomeration, driven by coordinated and high-quality development, will continue to grow at an average annual rate of 3.9%—the growth rate is much higher than that in Scenario 1. From the perspective of individual cities, the resilience of Beijing, Qinhuangdao, Xingtai, Baoding, Zhangjiakou, Cangzhou, Langfang, and Hengshui improve significantly compared to Scenario 1, whereas Shijiazhuang, Tangshan, Handan, and Chengde do not change significantly. The prediction results for Tianjin are more in line with the current reality. From a resilience perspective, the number of medium resilience areas will reduce from four in Scenario 1 to two cities (Chengde and Hengshui) in 2020, while Zhangjiakou and Xingtai will rise to high resilience areas. In 2025, compared with Scenario 1, Langfang will be added to the list of highest resilience areas, indicating that it will benefit from the BTH integration policy due to its geographical advantages. In 2030, compared with Scenario 1, only Zhangjiakou, Chengde, Hengshui, and Handan will be among the high resilience cities, and all the remaining cities will be regarded as the highest resilience areas. The results show that the BTH coordinated development strategy and high-quality urban development policy positively promote urban resilience in the BTH urban agglomeration.

Table 6 Prediction of future changes of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration based on Scenario 2

Predict unit	Beijing	Tianjin	Shijiazhuang	Tangshan	Qinhuangdao	Handan	Xingtai
2020 Predictive value	0.826	0.614	0.455	0.417	0.457	0.334	0.339
2025 Predictive value	0.948	0.742	0.556	0.514	0.548	0.410	0.421
2030 Predictive value	0.999	0.883	0.665	0.617	0.646	0.489	0.508

Predict unit	Baoding	Zhangjiakou	Chengde	Cangzhou	Langfang	Hengshui	Total
2020 Predictive value	0.371	0.330	0.305	0.376	0.417	0.304	0.427
2025 Predictive value	0.463	0.410	0.377	0.471	0.508	0.369	0.518
2030 Predictive value	0.560	0.494	0.454	0.571	0.603	0.437	0.616

4.3 Prediction of the development trends in urban resilience spatial pattern

From the spatial patterns of the prediction results, the resilience of cities in the BTH urban agglomeration will continue to have a “core-periphery” structure in the next few years, and large differences among cities will remain. However, these differences will gradually decrease. As core cities, the resilience of Beijing and Tianjin is predicted to remain higher than the average for the BTH urban agglomeration. Driven by the two cities of Beijing and Tianjin, in the next ten years, the cities in the core area of BTH will achieve the highest level of resilience and gradually join Shijiazhuang to form relatively concentrated areas of highest resilience. In comparison, the resilience levels of the other cities on both the north and south in the BTH urban agglomeration will be relatively low (Figures 9 and 10). A comparison of the prediction results in the two scenarios shows that the differences in resilience between cities in the BTH urban agglomeration gradually narrow as a result of coordinated and high-quality urban development. Zhangjiakou and Chengde, as the ecological connotation area in the northwest, have made significant contributions to the construction of the BTH ecological barrier, while their economic and infrastructure construction has been constrained

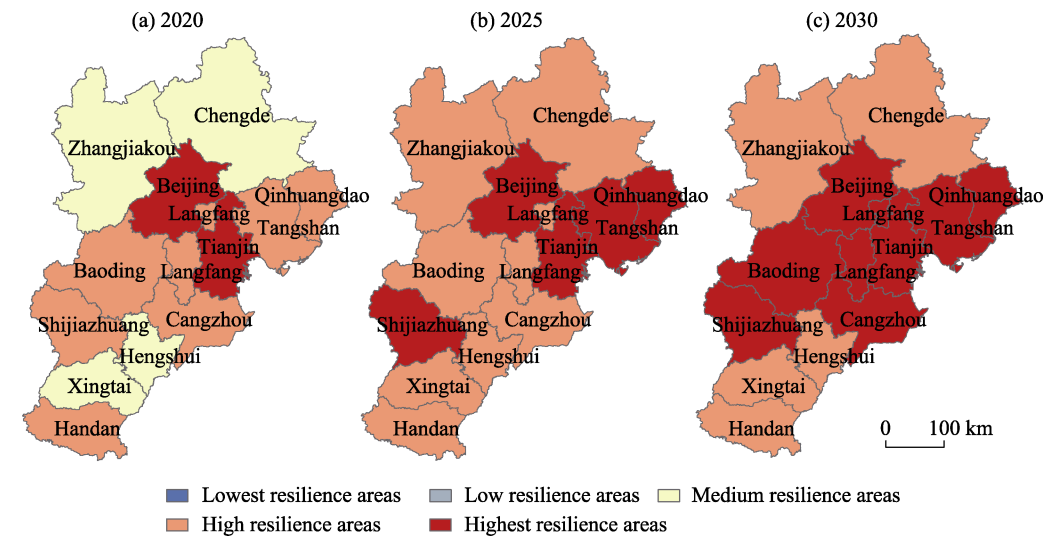


Figure 9 Schematic diagram of future spatial patterns in urban resilience in the Beijing-Tianjin-Hebei urban agglomeration based on Scenario 1

