

Article

Resilience of Urban Network Structure in China: The Perspective of Disruption

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Abstract: In light of the long-term pressure and short-term impact of economic and technological globalization, regional and urban resilience has become an important issue in research. As a new organizational form of regional urban systems, the resilience of urban networks generated by flow space has emerged as a popular subject of research. By gathering 2017 data from the Baidu search index, the Tencent location service, and social statistics, this study constructs information, transportation, and economic networks among 344 cities in China to analyze the spatial patterns of urban networks and explore their structural characteristics from the perspectives of hierarchy and assortativity. Transmissibility and diversity were used to represent the resilience of the network structure in interruption scenarios (node failure and maximum load attack). The results show the following: The information, transportation, and economic networks of cities at the prefecture level and higher in China exhibit a dense pattern of spatial distribution in the east and a sparse pattern in the west; however, there are significant differences in terms of hierarchy and assortativity. The order of resilience of network transmissibility and diversity from strong to weak was information, economic, transportation. Transmissibility and diversity had nearly identical scores in response to the interruption of urban nodes. Moreover, a highly heterogeneous network was more likely to cause shocks to the network structure, owing to its cross-regional urban links in case of disturbance. We identified 12 dominant nodes and 93 vulnerable nodes that can help accurately determine the impetus behind network structure resilience. The capacity of regions for resistance and recovery can be improved by strengthening the construction of emergency systems and risk prevention mechanisms.

Keywords: network structure resilience; information network; transportation network; economic network; big data; spatial analysis; geoinformation



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1. Introduction

With the increasing trend of globalization and the promotion of technology, the relationships among cities tend to be intimate and diverse. The improvement of high-speed connection infrastructure (such as aviation, high-speed rail, telecommunications and Internet, etc.) has strengthened the connections between cities, promoting intercity network relationships and externalities [1–3]. The space of flows proposed by Castells (1999) [4] has given birth to a network perspective on cities that describes the phenomenon of spatial connection in city networks. With flows of economy, information, traffic, and technology as the means of contact, cooperation, and connection among them at different spatial scales according to the given requirements, cities now form an inseparable organic system, namely a city network [5,6].

The network relationships among cities have penetrated into the original geographic spatial structures and have been reconstructed for cities at different levels and spatial scales [7–9]. In terms of geographic space, the network relationship is primarily manifested as increasing spatial differences and connections [10], which makes the interweaving of physical infrastructure and virtual networks yield richer connotations. Efficient and

comprehensive transportation systems and communication service facilities and innovative modes of economic development all promote regional synergy and development, which changes the mode of contact among people and shortens their perception of time and space.

With rapid urbanization, however, many kinds of cumulative and sudden risks to regional and urban systems also increase rapidly, including terrorist attacks, natural disasters, and so forth [11]. In other words, diverse and frequent network element flows, while facilitating the efficiency of regional production, may also lead to the transmission and spread of some crisis factors, i.e., negative network externalities [12]. The concept of resilience has become a focus of such international community disciplines as disaster alleviation, risk management, and urban planning, owing to its theoretical innovation and practical exploration in dynamic adjustment, integrated enhancement, multi-cooperation, and positive response. This has expanded the content and perspective of urban area research by integrating resilience among cities and regions [13,14].

The urban network structure is characterized by a particular state, spatial attributes, and interrelations among its elements in space. Even if it is the same node set, different connection modes and degrees form network structures with altered functions. The differences in structure and function directly affect regional resilience [15,16]. Therefore, evaluating the urban network structure is an important way to understand the interactive spatial relationships among cities and assess regional resilience. In recent years, the world has faced such developmental problems as unbalanced energy distribution, unequal economic development, and environmental risks. The sustainable development of regions has been threatened, particularly by climate change, air pollution, and accelerated urbanization [17,18].

Negative network externalities such as infectious diseases, Internet rumors, and the like can be transmitted and spread along urban networks, and even amplified to have a regional impact. This exposes the vulnerability of regions and cities, and has become a bottleneck restricting the sustainable development of regional systems. In the context of developing city networks, attention should be paid to network externalities. Furthermore, frequent natural and human disasters are highly likely to cause network disruptions that affect the proper functioning of nodes and which can have unpredictable consequences [19], even to the extent that perturbations to one component could have a domino effect on other parts of the network system [20]. Therefore, the performance of the network structure in response to disturbances or shocks in terms of resilience should especially not be ignored.

The multipoint global outbreak of the novel coronavirus disease in 2019 (COVID-19) has evolved from a public health emergency into a nontraditional disaster, and has shown that without the support of a safe urban development environment, urban prosperity and vitality can enhance a city's vulnerability and even cause short-term shock. In coping with COVID-19 in China, effective coordination mechanisms among cities, node lockdown of urban traffic networks, construction of inter-regional public health networks and regional and coordinated production of anti-epidemic materials reflect coordinated cooperation among cities in response to disaster and crisis. This has a benign synergetic effect on the network. Therefore, the important and outstanding questions in this context pertain to how complex network theory can be used to evaluate the resilience of the urban network structure and how theoretical concepts can be translated into the resilient development of regions.

As an effective way to measure regional resilience, the resilience of the urban network structure refers to the capacity of the urban network system to restore, maintain, or improve its original network performance and important functions in response to regional shocks [21]. Interruption simulation is emerging as an important pathway in testing the structural resilience of cognitive networks. The measurement of urban network structure resilience under disruption scenarios not only helps enhance regional stability, but is also important for coordinated regional spatial development. This study examines ways of measuring the structural characteristics and resilience of multi-source networks on a large regional scale. Interruption-based simulations are considered from two aspects: node fail-

ure, which characterizes the impact of disasters on different urban nodes, and maximum load attacks, whereby nodes are interrupted from the most “important” ones [22].

Specifically, we considered 344 cities at the prefecture level and above in China, including four municipalities directly under the central government, 294 prefecture-level cities, 30 autonomous prefectures, seven prefectures, and three leagues, as well as Shihezi city in Xinjiang, Laiwu city in Shandong, Xiantao city, Tianmen city, Qianjiang city, and Shennongjia in Hubei. Data from 2017 were obtained from big data, the Baidu search index, and the Tencent location service to construct urban spatial relationship matrices from the perspective of a space of flows, and social statistics data were used to construct an urban economic connection network. Based on this, from the perspectives of hierarchy and assortativity, the structural characteristics of urban networks were revealed in terms of network nodes and entire networks. The resilience of the urban network structure to disruption was then measured and compared through transmissibility and diversity.

The objectives of this paper are as follows: (1) To establish a framework by which to assess network structure resilience; (2) To reveal the spatial patterns and investigate the structural characteristics of China’s urban information, transportation, and economic networks; (3) To present the structural resilience of urban networks under disruption scenarios in order to identify the dominant and vulnerable nodes affecting resilience; and (4) To propose suggestions for optimization and provide a reference for strengthening regional cooperation, resource allocation, and development planning.

2. Literature Review

The word “resilience” originated from the Latin word “resiliere”, which means to bounce back. With social and technological development, it has been gradually applied to many disciplines, such as engineering, materials science, ecology, psychology, economics, and urban planning [23]. The earliest and most common use of the word is found in physics, to describe the capacity of metals to recover after deformation under external forces. Holling (1973) [24] first introduced the concept of resilience to ecosystem studies and used it to define the characteristics of ecosystem stability [25]. The concept was subsequently introduced to different disciplines and its connotations were expanded. With the deepening of research, the concept has undergone two thorough modifications and improvements, from the initial engineering sense to ecological resilience and then evolutionary resilience [24,26–28]. However, different interpretations of resilience have led to various definitions and ways to understand the term [29]. The most commonly used meaning of resilience is “the capacity of a system to absorb disturbance and reorganize while changing to still retain essentially the same function, structure, identity, and feedbacks” [30].

With global focus on the capacity of cities to withstand disasters, the “resilient city” has been proposed as a prelude to the study of urban resilience. Urban resilience targets the strengthening of urban systems against disturbances and maintaining or bettering the original structures and key functions in case of crises or extreme events [31]. In light of rapid urbanization and the emergence of a list of such “urban diseases” as strains on resources, urban waterlogging, traffic congestion, and environmental pollution, researchers have begun paying attention to the capacity for urban resilience [27,32]. As urban systems tend toward integrated development, improving the capacity of regional systems to deal with disasters has become a popular subject of research in the field of disaster management [14,18]. Scholars have not reached a consensus on the definition of urban resilience, but generally recognize the view of evolutionary resilience, which abandons the pursuit of a balanced state in favor of the belief that resilience is a dynamic system attribute, with an emphasis on continuous improvement and innovation.

Therefore, as a new way of thinking about urban risk management, urban resilience focuses on enhancing the ability of urban systems to organize themselves, functionally coordinate, and adapt to uncertainty [33]. At present, the relevant research is mainly focused on the impact of humanity and the environment on urban resilience, its theoretical framework, and ways to evaluate and simulate it. However, in the existing literature,

studies specifically addressing resilience at the urban scale are still immature. Most of them focus on the response to a single disturbance, the environmental system only, and static and one-way evaluation of urban resilience. There is a lack of analysis of the dynamic process, mechanism of action, and systematic multi-feedback process of urban resilience, and a real integration of theory and practice has not been completed [34].

The combination of resilience and regional space produced the concept of regional resilience. It has been demonstrated that urban network structures and regional resilience are closely related [16,35]. Past studies on regional resilience focused on theoretical exploration [36]. As one of the best ways to measure regional resilience, the resilience of urban network structures is defined as the capacity of the urban network system to restore, maintain, or improve the original network characteristics and important functions when faced with external acute shock and chronic pressure [21].

The related research can be summarized into two categories; the first focuses on industrial cluster networks and includes qualitative and quantitative research on cluster risks, network resilience, network function, and the topological structure. Node location, the hierarchical distribution of nodes, network assortativity, diversity, and connectivity, and other attributes are important factors affecting network resilience [16,37]. The second category focuses on regional spatial networks. Urban networks are constructed through economic, informational, infrastructural, and other links among cities, which are used to examine the characteristics of the network [38–40]. Specifically, previous studies on the resilience of regional network structures have almost entirely been limited to theoretical exploration. Most of them started from a single perspective, such as that of the financial network [41], infrastructure network [22], transportation network [42], supply network [43], and so forth.

In terms of research methods, static indicators of network topology in complex network theory have mostly been used. These are based on statistical or survey data [16,44]. The objects of such research include regions at small and medium-sized scales, such as cities and urban agglomerations [21,45]. Thus, no unified and effective framework for evaluating the resilience of urban network structures is available. Furthermore, resilience has mostly been assessed in network-related research only in terms of the structural properties of the network, while information of network flows has mostly been ignored [22]. An accurate and comprehensive overall structure of the resilience of the “flow space” of urban networks at a large regional scale needs to be determined.

Therefore, this study measures urban network structure resilience in terms of information, transportation, and economy. Compared with the existing literature, the innovations and contributions herein are as follows: first, the current research enriches the relevant descriptions and theories of regional and urban network resilience. Second, this research proposes a framework by which to measure the structural characteristics of urban networks and evaluate network structure resilience (the former is measured from hierarchical and assortative perspectives based on directed weighted matrices, and the response of urban networks to node failure and deliberate attack is evaluated in terms of transmissibility and diversity). Third, China’s urban system is not only large in scale but also very complex. Taking the multi-network of 344 cities in China as the research object, measuring its resilience has very important practical value. The construction of multi-perspective urban networks based on multi-source data helps to comprehensively understand regional spatial patterns and resilience in the face of disturbance. Finally, the resulting suggestions can be combined with the current urban networks and evaluation results to promote sustainable regional development as well as provide a scientific reference for territorial spatial planning in the future.

3. Data and Methods

3.1. Data Sources

We used 344 cities at the prefecture level and above in China as examples (Figure 1). Hong Kong, Macao, and Taiwan were excluded owing to unavailable data for these areas.

The data analyzed in this study include the Baidu search index, Tencent location service, and social statistics. The search index and location service data were provided by Baidu and Tencent, two of China's top three Internet companies (the third is Alibaba).