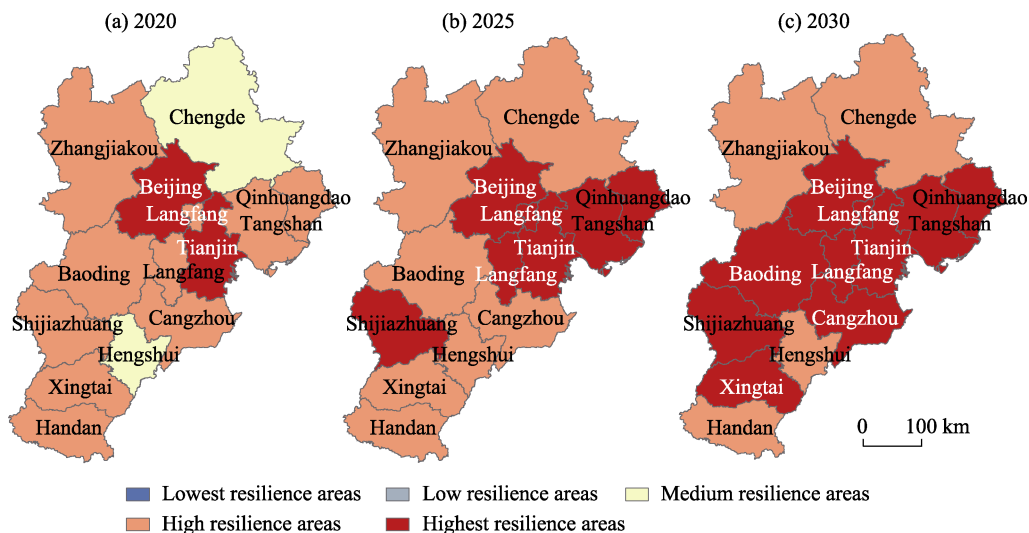


Figure 10 Schematic diagram of future spatial patterns of urban resilience in the Beijing-Tianjin-Hebei urban agglomeration based on Scenario 2

to a certain extent. In the future, resilience should be enhanced by improving the ecological compensation mechanism, developing environment-friendly industries, and improving infrastructure. Hengshui, Xingtai, and Handan in the south are farther from the core area and, in relative terms, less affected by the spillover effect from Beijing and Tianjin. Therefore, the construction of transportation infrastructure in the urban agglomeration should be accelerated. The spatio-temporal distances between cities should be shortened, and the development of links between Shijiazhuang and the three cities should be promoted. Overall, the urban resilience focus of the BTH urban agglomeration will gradually shift to the southwest between 2020 and 2030, with high levels of resilience in the central part and lower resilience levels in the northern and southern areas.

The prediction results of dynamic simulation under the two scenarios scientifically reflect the future development trend of each city's resilience level, providing a scientific basis for the construction and regulation of resilience in BTH urban agglomeration. The prediction results indicate that the resilience levels of cities in the BTH urban agglomeration will maintain an upward trend over the next ten years, which is in line with the current realistic background. While the resilience levels of cities may have a higher growth rate than the predicted results due to the BTH coordinated development, high-quality development, and various measures proposed for the future. Simultaneously, the imbalance in regional development should gradually disappear through resource sharing, joint support, coordinated promotion, and other mechanisms. The disparities among cities in the BTH urban agglomeration will be significantly reduced. Besides, the construction of urban resilience in the BTH urban agglomeration will also be impacted by frequent occurrences of weather extremities, an increase in public health emergencies, and challenges related to aging populations.

5 Discussion and conclusions

5.1 Discussion

This study found that urban agglomeration resilience is determined by urban, urban network,

and organizational resilience. It examined the spatio-temporal development characteristics of urban resilience in the BTH urban agglomeration by constructing an urban resilience assessment framework based on economy, society, infrastructure, and environment. It attempted to clarify the development laws, spatial distribution characteristics, and future development trends in urban resilience in BTH urban agglomeration, identify the existing problems in building it, and propose corresponding strategies. The main conclusions are as follows.

First, from 2000 to 2018, the comprehensive evaluation index of urban resilience in the BTH urban agglomeration showed a steady upward trend. Trends at the city level were consistent with the overall trend. However, levels of resilience between cities differed, with higher levels of resilience in the central core areas and lower levels in the surrounding non-core areas.

Second, the resilience levels of subsystems in the BTH urban agglomeration showed a steady upward trend. Nevertheless, there were significant differences in the growth rates of the subsystems of different cities and their relative contribution to overall resilience. Three types of resilience growth were identified: economic-oriented, infrastructure-oriented, and mixed. Economic resilience was the main factor influencing urban resilience. Spatially, the resilience of the three subsystems—economy, society, and infrastructure—was higher in the core area and lower in the non-core area. By contrast, ecological resilience was higher in the non-core areas and lower in the core areas.