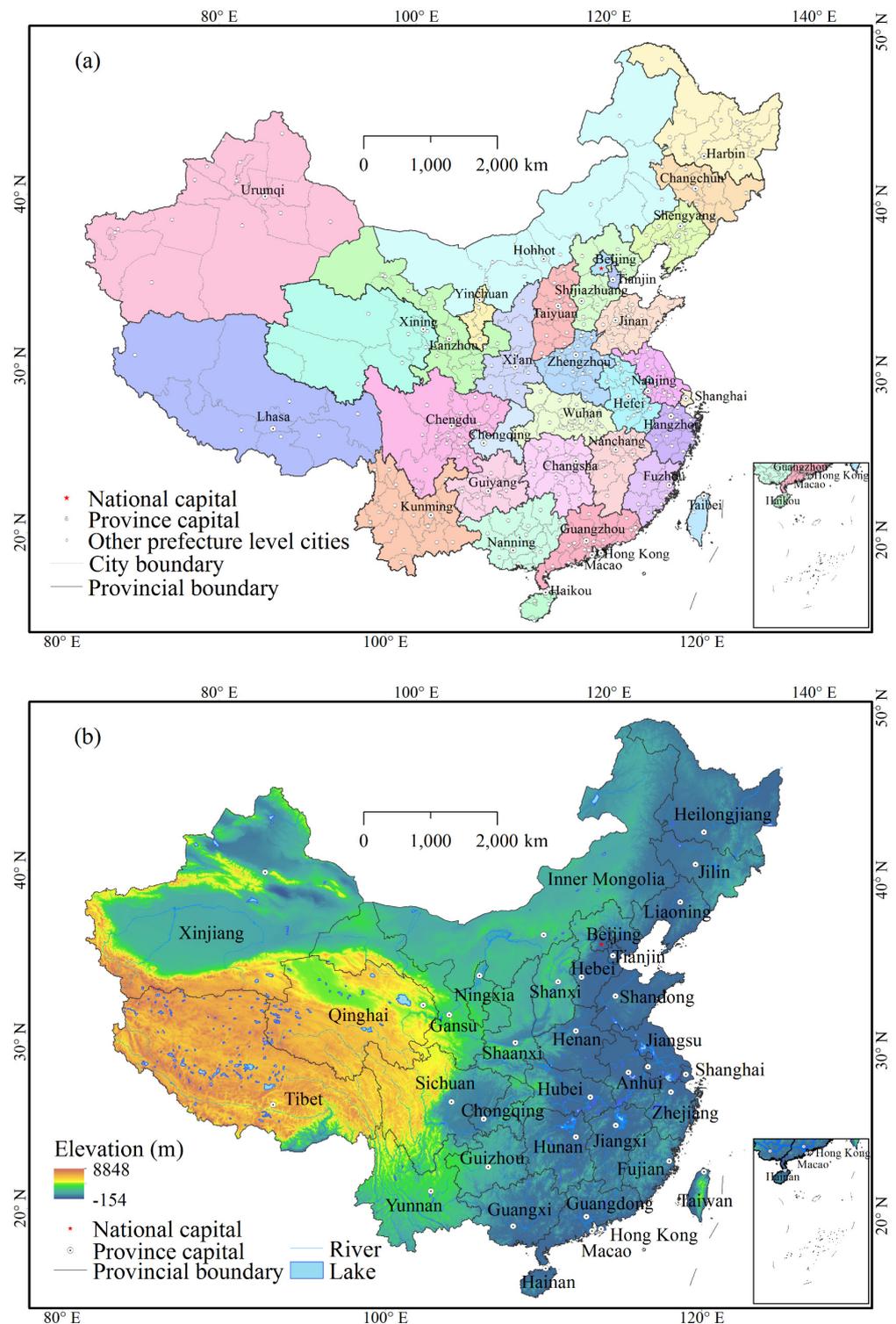


Figure 1. (a) Locations of major cities in China and (b) spatial distribution of elevation, rivers, and lakes.

Baidu Inc. provides a leading search engine as well as a knowledge- and information-centered Internet platform and AI. It is the largest search engine in China; in September

2020 it had 206 million daily active users and 544 million monthly active users [46]. The Baidu index includes Internet search and media indices, which can reflect the attention and information exchanges between cities. Intercity communication based on Internet technology makes it possible to study urban information connections on a macro scale. We acquired the Baidu search index between pairs of cities for all 344 cities considered here from January 1 to December 31, 2017. This was used to construct an information network by calculating the intensity of information flow. The search index was obtained from the Baidu index platform (<http://index.baidu.com>, accessed on 12 November 2021) [47], a website dedicated to publishing Internet search indices for every keyword.

Tencent is one of the largest integrated Internet service providers in the world and the enterprise with the largest number of online service users in China. Its businesses are related to gaming, social networking, and communications. The representative services are WeChat, QQ, and other software. In 2018, WeChat monthly active users reached 1.15 billion, and QQ monthly active users reached 650 million. It uses smartphones as carriers to obtain the geographic locations of end users through base stations of its network operators and the Global Positioning System (GPS), BeiDou navigation satellite system (BDS), and other navigation satellites [39]. The Tencent location service comprises data on population travel by air, train, and bus between cities, including the population flow in the three traffic modes of aviation, railway, and highway, which reflects the capacity of urban transportation to a certain extent. Data from 1 January to 31 December 2017 were supplied by the Tencent population migration location big data platform (<https://heat.qq.com/qianxi.php>, accessed on 12 November 2021) [48] and used to calculate the intensity of population flow to construct the transportation network.

Social statistical data, including the urban GDP and the year-end urban population employed in the secondary and tertiary industries per unit (with a total of 18 industries) were derived from the Chinese Urban Statistical Yearbook 2018; some default data were derived from the statistical yearbooks of some provinces from 2018. Vector files of administrative boundaries and urban administrative centers at a scale of 1:1,000,000 were provided by the basic geographical database of the National Geomatics Center of China (<http://www.ngcc.cn/ngcc/>, accessed on 12 November 2021).

3.2. Methods

3.2.1. Calculation of Intensity of Urban Connections

(1) The intensity of information flow (R_k) is expressed by the mutual search index between cities A and B :

$$R_k = A_b \times B_a \quad (1)$$

where A_b is the Baidu search index of city A with respect to city B , and B_a is the Baidu search index of city B with respect to city A .

(2) The intensity of population mobility (P) was measured by population flow between cities A and B :

$$P = P_{ab} + P_{ba} \quad (2)$$

where P_{ab} is the population flow from city A into city B and P_{ba} is the population flow from city B into city A .

(3) Intensity of economic connection. The urban function is the internal mechanism of generating and developing an urban economic connection network. According to different scopes of contact, the urban function can be divided into outward and inward functions [49]. We selected the urban working population G as the urban function measurement index. Whether a city had an outward function capacity E was determined by the locational quotient of employees of its industries in a certain sector, and the locational quotient Lq_{ij} of employees in sector j in city i was calculated using Equation (3) [50]:

$$Lq_{ij} = (G_{ij}/G_i) / (G_j/G), i = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (3)$$

If $L_{qij} < 1$, this means there is no outward function in department j in city i , that is, $E_i = 0$; if $L_{qij} > 1$, it means there is an outward function in department j in city i . Once the proportion of total employees in city i allocated to department j exceeds the national distribution proportion, department j is a specialized department in city i relative to the country and can provide services to regions outside the city. Equation (4) can be used to calculate the outward function capacity E_{ij} of department j in city i :

$$E_{ij} = G_{ij} - G_i * (G_j / G) \quad (4)$$

The total outward functional capacity E_i of m departments in city i can be calculated as follows:

$$E_i = \sum_{j=1}^m E_{ij} \quad (5)$$

The functional efficiency N_i of city i is expressed by the GDP per employee:

$$N_i = \text{GDP}_i / G_i \quad (6)$$

The outward functional capacity F_i of city i is:

$$F_i = E_i \times N_i \quad (7)$$

As primary industries such as agriculture, forestry, animal husbandry, and fishery usually constitute a non-basic sector of the city, we selected 18 occupational categories covered by secondary and tertiary industries, excluding those as classification criteria for industries in the city; that is, $m = 18$. Based on the results of the calculation of the outward function capacity of the city, we used the gravity model to measure the intensity of economic connection and then constructed an economic connection network. The formula is as follows:

$$R_{ij} = (F_i \times F_j) / D_{ij}^2 \quad (8)$$

where R_{ij} represents the intensity of economic connection between cities i and j , F_i and F_j are the outward function capacity of city i and city j , respectively, and D_{ij} refers to the straight-line distance between these cities.

3.2.2. Measurement of Network Structural Characteristics

Based on complex network analysis, we describe the network structural characteristics from two perspectives, hierarchical and assortative. They are described as follows:

(1) The hierarchy represents the levels of city nodes in the network. The higher the hierarchical value, the more prominent the status of core cities in the network. On the contrary, attenuation or failure of a city may have little influence on the network structure. That is to say, the hierarchy has a dual effect of robustness and fragility in a network. In contrast to commonly used methods [51], in this study we considered the weights of the edges of networks when calculating the hierarchy and used the weighted degree and its distribution to express it. The weighted degree represents the sum of the weights of the edges connected with a given node. The larger the value, the closer the connection between nodes. The distribution of the weighted degree, that is, the probability or frequency distribution of the weighted degree of all nodes in a network, can reflect the macrostructural characteristics of the network. The larger the slope, the more significant the hierarchy [16]. The expression for it is as follows:

$$W_m = C \times (W_m^*)^a \quad (9)$$

where W_m is the weighted degree of city m , W_m^* represents the rank of the weighted degree of city m in a network, C is a constant, and a is the slope of the curve of the distribution of the weighted degree.

(2) Assortativity reflects the degree of correlation between nodes in a network. If a city in a network tends to develop in groups with cities at a similar level and similar status, this indicates that the network has assortativity. Correspondingly, if the connections among cities surpass its status, cultural factors, and developmental differences, this indicates that the network has disassortativity [52]. The assortative network is easily affected by factors such as solidified connection paths and blocked structures, rendering them poor in terms of innovation and information penetration. When subjected to external shocks, it is difficult to ensure that they can avoid the risk of recession. On the contrary, due to its heterogeneity and openness, a disassortative network is resistant and resilient when facing risks in a region. The literature has used degree correlation, weighted degree–degree correlation, and other indicators to measure the assortativity of networks [52]; here, we used weighted degree correlation to characterize assortativity. If a node with a large neighbor-weighted average degree (NWAD) in a network tends to be connected to a node with a large weighted degree, this means that the network has assortativity; otherwise, it has disassortativity. The formula for the NWAD is as follows:

$$\overline{W}_m = \frac{1}{K_m} \sum_{i \in G_m} W_i \quad (10)$$

where \overline{W}_m is the weighted degree average of all neighbor nodes directly connected to node m (NWAD), W_i is the weighted degree of adjacent node i directly connected to city m , K_m is the degree of city m , and G_m is the set of all adjacent nodes in city m . The weighted degree correlation can be described as:

$$\overline{W}_m = D + bW_m \quad (11)$$

where D is a constant and b is the coefficient of the weighted degree correlation. If $b > 0$, the network has assortativity; otherwise, it has disassortativity.

3.2.3. Assessment of Network Structure Resilience

Resilience, as an attribute of a complex network, refers to the ability of the network system to respond to sudden external shocks and disturbances. Although a complex network can efficiently transmit resources, it may also be susceptible to unexpected perturbations. Interference to a node in the system may cause a domino effect, which will affect the partial cascade of the network [20]. The relevant literature has mostly used single indicators to measure resilience, such as transmissibility, diversity, or connectivity [53–55]. We simulated changes in the network from the perspectives of transmissibility and diversity under scenarios of node failure and maximum load attack in order to evaluate structural resilience. Node failure considers the impact of a disaster on different urban nodes. As targets of the attack, urban nodes are removed in turn. Maximum load attacks include the impact of terrorist attacks, military conflicts, or other artificial forces, and involve removing nodes by descending weighted degree, simulating node failure from the most “important” ones on down [22]. This assumes that a node loses efficacy immediately after an attack, and all edges directly connected to it are also removed. Transmissibility and diversity were measured as described below.

Transmissibility describes the ability of elements in the network to diffuse, which is generally evaluated by path-related indicators of the network. In a network with high transmissibility, the transmission and exchange of elements between urban nodes can be implemented more quickly, which is conducive to promoting learning, innovation, and communication among cities and can enhance the resistance of the network to external shocks so that it has higher resilience. Network efficiency (E) is widely used to measure the resilience of a network’s transmissibility. The larger the value, the better the transmissibility. It is expressed as follows [55]:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{D_{ij}} \quad (12)$$

where D_{ij} is the shortest path from urban nodes i to j , N is the number of urban nodes in the network, and G is the set of urban nodes in the network after removing a certain node.

Diversity refers to the fault tolerance of the network. That is, when elements in a network are affected by an external impact or attack while communicating through a specific path, they can quickly choose another path in order to ensure and maintain the normal operation of the network. This is also the most effective method to restore the network [56]. Moreover, the diversity of an urban network depends on whether there are other branches that are independent of common paths between cities. The average number of independent paths (V) is used to measure the resilience of the network's diversity, according to the following formula [42]:

$$V = \frac{\sum_{i \neq j \in G} n_{ij}}{N(N-1)} \quad (13)$$

where n_{ij} is the number of independent paths between nodes i and j .

Figure 2 shows the framework for assessing the resilience of the network structure.

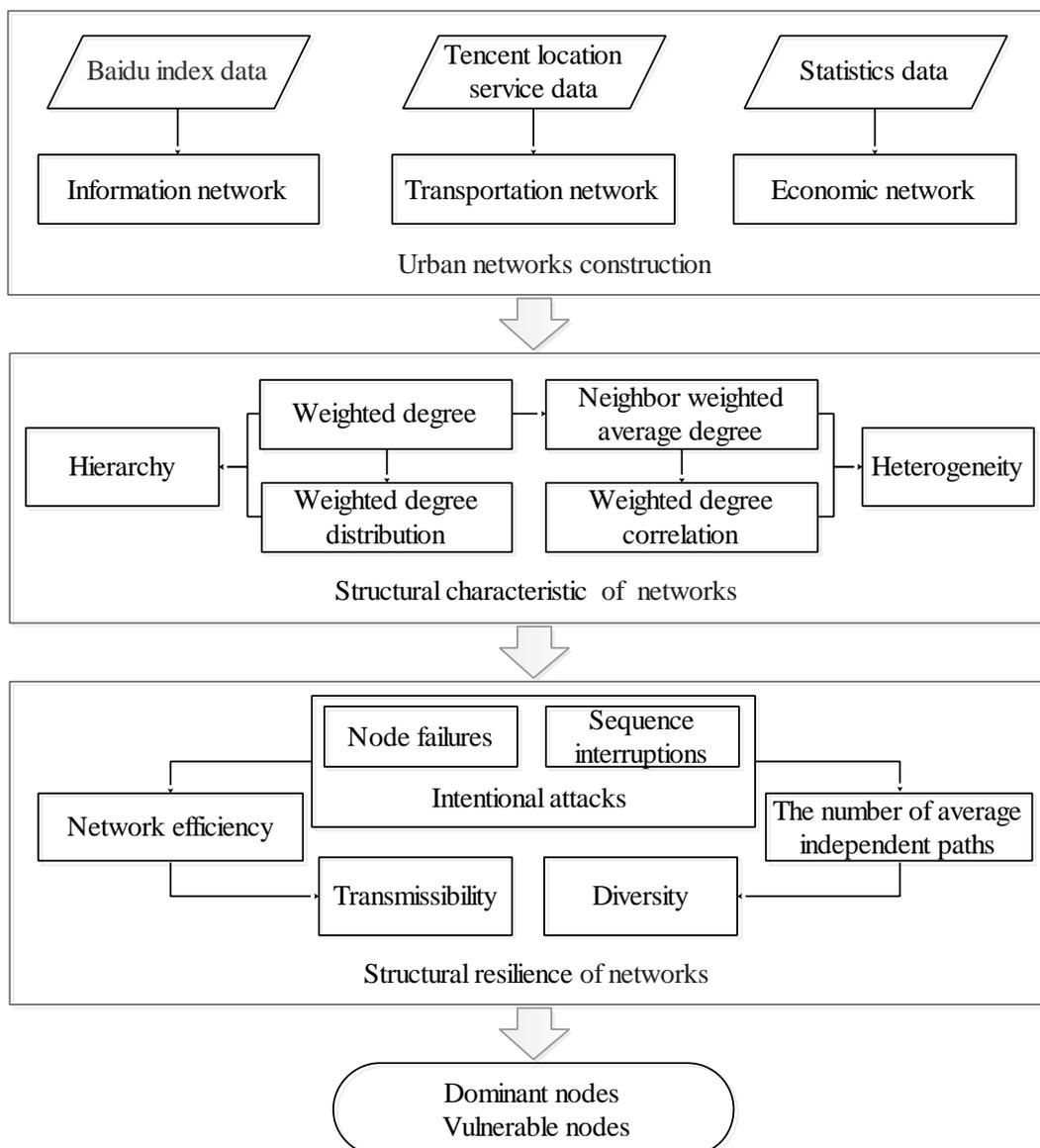


Figure 2. Framework for assessing resilience of network structure.

4. Results

4.1. Spatial Pattern of Urban Connection Networks

We used the XY to Line tool in ArcGIS to visually express the network of information, transportation, and economic connections based on the intensity of information flow, population flow, and economic ties among cities. The natural breakpoint method was used to divide each network into four levels. As many different urban nodes and connections are needed to improve the effect of the network's expression, the connections between urban nodes whose information, transportation, and economic networks are at the fourth level (the lowest level, with the largest number) are not shown. The spatial pattern of each connection network is presented in Figure 3.

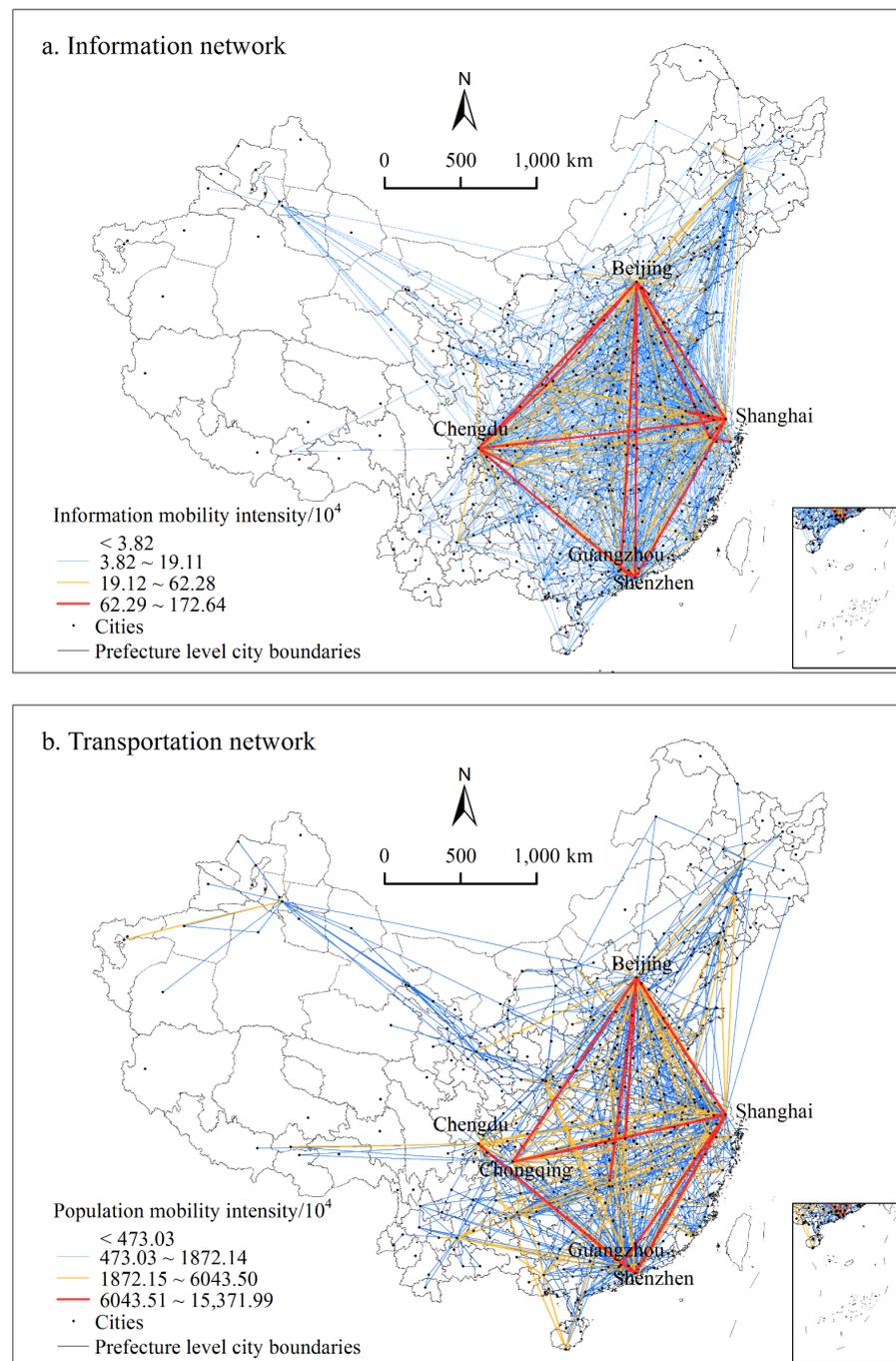


Figure 3. Cont.

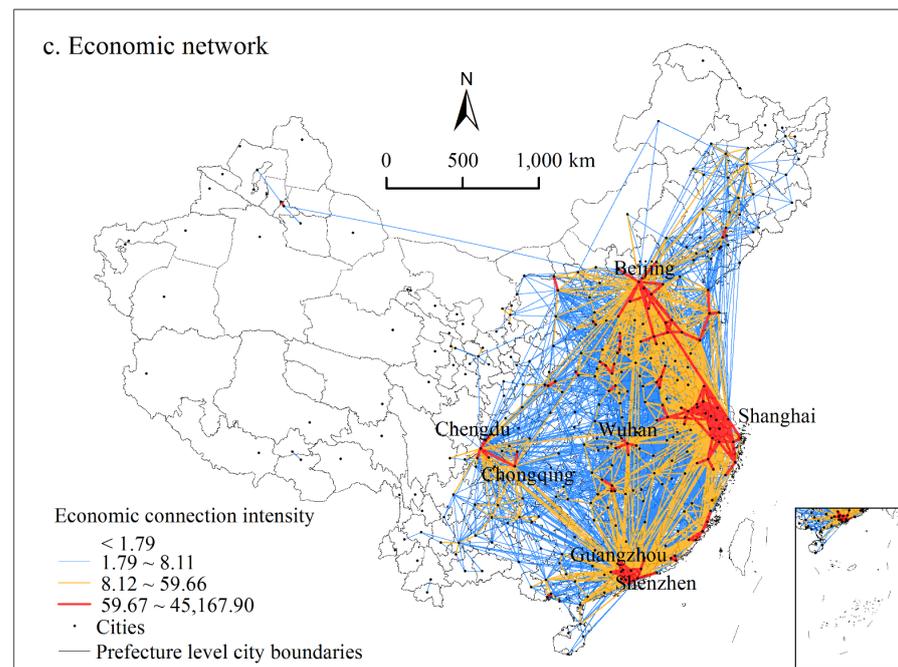


Figure 3. Spatial patterns of urban networks: (a) information network; (b) transportation network; (c) economic network.

The information network is shown in Figure 3a; it contains 53,254 connection routes. The intensity of information flow between cities at the first level (622,900–1,726,400) presents a flat rhombus-shaped spatial structure, with the vertices at Beijing, Shanghai, Guangzhou–Shenzhen, and Chengdu. There are strong information links between each vertex and its adjacent city nodes, such as Beijing–Tianjin, Shanghai–Suzhou–Hangzhou–Nanjing, Shenzhen–Dongguan, Guangzhou–Foshan, and Chengdu–Chongqing. Beijing and Chengdu have strong links with Xi’an. The spatial structure of the second level (191,200–622,800) presents the radiation connection mode with Beijing–Tianjin–Hebei, the Yangtze River Delta, Pearl River Delta, Chengdu–Chongqing urban agglomeration, and surrounding central cities such as Hangzhou, Wuhan, Zhengzhou, and Xi’an. The third level (38,200–191,100) reflects the information association among provincial capitals. The fourth level (<38,200) accounts for roughly 97% of all information links, indicating that the intensity of information attention among most cities is still weak.