Third, the spatial differences in urban resilience in the BTH urban agglomeration decreased from 2000 to 2018. The main difference comes from the difference among cities in the core area. The gravity center of urban resilience is always located in Langfang, moving slightly toward the southwest from 2000 to 2018.

Finally, the study found that urban resilience will continue to increase in the next ten years, and all cities in the BTH urban agglomeration will reach high resilience by 2030. Although large differences among cities will remain, the differences will gradually decrease. The BTH urban agglomeration's resilience center of gravity will gradually move to the southwest over the next decade, showing a spatial pattern of high resilience in the central part and lower resilience in the northern and southern areas. The policy of the BTH coordinated development and high-quality urban development will play a significant role in promoting resilience development in the BTH urban agglomeration.

5.2 Policy recommendations

While recognizing existing challenges, such as large regional differences in resilience development levels, unbalanced spatial distribution, and different resilience development levels of subsystems, the following suggestions are made, based on the results of the BTH urban agglomeration's urban resilience assessment.

First, the integration of peripheral cities into the BTH urban agglomeration should be accelerated to improve the resilience of cities outside the core area. Owing to the high level of urban resilience in the central core area of the BTH urban agglomeration and the low level and slow economic development of the surrounding non-core areas, the leading role of Beijing and Tianjin should be maintained. Meanwhile, strengthen the spillover effect of Shijiazhuang to enhance linkages with Hengshui and Xingtai. Additionally, the social, economic,

and infrastructure construction of the non-core cities should be accelerated to develop a well-coordinated and closely-connected urban system, and accelerate the coordinated development of BTH.

Second, “relief” and “cultivation” should be carried out simultaneously to improve economic resilience. Because of the significant differences in urban economic resilience within the BTH urban agglomeration, Tianjin and Hebei should seize the opportunity of Beijing’s relief of non-capital core functions and find their industrial development direction based on urban development actively adjust their industrial structure. Through the optimization of the development environment and other means, they should actively undertake the transformation of scientific and technological achievements in the capital to gradually eliminate the “gap” in economic development between the cities. Simultaneously, the talent, technology, and capital advantages of BTH should be given full play to innovation as the leader, and focus on cultivating strategic emerging industries based on big data, artificial intelligence, 5G, etc. They should also actively cultivate new formats and business models, build new momentum for development and enhance the cities’ competitiveness and ability to withstand various economic risks.

Third, we should co-construct and share public services to improve the community and infrastructural resilience. Currently, there are wide disparities in the level of public services in terms of community facilities, basic education, healthcare, employment, and social security in BTH. Except for some core cities and Shijiazhuang, most others have low social and infrastructural resilience levels. It should promote the extension of high-quality education and medical resources from the Beijing-Tianjin region to low-level areas by exploring cooperation and joint operation, to strengthen the cross-regional convergence of employment, pension, and social security, improve the level of regional public services and enhance the social resilience in the face of shocking events. They should also seize the opportunity of new infrastructure construction, improve traditional infrastructure construction while actively laying out a new generation of information infrastructure, drive industrial transformation with technological innovation, and enhance the infrastructural resilience.

Last, we should strengthen coordinated eco-environmental management to improve ecological resilience. Based on the current situation, where the resilience of the urban ecological environment in the BTH urban agglomeration is low and slow to improve, it is necessary to break through the belief regarding urban autonomy and build a mechanism for joint construction and sharing of the environment in the BTH urban agglomeration. Afterward, we should establish joint pollution prevention and control systems, and set a unified environmental access threshold. In this way, the coordinated management of the ecological environment within the BTH region will be realized, and its resilience will improve. At the same time, according to the positioning and ecological background of the cities in the BTH urban agglomeration, we propose different green development paths and the vigorous promotion of a green economy, in line with the basic concept of green development, to ensure that social and economic development does not harm the environment.

5.3 Conclusions

This study evaluated and forecasted the urban resilience of the BTH urban agglomeration using the entropy method and gray prediction model. The current problems and future de-

velopment trends of the resilience of the BTH urban agglomeration were described scientifically. Meanwhile, this study still had some limitations. There are three levels of influence in urban agglomeration resilience: urban, urban network, and organizational. However, due to great differences in the influencing factors, mechanisms, and assessment methods affecting the resilience of the three systems, this study focused only on urban resilience. Nevertheless, it should be noted that cities within urban agglomerations are closely connected. The resilience of individual cities within the urban agglomeration is not only determined by the cities themselves, but also by the interactions between cities through transportation, economy, etc. Therefore, future research could start from a broader perspective to study the resilience of urban agglomerations. Furthermore, owing to limited data, only a few representative statistical indicators were selected for each subsystem. In future research, network Big Data should be combined to obtain more realistic conclusions. In terms of the factors influencing urban resilience, in addition to the subsystems involved in the study, cities' climatic conditions, topography, and natural substrate also affect the level of urban resilience. Additionally, the impact of regional development policies and organizations on urban resilience cannot be ignored. These factors should be considered in future research.

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