Figure 3b shows the transportation network, with 13,489 routes. At the first level, the intensity of population flow among cities forms a rhombus-shaped spatial structure, with Beijing, Shanghai, Guangzhou–Shenzhen, and Chengdu–Chongqing as vertices, which is similar to the first level in the information network. Wuhan and Changsha act as important hubs, and play a supporting role in connecting the east to the west and integrating the south with the north. In addition, traffic links between core regional cities and their surrounding sub-central cities are also compact, such as Shanghai–Suzhou, Shenzhen–Huizhou–Dongguan, Guangzhou–Foshan–Dongguan, and Xi’an–Xianyang. The second level presents a trapezoidal spatial pattern with five urban agglomerations, Beijing–Tianjin–Hebei, the Yangtze River Delta, Pearl River Delta, Liaozhongnan, and Chengdu–Chongqing, as vertices. The surrounding urban agglomeration lies along the the middle reaches of the Yangtze River; Beijing–Lanzhou, Chengdu–Lhasa, and Urumqi–Kashgar also show strong cross-regional traffic links. The third level mainly consists of short-distance population flow between cities. In addition to the six urban agglomerations at the second level, a stronger population flow occurs among the inner cities of Ha–Chang, Zhongyuan, Guanzhong Plain, Central Yunnan, and Lan–Xi and the northern slopes of the Tianshan Mountains. The fourth level accounts for about 92% of all traffic links, indicating that the intensity

of traffic links between most cities is still relatively weak. Surprisingly, Beijing–Lanzhou, Chengdu–Lhasa, and Urumqi–Kashgar have strong cross-regional traffic links.

The economic network is shown in Figure 3c, and contains 58,653 routes. Distinct from other networks, its attenuation of spatial distance has a greater impact on the intensity of the economic connection between cities. We see that the intensity of economic connection among cities at the first level presents a spatial structure of “arrow fitted to the bowstring” from east to west; that is, the most economically developed urban agglomerations of Beijing–Tianjin–Hebei and the Pearl River Delta form the two ends of the arm of the bow, and the Yangtze River Delta urban agglomeration, at the end of the bow, bends toward the Chengdu–Chongqing urban agglomeration in the hinterland of China. In addition, the Yangtze River Delta urban agglomeration has the most frequent economic connections of the four major urban agglomerations, forming a dense area of economic radiation among cities, with Shanghai at the center. The scope of economic radiation of the Beijing–Tianjin–Hebei urban agglomeration is relatively weak, but is closely connected to the Shandong Peninsula urban agglomeration. The pattern of spatial distribution of the Pearl River Delta urban agglomeration is pentagram-shaped, with Shenzhen, Qingyuan, Zhuhai, Huizhou, and Zhaoqing as vertices. The economic connections between the cities of the Chengdu–Chongqing urban agglomeration are the sparsest, forming an umbrella-shaped spatial structure with Chongqing as the handle and Chengdu as the top. The second level has a pattern of spatial distribution similar to the first level, however, the “arrow fitted to the bowstring” pattern is more significant and the connection routes are more intensive. The third level of economic connections is close. Most of them are distributed to the east of the Hu Huanyong line. Only Urumqi and Hohhot, Karamay and Turpan, and Lhasa and Lhoka have weak links in the west. The fourth level accounts for about 82% of all economic connections.

To sum up, the overall spatial pattern of the above three networks shows the spatial characteristics of density in the east and sparsity in the west. The transportation network constructed by using inter-city population movement data reveals that a cross-regional top-level urban network structure has formed, because population flow is not only an important driving force for the reallocation of production factors in space but also promotes the reaggregation and diffusion of social and economic factors. In particular, it is the frequent exchange of various elements between national central cities, such as Beijing, Shanghai, Guangzhou, Shenzhen, Chongqing, Chengdu, and so forth. Moreover, compared with the transportation network, the rhombus-shaped structure of the information network is flatter, that is, the information exchange among cities is more active and less restricted by region and distance; however, the connections between them still tend to focus on developed cities. Compared with other networks, the economic network reflects a more conservative exchange of economic elements among cities; the ability for cross-regional interaction is weaker, and the gap between the rich and the poor between the east and the west is larger.

4.2. Structural Characteristics of Urban Networks

4.2.1. Hierarchy (Weighted Degree and Weighted Degree Distribution)

Based on the weighted degree of the network, the intensity of correlations among urban nodes and the network hierarchy were measured. The results of the weighted degree are shown in Figure 4. In the information network, large cities with developed economies and fast information dissemination are in a leading position, and are important distributed nodes in the context of information flow. Most cities in northwest China pay close attention to and rely on provincial capitals, which leads to the formation of a relatively closed regional “lock-in” effect. This is not conducive to the dissemination and innovation of informational elements, owing to imperfect infrastructure and insufficient resource allocation. In the transportation network, cities with complete and developed transportation systems are higher in the hierarchy, and are important distributed nodes. Such cities rely on other cities to form a spatial pattern of “high inside and low outside” in space, reflecting the robustness of small areas and the vulnerability of large areas. The distributed nodes in the western

region only include provincial capital cities, such as Lanzhou, Xining, and Lhasa. The extreme dependence of non-core cities on port cities is not conducive to the formation of a resilient transportation network. However, affected by the attenuation of spatial distance, the hierarchy of the economic network gradually decreases from east to west, and the gap between them is large. The core cities in the east have a significant radiating effect on the surrounding non-core cities. However, there are few core cities in the western region, and it has a weak economy.

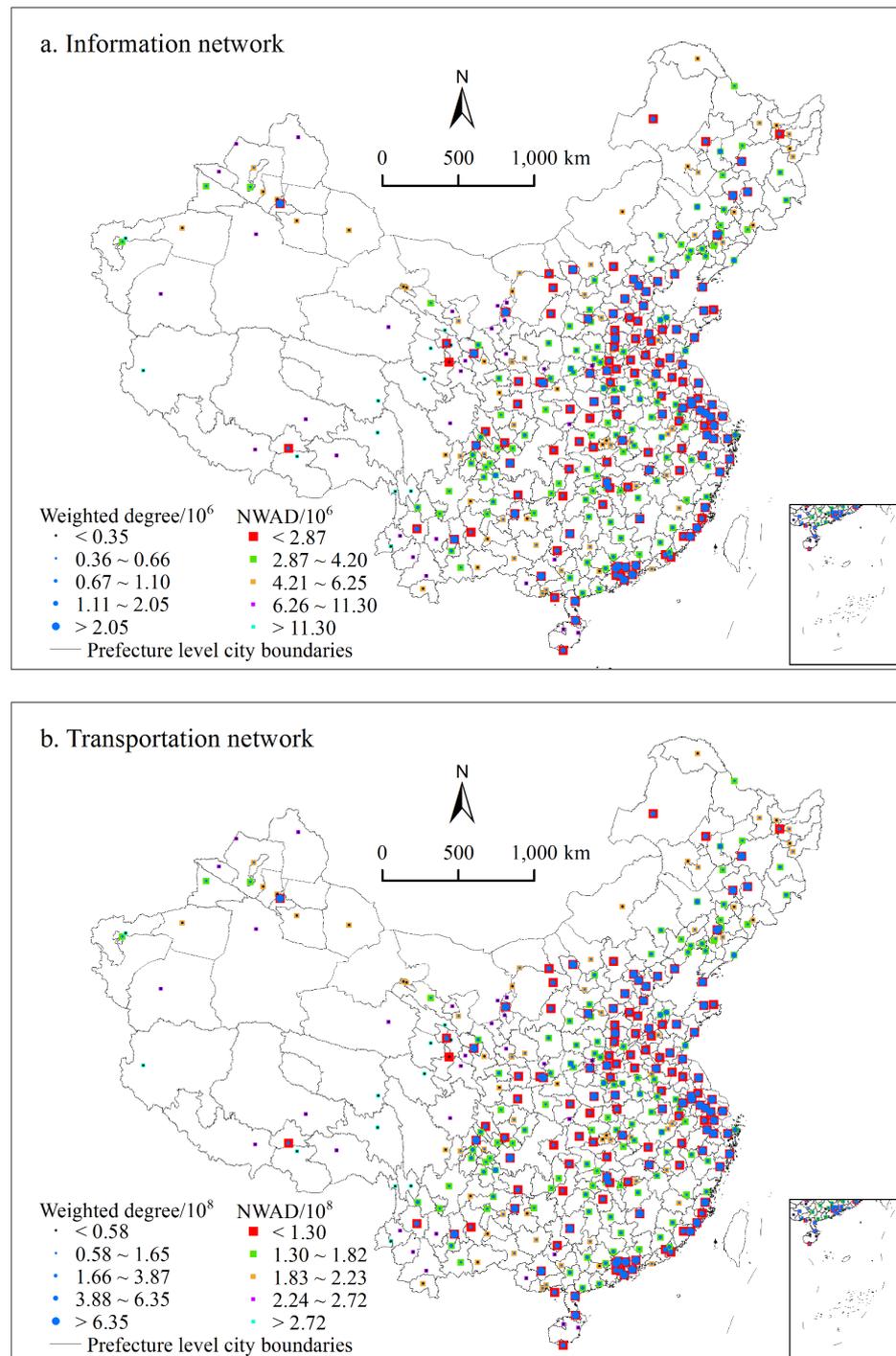


Figure 4. Cont.

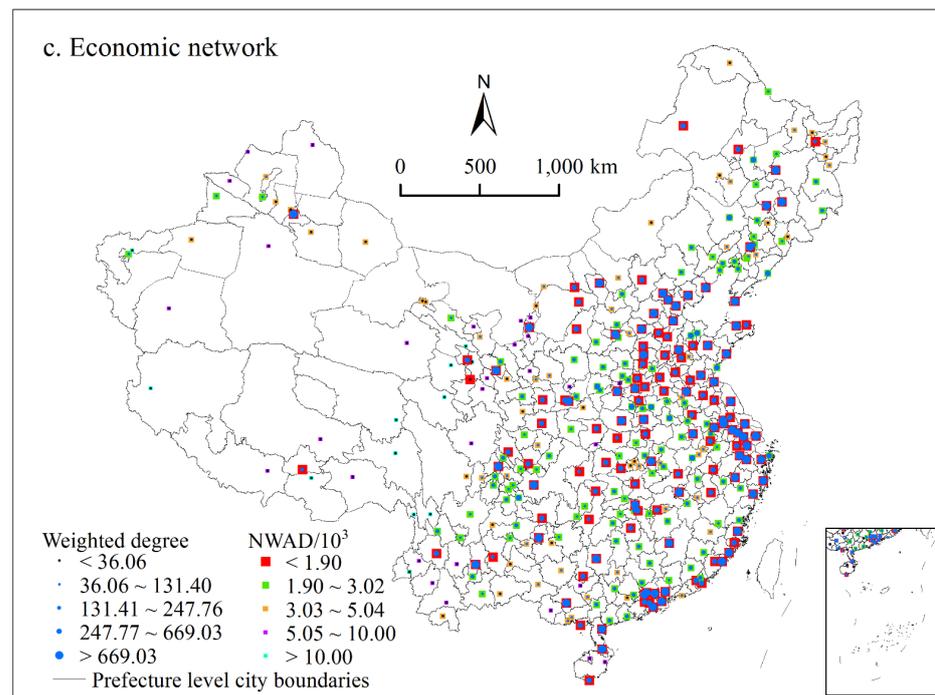


Figure 4. Weighted degree and neighbor-weighted average degree (NWAD) of networks: (a) information network; (b) transportation network; (c) economic network.

We ranked the weighted degrees of city nodes in the information, transportation, and economic networks and drew power-law curves to analyze their overall hierarchy. The curves in Figure 5 represent the weighted degree distributions of the three networks. They show that slope $|a|$ of the curve of the weighted degree distribution is relatively large, between 0.9 and 1.8. This indicates that the hierarchy of the three networks is relatively significant. The $|a|$ of the economic, information, and transportation networks is 1.727, 1.229, and 0.998, respectively, indicating that the overall hierarchies of the three networks are different. The economic network has the highest level, and its hierarchical structure between cities is the most significant, with robust urban agglomerations and core cities. However, the excessive rightward concentration is not conducive to resilient development of the network structure. Moreover, while the information network has high-value regions dominated by core cities or provincial capitals, its spatial distribution is relatively scattered, and homogenization is prominent. The $|a|$ of the transportation network is the smallest, that is, its hierarchy is the lowest. The number of core cities with high weighted degrees is small, and they are spatially scattered.

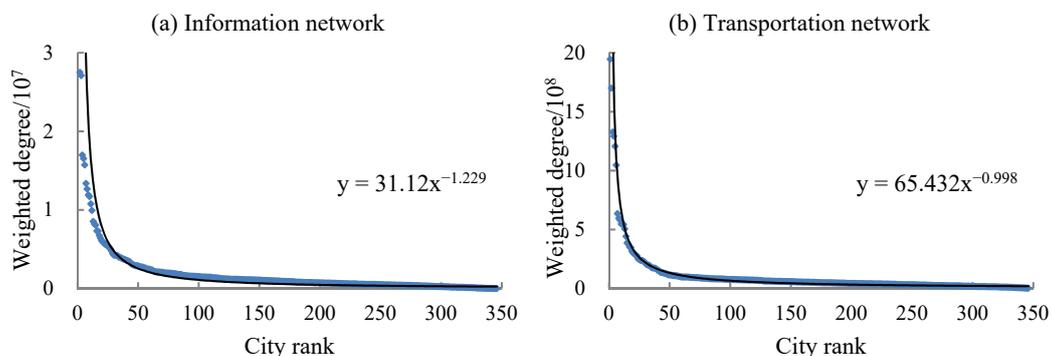


Figure 5. Cont.

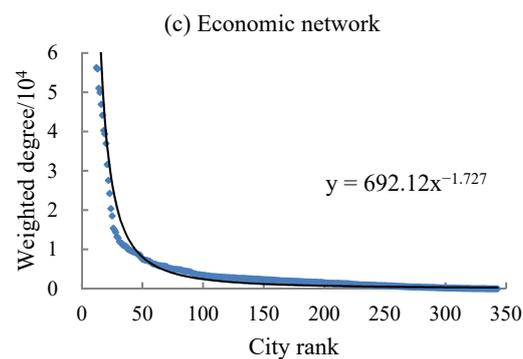


Figure 5. Weighted degree distribution of urban networks: (a) information network; (b) transportation network; (c) economic network.

4.2.2. Assortativity (Neighbor-Weighted Average Degree and Weighted Degree Correlation)

The neighbor-weighted average degree is defined as the average value of the weighted degree of neighbor nodes directly connected to a given node. We measured the preference dependence of city nodes and the assortativity of the network based on the NWAD, as shown in Figure 4. We found that the NWAD of nodes with a high weighted degree in urban networks is very small, and they are all at the fifth level. Compared with other networks, the information network has the largest number of cities with low NWAD. This indicates that they are scattered in space and have more contact with nodes at other levels. In other words, nodes with a high weighted degree in the information network tend to connect with nodes with a low weighted degree. This phenomenon of preferring such connections aids the transmission and diffusion of information through the network and reduces the time needed for information dissemination to converge. In the transportation network, although the number of cities with NWAD at the fifth level is small, their spatially prominent disassortative distribution significantly increases the opportunity for population and material flows between cities. In the economic network, although a large number of cities have large NWAD at the fifth level, their agglomeration and contiguous spatial distribution can be used to easily form a local network structure with efficient resource circulation, which is not conducive to long-term development of the overall network structure. In addition, at the fifth level, some nodes with low weighted degree have similar neighbors. Such nodes have a greater impact on the circulation and dissemination of elements of the entire network. Attention should be paid to strengthening their ability to interact with nodes with high weighted degree.

We used the linear distribution of the NWAD and weighted degree (Figure 6) to characterize the overall assortativity of each network. The coefficients of weighted degree correlation, b , of the three networks were all negative, ranging from -0.3 to -0.02 , indicating that the information, transportation, and economic connection networks are all disassortative. Specifically, the values of b for the three networks, respectively, are -0.294 , -0.128 , and -0.026 , which indicates not only that their disassortativity is significantly different, but also that the order of disassortativity from high to low is information > transportation > economic.

In the information network, nodes with a high weighted degree are not only connected to cities at the same level, but can also take care of cities that are different from them. This enables the network as a whole to have more possibilities for connections and to exhibit a trend of more flatness. Moreover, the disassortative and diversified connection paths ensure the innovation and efficiency of information transmission between cities, which lends higher structural resilience to the network. The transportation network benefits from China's extensive traffic infrastructure, which has high disassortativity. While core comprehensive transportation hubs can exploit the advantage of their location, they also have a significant radiating effect on surrounding cities. There are even some cross-

regional connection cities. Therefore, the trend of network flattening is conspicuous and disassortativity is higher. Although the economic network as a whole shows the characteristics of disassortativity, it is weak. The connections between cities tend to be of groups or regions, reflecting strong assortativity with metropolitan areas as the core and weak disassortativity with edge regions. The inherent path dependence and regional “lock-in” of some cities is not only not conducive to the flow and innovation of economic elements, but may also lead to a larger gap between the rich and the poor; thus the network’s disassortativity is low.

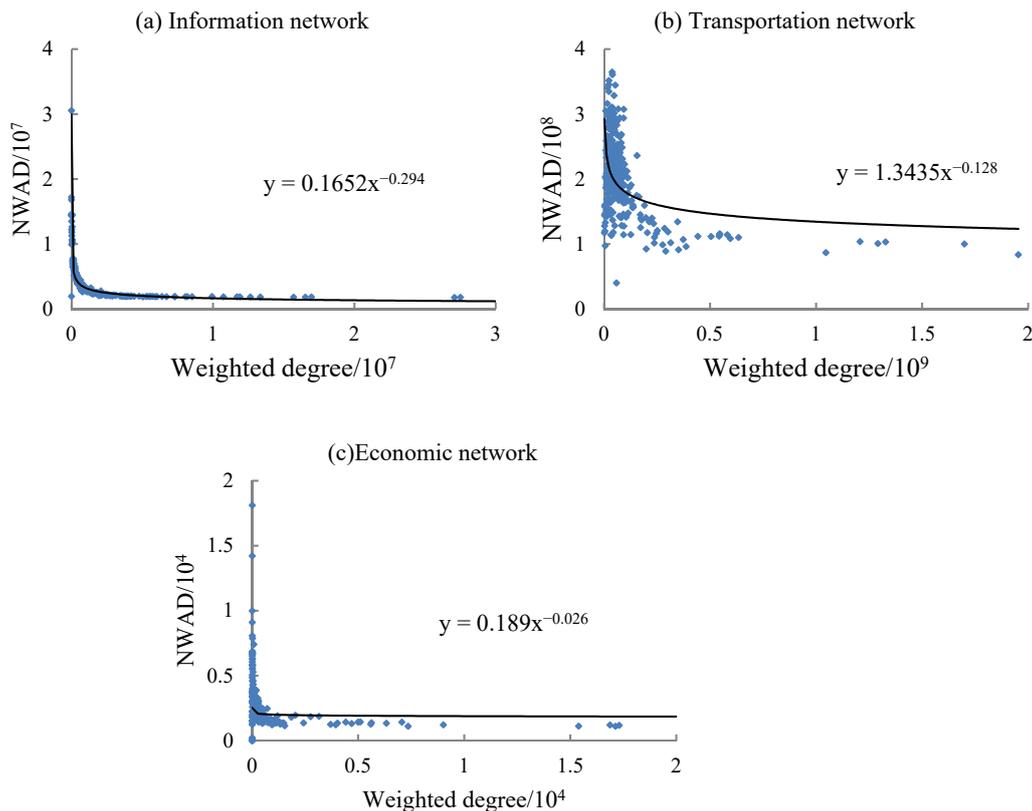


Figure 6. Weighted degree correlation of networks: (a) information network; (b) transportation network; (c) economic network.

4.3. Structural Resilience of Urban Networks under Disruption Scenarios

4.3.1. Transmissibility and Diversity of Urban Networks under Node Failures

When simulating network disruption, we mainly consider the impact of disasters or malicious attacks on the overall network structure. To reflect the impact of disasters that cause different urban nodes of regional networks to be interrupted, we simulated attacks on the 344 urban nodes of networks in China considered in this study. Changes in transmissibility and diversity (Figure 7) were obtained by simulating the failure of each city in the information, transportation, and economic networks. We ranked the 344 cities that had their network transmissibility affected, and found that the change trend of network diversity under node failure was very similar to that of network transmissibility. Only a few cities showed a preference for transmissibility or the impact of diversity. That is, when a disaster or crisis occurred, the network efficiency and the number of alternate paths were affected simultaneously. With an increase in the cost of urban interaction and communication, the resistance, response, and resilience of the network structure were weakened at the same time, exposing its vulnerability. On the whole, the order of transmissibility, from high to low, was information > economic > transportation, with network efficiency values of 0.51, 0.45, and 0.22, respectively. Similarly, the order of network

diversity, from high to low, was information > economic > transportation, with values of 85, 70, and 15, respectively.

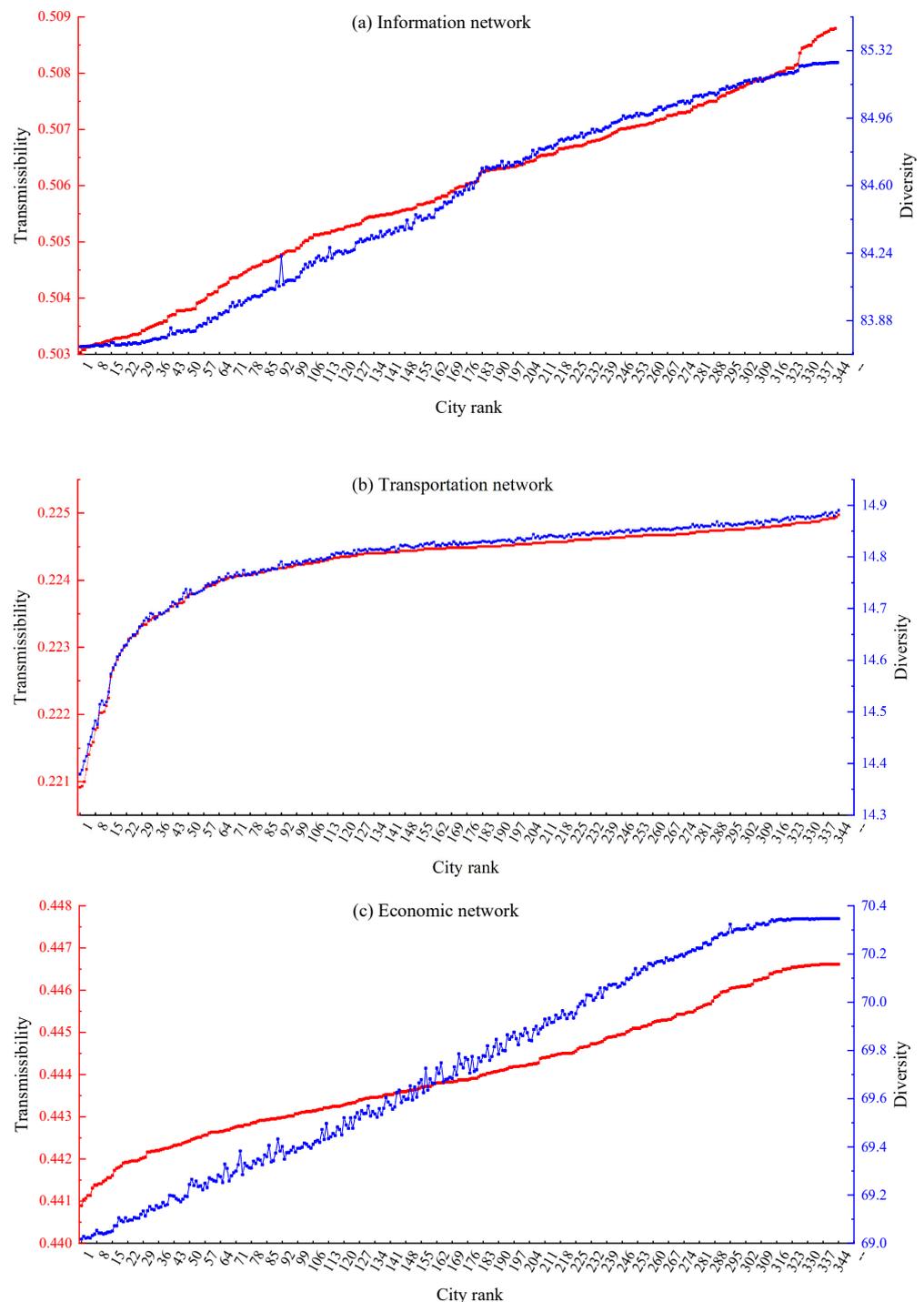


Figure 7. Changes of transmissibility and diversity in different networks after city failure: (a) information network; (b) transportation network; (c) economic network.

Figure 7a shows that after the interruption of urban nodes, the transmission efficiency of the information network was between 0.503 and 0.509 and the average number of independent paths was between 83.74 and 85.32. The proportion of cities higher than the overall transmissibility and diversity was 49.42% and 66.28%, respectively. The ratio of cities with values of transmissibility and diversity higher than the overall network was

49.42% and 66.28%, respectively. Figure 7b indicates that the transmission efficiency of the transportation network ranged from 0.22 to 0.225 after node failure, and the average number of independent paths ranged from 14.3 to 14.9. The ratio of cities with values of transmissibility and diversity higher than the overall network was 30.52% and 62.21%, respectively. Figure 7c shows that the transmission efficiency of the economic network was from 0.44 to 0.448 after node failure, and the average number of independent paths ranged from 69 to 70.4. The ratio of cities with transmissibility and diversity higher than the overall network was 53.50% and 63.95%, respectively.

To summarize, in the information network, the average number of independent paths between cities was the highest, as was the transmission capability of informational elements, with this providing more potential candidates to deal with dilemmas. This was followed by the economic network. When any node was interrupted, the number of available transfer paths was 70, that is, the exchange and transmission of elements between cities was slightly lower than that of the information network. Finally, the transportation network, impacted by the natural environment and the construction of transportation facilities, had the lowest transmissibility and diversity, and correspondingly the lowest structural resilience.

Cities affecting network transmissibility and diversity were ranked in order to more clearly reflect the status of the network structure after a city had been interrupted. The top ten and bottom ten cities are listed in Table 1. Surprisingly, the top ten cities in all three networks included Beijing, Shanghai, Chengdu, and Shenzhen, indicating that these four cities not only have indispensable network transmission functions in China's urban networks, but also may have the largest negative externalities. Second, besides Guangzhou some new first-tier cities (Nanjing, Chongqing, Suzhou, Wuhan, Tianjin, etc.) also have stronger links with other cities. These cities have greater advantages in terms of talent and resource aggregation, urban hubs, and urban activeness. However, because uncertainties, disturbances, and shocks facing regional development have been unprecedentedly complex, attention should also be paid to their spatial spillover effects.

(1) In the information network, Chengdu was the first to bear the brunt of disruption. When it was interrupted, the transmission efficiency of the network decreased from 0.505 to 0.503, and the average number of independent paths decreased from 84.764 to 83.74, which had the greatest impact on the network structure. Among the top ten cities, Beijing–Shanghai, Nanjing–Shenzhen, and Guangzhou–Hangzhou–Zhengzhou had the same impact on transmissibility. Xi'an and Wuhan also had a higher impact on transmissibility than other cities. In terms of diversity, Beijing and Zhengzhou rose in the ranking, Shanghai slightly declined, and Qingdao and Xiamen replaced Guangzhou and Hangzhou in the top ten. This indicates that among the top ten cities that affected the transmissibility and diversity of the information network, the top seven and their scores were very similar. The bottom ten were mainly distributed in the Qinghai–Tibet region, and interruptions to them had little impact on overall network transmissibility, but needed more attention.

(2) In the transportation network, Chongqing performed the most important transmissibility function in the network structure. When it was interrupted, the transmission efficiency of the network decreased from 0.224 to 0.22, and the average number of independent paths decreased from 14.839 to 14.379. Hangzhou, Wuhan, Nanjing, and Tianjin were among the top ten cities in the transportation network. The top six cities in terms of diversity were identical to those that affected network transmissibility. Wuhan ranked above Hangzhou, while Suzhou was in the top ten instead of Tianjin. The bottom ten cities included remote areas of Xinjiang as well as cities at the junction of some northeast and southern provinces.

(3) In the economic network, Beijing contributed the most to network robustness. Its failure resulted in decreases in the transmission efficiency of the network, from 0.444 to 0.44, and in the average number of independent paths, from 69.932 to 69.017. Suzhou, Tianjin, Chongqing, Dongguan, and Foshan ranked among the top ten cities affecting network transmissibility, while the failure of nodes in Shenzhen–Suzhou, Tianjin–Chongqing, and Dongguan–Foshan had the same impact on network transmissibility. Among the cities

that affected diversity, Shanghai and Suzhou rose in the rankings while Chengdu and Dongguan declined. Nantong and Wuxi were ranked in the top ten instead of Chongqing and Foshan, indicating that the ranking of the top seven cities that affected transmissibility and diversity changed only slightly. The bottom ten mainly included cities in Qinghai–Tibet and most cities along the edge of Xinjiang.

4.3.2. Urban Network Resilience under Maximum Load Attack

A maximum load attack involves attacking nodes of a network in descending order of weighted degree. It simulates the impact of a malicious attack (terrorist attack, military conflict, or other human forces) on regional networks; therefore, a small attack can lead to large changes in the network's topological structure. For example, a change in the original flow transmission or connectivity may lead to an increase in the length of the optimal path of transmission, or render it unusable. Figure 8 shows the result of network transmissibility and diversity in case of a maximum load attack changing the resilience of networks.

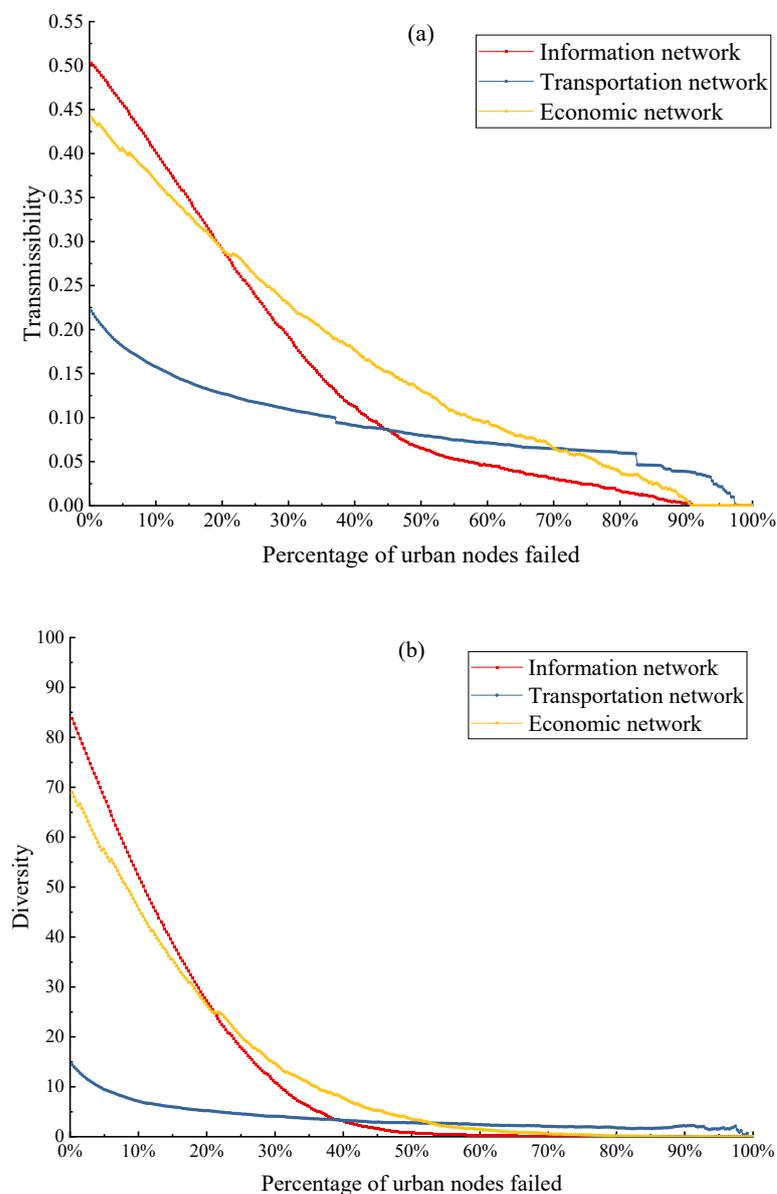


Figure 8. Changes of transmissibility (a) and diversity (b) in networks after maximum load attack.

Table 1. Top ten and bottom ten cities affecting network transmissibility (E) and diversity (V).

Rank Order	Information Network				Transportation Network				Economic Network			
	City	E	City	V	City	E	City	V	City	E	City	V
1	Chengdu	0.503	Chengdu	83.7408	Chongqing	0.2209	Chongqing	14.3793	Beijing	0.4408	Beijing	69.0172
2	Beijing	0.5031	Shanghai	83.7425	Shanghai	0.221	Shanghai	14.3878	Chengdu	0.4409	Shanghai	69.0204
3	Shanghai	0.5031	Beijing	83.7427	Beijing	0.2211	Beijing	14.4045	Shanghai	0.441	Suzhou	69.0217
4	Nanjing	0.5032	Nanjing	83.7431	Guangzhou	0.2214	Guangzhou	14.4371	Shenzhen	0.4411	Shenzhen	69.0232
5	Shenzhen	0.5032	Shenzhen	83.7433	Shenzhen	0.2215	Shenzhen	14.451	Suzhou	0.4411	Chengdu	69.0283
6	Xi'an	0.5033	Xi'an	83.7435	Chengdu	0.2216	Chengdu	14.4674	Guangzhou	0.4413	Guangzhou	69.0323
7	Wuhan	0.5034	Wuhan	83.7441	Hangzhou	0.2217	Wuhan	14.4755	Tianjin	0.4413	Tianjin	69.038
8	Guangzhou	0.5035	Zhengzhou	83.7446	Wuhan	0.2218	Hangzhou	14.4826	Chongqing	0.4413	Nantong	69.0383
9	Hangzhou	0.5035	Qingdao	83.7453	Nanjing	0.222	Suzhou	14.5135	Dongguan	0.4414	Wuxi	69.0412
10	Zhengzhou	0.5035	Xiamen	83.7468	Tianjin	0.2221	Nanjing	14.5146	Foshan	0.4414	Dongguan	69.0424
...
335	Nujiang	0.5083	Haidong	85.2509	Bazhou	0.2246	Jiamusi	14.8793	Tulufan	0.4463	Kashgar	70.3458
336	Changdu	0.5083	Diqing	85.2511	Jiamusi	0.2246	Yunfu	14.8794	Tarbagatay	0.4464	Aksu	70.3458
337	Diqing	0.5083	Hainanzhou	85.2511	Kashgar	0.2247	Huai'an	14.8795	Yushuzhou	0.4464	Guoluo	70.3458
338	Shennongjia	0.5084	Changdu	85.2523	Yunfu	0.2247	Tulufan	14.8798	Kezhou	0.4465	Tarbagatay	70.3459
339	Lhoka	0.5085	Lhoka	85.2541	Changjizhou	0.2247	Changjizhou	14.8827	Guoluo	0.4465	Yushuzhou	70.346
340	Ali	0.5086	Ali	85.2547	Meizhou	0.2248	Meizhou	14.8839	Aletai	0.4465	Kezhou	70.346
341	Haibei	0.5087	Haibei	85.256	Ningde	0.2248	Kashgar	14.886	Hotan	0.4466	Shihezi	70.346
342	Guoluo	0.5087	Guoluo	85.2562	Tulufan	0.2248	Jieyang	14.8858	Ali	0.4466	Hotan	70.3462
343	Kezhou	0.5088	Huangnanzhou	85.257	Jieyang	0.2249	Ningde	14.8865	Shihezi	0.4466	Ali	70.3466
344	Huangnanzhou	0.5088	Kezhou	85.257	Ili	0.225	Ili	14.8905	Aksu	0.4467	Aletai	70.3466

Figure 8a shows changes in the transmissibility of the information, transportation, and economic networks with the number of failed urban nodes as a percentage of the total number of nodes in each. Although the information network had the highest transmissibility, the curve of its rate of decline is the steepest. When 20% of urban nodes failed, the transmissibility of the information and economic networks was the same, 0.292. With the interruption of more urban nodes, the information network declined the fastest. When 45% of urban nodes failed, the transmission capacity of the information network was identical to that of the transportation network, 0.086. When 90% of urban nodes failed, the network's transmissibility dropped to nearly zero, similar to that of the economic network. With the continued interruption of nodes, the rate of decline was slightly slower for the economic network than the information network. When 70% of urban nodes failed, the transmission capacity of the economic network was the same as that of the transportation network, 0.065. The transportation network had the lowest transmissibility and the slowest speed of decline with the increasing number of interrupted nodes, and its transmission capacity decreased to zero when 98% of urban nodes failed.

Figure 8b shows changes in the diversity of different networks with increasing percentage of failing urban nodes. As the number of failed nodes increased, the resilience of the network decreased continuously, with the resilience of the information network decreasing more quickly than that of the transportation network. This trend was virtually the same as the decline in transmissibility. The difference was that when 50% of urban nodes failed, the diversity of the information network was less than one. This means that only half of the cities were interrupted, and there were nearly no alternative independent paths between them, indicating that information exchange between cities was seriously hindered. In the economic network, as the rate of interrupted urban nodes rose to 63%, the average number of independent paths between cities was less than one. The transportation network had a more robust structure. Only when 98% of urban nodes failed was the number of alternative independent paths in the network less than one. In other words, the interruption of large city nodes in a heterogeneous network caused by a malicious attack is more likely to cause overall network paralysis and then to lead to regional disaster. Although nodes with large loads had an absolute advantage in terms of information innovation, trade, and transportation in regional networks, they were the weakness of the network in the context of resilience. Therefore, the key to improving network resilience and stability is to prevent such nodes from being attacked.

4.3.3. Dominant and Vulnerable Nodes

To analyze the resilience of the comprehensive urban network based on multiple elements and identify the dominant and vulnerable nodes, the comprehensive intensity of connection was calculated. We normalized the intensity of information flow, population mobility, and economic connection and assigned the same weight (1/3) to the three networks in order to construct a comprehensive network matrix according to multi-element flow.

We simulated node failures of the comprehensive network in a manner similar to that above. The transmissibility and diversity of the overall network after each node was attacked were mapped to each city node in order to show it more clearly in space. As shown in Figure 9, the spatial pattern of the comprehensive network's transmissibility and diversity after the interruption of different nodes indicates characteristics of high spatial differentiation. Distinct from the information, transportation, and economic networks, Shanghai had the greatest impact transmissibility and diversity. When it was attacked, the transmissibility of the comprehensive network decreased from 0.1998 to 0.1963 and the diversity decreased from 11.6855 to 11.2773.

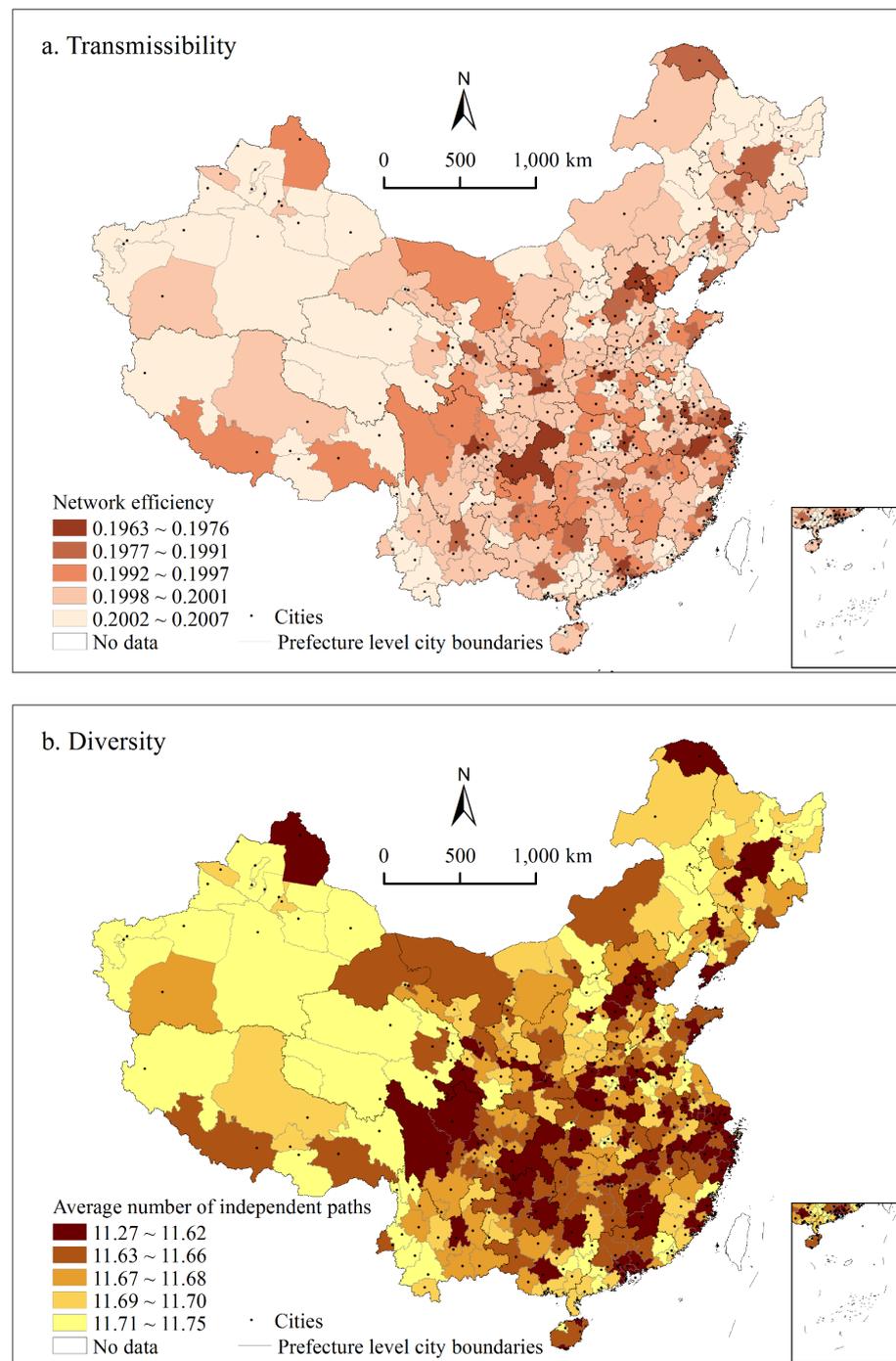


Figure 9. Comprehensive network's (a) transmissibility and (b) diversity after node failure.

The identification of dominant and vulnerable nodes was based on the transmissibility and diversity of the comprehensive network. Nodes whose network transmissibility and diversity were at the first level were identified as dominant nodes, while those at the fifth level were identified as vulnerable nodes. Twelve dominant nodes and 93 vulnerable nodes were identified (Figure 10). Specifically, as key nodes supporting the network structure, the dominant nodes were typically cities with high centrality and control power, including Shanghai, Beijing, Chongqing, Guangzhou, Shenzhen, Chengdu, Hangzhou, Wuhan, Nanjing, Tianjin, Zhengzhou, and Xi'an. These cities are highly economically developed and are mature transportation hubs. Moreover, they each have a distinct geographical advantage in terms of the distribution and allocation of resources, and radiate economic

benefits to surrounding cities. If these cities were disturbed, it would have a major impact on the entire network structure. Therefore, the stability of these urban nodes is important to ensure the resilience of China's regional network.

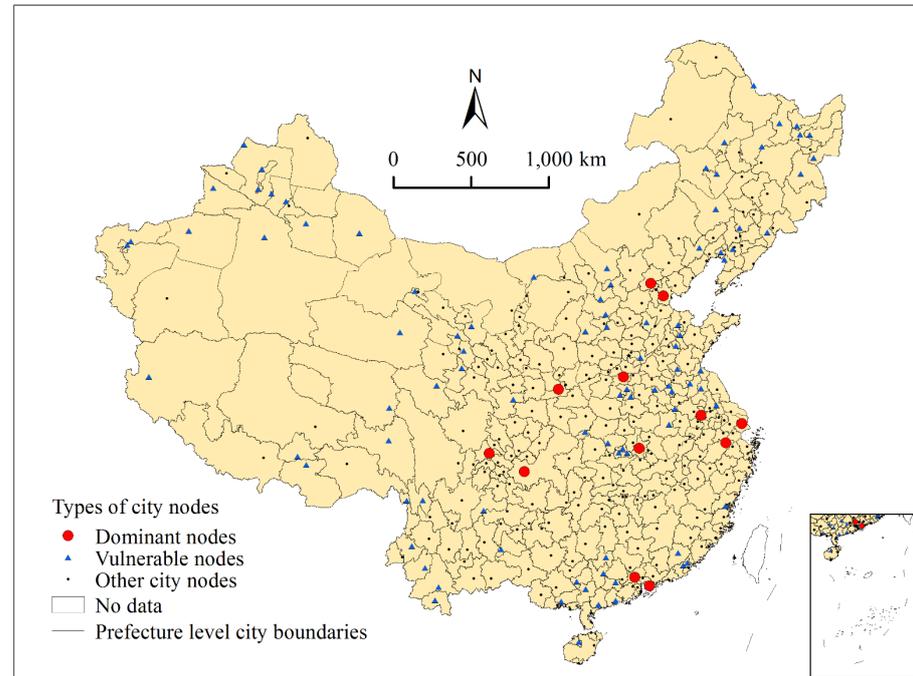


Figure 10. Spatial distribution of dominant and vulnerable nodes.

Most vulnerable nodes were small and medium-sized cities or cities dominated by ethnic minorities in northwest and northeast China. Their spatial distribution was characterized by agglomeration. When a node was attacked, the regional “lock-in” effect formed by spatial agglomeration might not have had a significant impact on the larger regional environment. However, a shortage of resources, an imbalance of supply and demand, and unstable development were observed within small regions. A few scattered vulnerable nodes were also noted (Hengshui, Puyang, Zaozhuang, Ningde, Taizhou, Zhaotong, and Longnan), often far from provincial capitals, along the edges of provinces or at their junction. Restricted by administrative barriers and imperfect transportation infrastructure, these cities have become the so-called untouched cities. However, they may have great potential for development.

5. Discussion

In an increasingly globally-connected world, the regional resilience of networks has become a recent trend of research. A growing number of researchers are acknowledging the importance of understanding urban network resilience. However, the literature still lacks a clear system for measuring network structure resilience for a better understanding of regional resilience. Moreover, few studies have examined the resilience of urban networks, and most of them have focused on the relationships between cities within urban agglomerations while ignoring the effect of the overall regional environment. The measurement of urban network structure resilience in China conducted in this study can not only help clarify the relationships between cities but also further expand and enrich the theoretical framework of the resilience of the urban network system and support the resilient and sustainable development of regions. Moreover, simulated interruptions of urban networks can be used to understand the capacity of the urban system in the face of crisis. This provides a scientific reference for urban organization networks in other regions of the world.

5.1. Research Significance and Signatures of Urban Networks

In the process of assessing the resilience of the urban network structure, constructing the information and transportation networks based on space of flows big data helped us go beyond the statistical data which have commonly been used in past work, and enabled us to construct multi-source urban networks at a large regional scale. Against the background of the space of flows, the network connections between cities must be considered in regional urban development. Although territorial space planning has begun to focus on the resilience of regions and cities in recent years, it is only in the stage of theoretical exploration. This research on the structural resilience of multi-source urban networks provides further insight for better understanding of regional systems and their spatial structures. On the one hand, it can enhance understanding of the current interaction relationships of regional space from a global perspective, and the spatial distribution patterns of different urban networks can also help in examining the implementation of relevant regional planning. On the other hand, our evaluation of network structure resilience can not only provide a reference for relevant regional development planning in the future, but is also conducive to promoting unified territorial spatial planning and conforming to the current concept of multi-planning integration.

The distribution patterns of the information, transportation, and economic urban networks of 344 cities in China correspond to flat rhombus-shaped, rhombus-shaped, and “arrow fitted to the bowstring”, respectively. This spatial differentiation indicates that a single-element network is not enough to represent the spatial characteristics of an entire urban network. There are weaknesses in a single-element network, and the virtues of multiple networks could make up for them. For example, the supplementing and renewal of resources could be realized in many other ways to promote the exchange of elements between cities. Therefore, the integration and superposition of multi-source networks should be considered in future work. In addition, there are significant differences in the topological structure and characteristics of the information, transportation, and economic networks in China.

The information network has the strongest disassortative connection and high hierarchy. While leading in terms of the heterogeneity and openness of surrounding cities, core cities can radiate benefits to less developed cities to ensure innovation and the flow of resources. It is necessary to improve or guarantee network structure resilience. The transportation network has the structural characteristics of high heterogeneity and the lowest hierarchy, indicating that its connections and objects are relatively complex and heterogeneous, and the network is dense and flat. However, a lack of leading nodes makes it difficult to improve overall network capacity and tends to lead to a low level of balanced development.

The economic network has the highest hierarchy and the lowest disassortativity, which means it may incur such risks as speculative urban development, solidification of connection paths, and global structure closures caused by regional “lock-in” and path dependence. For such less-developed urban networks, comprehensively improving the intensity of the connections among different hierarchical networks is often key to enhancing regional resilience. Further, the urban networks showed strong cross-regional interactive relationships, presenting a top-level urban network structure. It has been shown that previous development planning, which mostly adopted the mosaic concept, may not apply to the current development background of space of flows and networking. The flow of population, capital, and even some negative elements will spread to larger regions along the urban network while spreading in local space, and show stronger diffusion in other metropolitan areas due to rapid element exchange. Accordingly, at a time when the COVID-19 epidemic has not yet been fully controlled, governments and policymakers should not only pay attention to the spatial interaction capabilities of administrative boundaries or urban agglomerations, but also focus on other, stronger interactive areas in order to prevent negative externalities as much as possible.

Our measurement of the urban network hierarchy and assortativity, based on weighted degree and NWAD and drawing on complex network theory, revealed the spatial structure of the network and reflected the functional differentiation and imbalance in the network structure. Crespo et al. [16] and Peng et al. [21] used only degree distribution and degree correlation to measure the connections between urban nodes. They ignored the elements passing through the arcs, especially the population flow between cities, which can bring positive or negative externalities, and might thus have overestimated or underestimated the capacity of nodes in the urban network. Therefore, the construction of multi-perspective urban networks herein based on multi-source data at a large regional scale and an assessment of their resilience not only contributes to understanding intercity relationships but is also conducive to avoiding the one-sidedness that arises from using a single element. Calculating the hierarchy and assortativity of networks by considering a weighted factor can not only provide more numerous and practical case references for examining the topological structure of networks, but can also be a measure of the functional resilience of urban networks to some extent.

The cities that had the greatest impact on the structural resilience of the information, transportation, and economic networks varied depending on their functions in these networks. Chengdu, the leading city in the information network, has attracted considerable research attention because of its unique location advantages and famous tourist destinations. Chongqing, the major labor-exporting city [9], is a developed transportation hub. This contributes to the resilience of the transportation network. Its location plays a major role in connecting the south to the north and the east to the west. Beijing, a national political and cultural center, has been attracting innovation and the exchange of elements. In addition, the established first-tier cities (Shanghai, Guangzhou, and Shenzhen) and some new first-tier cities (Nanjing, Suzhou, Tianjin, Wuhan, etc.) have greater advantages in talent and resource aggregation, urban hubs, and urban activeness. However, attention should also be paid to these cities' spillover effects.

The results of transmissibility and diversity under interruption scenarios revealed differences in the resistance of city nodes in different networks to interventions. However, when faced with disaster or malicious attack, the failure of city nodes in a network had a synchronous impact on network transmissibility and diversity, which is consistent with the results obtained by Peng et al. [21]. Furthermore, the information network was more resilient than the economic and transportation networks, which face lower risks in case of malicious attack owing to low transmission efficiency. In other words, interruptions of large city nodes in heterogeneous networks will likely cause network paralysis because of the rapid transmission and accumulation of risk, highlighting the vulnerability of the network. Therefore, the failure of dominant nodes should be prioritized, emergency systems should be strengthened, and risk prevention mechanisms should be enhanced in order to ensure the wide and smooth flow of elements in the network. Vulnerable nodes should seek to improve their resistance to risk, promote the circulation of elements, and enhance node centrality in order to ensure regional connectivity.

5.2. Suggestions for Improving Regional Resilience

In light of the dual impact of environmental changes and human activities, effectively coping with the cumulative risks or impacts of economic, social, and environmental factors has become a common concern of the international community. With the transformation of local space to space of flows or network space, the relationships between cities and regions are increasingly close. As the main force of national economic development, economic zones or urban agglomerations play an extremely prominent role. However, multivariate and frequent element flows may lead to regional disturbance or collapse due to negative external effects even while strengthening regional relations. In this context, although current territorial spatial planning has paid attention to urban resilience, its exploration of regional resilience under cross-regional connections led by the space of flows is far from enough, and there are no feasible measures. Therefore, regional integration and

coordinated development must be considered in future regional planning and building. That is, regional or urban networks must have the resilience to resist external interference in order to ensure regional coordination, stability, and sustainable development. The resilience of a network is significantly influenced by its topological structures, which affect its function [55]. Moreover, the connections between cities in the network restrict their hierarchical positions in the network. Given the different aspects of the urban network structure, strategies and suggestions for optimization are proposed here.

First, the excessive concentration or decentralization of urban rights is not conducive to the formation of a resilient network structure. The economic network, with the most significant hierarchy, has the strongest core cities (groups), and regional path dependence is most easily formed in it. For example, the Beijing–Tianjin–Hebei, Yangtze River Delta, Pearl River Delta, and Chengdu–Chongqing urban agglomerations have core cities with strong economic development, including Beijing, Shanghai, Guangzhou, Shenzhen, Chongqing, and Chengdu. However, while promoting the robust development of a regional economic network it is easy to ignore the radiation of benefits to surrounding small cities, which is unfavorable for the formation of a resilient structure in a large regional network. Therefore, it is necessary to establish a better regional cooperation mechanism and promote the transformation of the hierarchical system of jurisdiction to a network system. On the one hand, more connections could be established between central and more peripheral cities, and on the other hand, a flat network development mechanism with complementary functions and cross-regional cooperation could be formed. The hierarchical system within urban agglomerations should also be improved. Normally, the demarcation of the scope of urban agglomerations is not economically based, but depends on the relative spatial location of cities, that is, the administrative boundaries. Although some core cities are prioritized in terms of development over peripheral cities, today, driven by globalization and informatization, the integration of regional development is crucial. While ensuring the leading role of core cities, surrounding cities should also be considered in order to avoid emphasizing the core and neglecting the edges.

Second, strengthening the functional mixing of disassortative networks could promote the rapid exchange and transmission of elements among cities, thereby enhancing the resilience of the network structure. The economic network has a relatively stable economic development model due to the influence of distance attenuation. Thus, under the new normal, it should seek more open urban exchanges and cooperation. While striving to promote the rapid development of the internal economy of urban agglomerations, it should also pay attention to strengthening interactions with nodes with low degrees, especially in the central and western regions, in order to form more economic hubs and improve the overall economic environment. For the transportation network, restricted by the natural environment and public infrastructure, improvements in aviation, railway, and highway transportation facilities could significantly increase the probability of population migration between cities. In addition, attention should be paid to the planning and construction of cross-provincial urban and rural traffic systems, and cities should be interconnected through continual improvements in the relevant infrastructure and service facilities. This would improve network structure resilience. For information networks, with high heterogeneity in terms of resource allocation, too much attention is still being paid to large cities at the cost of small and medium-sized cities along the edges, which are restricted by provincial administrative barriers. This phenomenon is not conducive to the average distribution of resources such as information and technology, and can lead to the long-term legacy of “dead corner” cities, which renders the network vulnerable. In urban networks, disassortative connections between core cities and burgeoning and peripheral cities increase the possibility for opportunistic behaviors and avoiding conformist behaviors, thereby promoting the learning and innovation of all city nodes in the network. Therefore, strengthening cooperation and coordination between provinces and regions and assisting nodes with low degrees are key to enhancing the resilience of the network structure.

Third, high transmission efficiency and a variety of independent paths are the premise for ensuring normal operation of the network under external disturbance. Due to differences in levels of knowledge, distance from national centers, and cultural differences, China should advocate the planning and construction of regional and sub-regional science centers in areas of the northwest and some edge cities (vulnerable nodes). For example, such centers could be considered in Lanzhou, Kunming, Xining, Yinchuan, and other cities in order to provide a larger and broader network of scientific cooperation based on the prior integration of local regions. This would help break administrative barriers and move towards real regional integration, and in turn would improve innovation and the dissemination of scientific knowledge, information technology, and other resources. More importantly, establishing a sound emergency plan and implementing measures to form a scientific, open, and efficient regional network environment could improve the efficiency of resource utilization and is the premise for ensuring stable and sustainable development of the regional network.

Internationalization and informatization are general trends nowadays, and communication and cooperation between cities will be the focus of social development in the future. For long-term sustainable development, it is necessary to learn from the experience of a resilient network and to create robust network structures in order to resist and adapt to external shocks and pressures. However, in the process of pursuing efficient exchanges between cities, we should also pay attention to the diffusion of unfavorable factors between regions, such as viruses and terrorism.

5.3. Limitations and Directions for Future Research

Although this study constructed three urban networks in China, there were a few limitations in the data acquisition. On the Baidu search index, different search keywords such as “Beijing” and “Beijing city” yielded different results. To guarantee consistency of the search results, we eliminated the word “city” and used only the city name as a keyword. Moreover, although the Tencent location service collects data from various smart clients, there are omissions in terms of representation; for instance, people without mobile phones, such as the elderly and children, are not considered. Furthermore, for privacy-related reasons, Tencent does not disclose the social attributes (profession, gender, and age) of the given population. Thus, we could not obtain the travel routes and purposes of travel for all parties considered [39]. Nevertheless, such data can still be used to construct urban transportation networks in large regional environments. Errors and lags compromised the social statistics data to some extent, which limited the selection of the research period.

On the other hand, substitutable data are so difficult to obtain that we could not construct an economic connection network based on flow space data; thus, we adopted the gravity model. In addition, when identifying the dominant and vulnerable nodes, the comprehensive urban network was constructed based on the elements of information, transportation, and the economy. However, in the contexts of globalization and localization, the urban network of virtual and real interactions has a wider connotation. Hence, the interaction of elements in actual complex social networks should not be ignored.

Although the above procedures are so complex that it is inherently difficult to perform measurements with limited indicators, it is indeed a meaningful attempt. Moreover, owing to the massive amounts of data, this study only evaluated the structure resilience of information, economic, and transportation networks in 2017. Second, the network spatial pattern of some local regions or urban agglomerations was not exhaustively demonstrated because of the great hierarchical differences in connection intensity between cities. Third, the evaluation of network structure resilience herein focuses more on the positive externalities of urban networks and lacks quantitative measurement of the negative externalities, and thus qualitatively describes them based on the analytical results.

Whether the spatial structure of an urban network is resilient to disturbances is related to the stable and sustainable development of the regional urban system. In the future, research on the resilience and evolution of integrated urban networks using multi-

source datasets based on long time series could offer many rewards, especially when local and global interactions are combined. Furthermore, the influence factors and formation mechanisms of complex urban network structure resilience need to be further examined and discussed. Last but not least, there should also be a focus on quantitative evaluation and measurement of network externalities.

6. Conclusions

This study established a framework to measure network structure resilience and quantitatively assessed the structural resilience of China's urban networks from the perspective of their structural characteristics, with the goal of advancing sustainable and healthy regional development. This framework can also be used to measure local and global urban relationship networks. However, the gravity model used to construct the economic network in this study may not be suitable for global regions with large differences in geographic contexts. Baidu search index, Tencent location service, and social statistics data were obtained to construct information, transportation, and economic connection networks, respectively. The methods of social network analysis, weighted degree and weighted degree distribution, the NWAD, and weighted degree correlation were used to measure the structural characteristics of the networks from the perspectives of hierarchy and assortativity. We also simulated interruptions to the networks based on node failures and maximum load attacks, and measured their structural resilience in terms of transmissibility and diversity. The main conclusions are as follows:

- (1) The pattern of spatial distribution of the information, transportation, and economic networks of cities at the prefecture level and above in China in 2017 is characterized by density in the east and sparsity in the west. Compared with the transportation network, the information network is more active in the exchange of elements among cities because it is less limited by region and distance. Even so, it tends to be more active in developed cities or regions. The economic network is affected by distance attenuation, which reflects the conservative exchange of elements among cities, and its cross-regional interaction is weak.
- (2) The information, transportation, and economic networks have different structural characteristics in terms of hierarchy and disassortativity. The information network, with a high hierarchy and the strongest heterogeneous connection, has the highest transmissibility and diversity, whereas the economic network has the highest hierarchy and the lowest disassortativity. The transportation network has high heterogeneity, but its hierarchy, transmissibility, and diversity are the lowest.
- (3) In the face of an external impact or interference, a highly heterogeneous network is more likely to experience structural shocks owing to its cross-regional urban links. Core cities can use their control and competitive advantages to stimulate regional conformity and to improve the overall efficiency of the network. Moreover, numerous and diversified heterogeneous connections can activate the vitality of the functional complementarity of the network and directional cooperation by softening path inertia between core cities and general nodes. However, this also exposes the vulnerability of the network in a complex regional environment.
- (4) Identifying dominant and vulnerable nodes can help accurately determine the motivation of network structure resilience. When the network is paralyzed in the case of a crisis, as the core cities of China's urban network, 12 dominant nodes seriously interfere with the resilience of the network. Therefore, government officials should try to reduce the possibility that dominant nodes will fail and should improve their response capacity by strengthening the construction of emergency systems and risk prevention mechanisms. As edge nodes, the 93 vulnerable nodes should focus on enhancing resistance to risk by promoting the circulation of elements and by enhancing their centrality. Furthermore, it is necessary to strengthen the relationships between vulnerable nodes and adjacent regions in order to form a more resilient intraregional structure.

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