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RESEARCH ARTICLE

Structural resilience analysis of rural networks based on complex network theory

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Abstract Amidst the rapid pace of urban development, rural communities continually face the challenges posed by erratic natural disasters and human-induced disturbances. Evaluating and improving the resilience of rural areas is crucial for achieving sustainable development. Examining the rural network framework serves as a method to achieve rural resilience. This study established a contact network encompassing 13 villages in Shiba town, Mingguang City, through the collection of time-distance data, questionnaire interview data, and map vector data to examine the spatial patterns of the rural network. The examination of structural resilience was conducted through the framework of complex network theory. The examination of the network's transitivity and diversity through the frameworks of hierarchy, matching, transitivity, and aggregation reveals its resilience to disruption simulations, such as node failure. The findings indicate that the network exhibits a configuration marked by a dense central region, sparse connections in the north, and a lack of connectivity in the south. The network exhibits a flat structure, with nodes that are relatively uniform in nature. The network exhibits significant disassortativity, classifying it as a disassortative network, where villages with higher node degrees tend to connect with those having lower node degrees. The local transitivity of the network is significantly elevated, with approximately 90% of settlements necessitating just one transfer to establish direct communication. The network exhibits significant clustering effects, marked by robust connections among villages and a few isolated node villages. The transitivity of the network and its diverse spatial patterns show markedly different characteristics when subjected to interruption simulation. The study identified two primary nodes and one susceptible node. The findings from the study precisely reflect the characteristics of the rural network. This can provide theoretical perspectives for analyzing the resilience of rural network structures and support decision-making in rural planning and development.

Keywords rural resilience, network structure, complex networks, disruption simulation, Shiba Town

1 Introduction

The worldwide analysis of the traits and evaluation standards of resilient rural regions has been continuous, emphasizing their capacities in catastrophe avoidance, mitigation, recovery, and reconstruction (Sun et al., 2023). This study has concentrated on alleviating rural poverty and implementing sustainable development strategies. Researchers have conducted comprehensive studies on the multiple factors influencing rural resilience and have utilized case studies to examine different approaches for assessing the resilience of rural regions (Yang et al., 2022). The theoretical frameworks supporting these investigations encompass the "disturbance-response" model, the socio-ecological framework, the adaptive cycle model, and additional established theoretical constructs. The findings of this research have been significant in shaping sustainable rural development plans. Scientists typically commence their research at the rural community level, selecting representative villages as case studies and performing thorough evaluations and analyses of resilience across various dimensions, guided by the conceptual framework of resilient communities (Tao et al., 2025). The principal research methodologies include structured interviews, semi-structured interviews, focus group discussions, participatory observation, and survey questionnaires. In recent years, scholars have increasingly integrated resilience theory into rural geography, analyzing the

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conceptual implications of resilient rural areas. Their assessment of rural resilience has primarily concentrated on individual village case studies employing subjective evaluation frameworks, occasionally neglecting the objective interconnections among villages that significantly influence the overall resilience of the rural system (Li, 2023; Turečková et al., 2024). A notable deficiency exists in the literature regarding the impact of network structures derived from specific villages and their interconnections on the overall resilience of rural areas. The characteristics of network structure—encompassing size, quantity, location, strength, and degree of aggregation of nodes and connections—are crucial for understanding regional functionality and resilience. Consequently, network structure serves as a fundamental basis for delineating spatial network patterns and evaluating the resilience capacity of rural regions, leading to the development of the concept of rural network structure resilience (Jia, 2018; Zhou and Gu, 2025).

The term "structural resilience of rural networks" can be initially defined as the capacity of a regional rural network to withstand external disturbances and the influence of the network's structure on the region's ability to recover, sustain, or improve its inherent systemic attributes and essential functions (Peng et al., 2018). The structural resilience of rural networks demonstrates a traditional kind of regional resilience within a geographical context, notwithstanding the current research shortcomings in this area. Various aspects of network resilience have been investigated in regional contexts in international research, with Lozano et al. (2007) utilizing quantitative modeling to assess the relationship between network diversity and the resilience of regional innovation networks. Reggiani outlines the comprehensive framework for analyzing network resilience in transportation systems and explores stochastic and scale-free networks. Summarized the comprehensive research framework on network resilience in transportation systems and analyzed stochastic and scale-free networks (Reggiani, 2013). Cavallaro et al. (2014) incorporated social network attributes into the HSPN model to assess the ecological resilience of urban systems. Peng Chong examined the city cluster in the middle Yangtze River region, developed an urban network through economic, informational, and transportation linkages, utilized Gephi to assess structural resilience and spatial characteristics, and proposed an optimization strategy (Peng et al., 2018). Additionally, he performed an analysis of the passenger network within the city cluster in the central Yangtze River region, constructed a network using highway and railway passenger transport data, and applied complex network theory to examine the resilience attributes of the overall network and its individual nodes in reaction to external disturbances, while exploring the key factors influencing the network's resilience (Peng et al., 2019). Hou Langong analyzes the Chengdu-Chongqing urban agglomeration and constructs a transport and information connectivity network employing railway passenger transport data and Baidu index big data from 2014 and 2018. We first examine the network density and spatial patterns through complex network theory and Ucinet tools, then assess static indicators of structural resilience, such as hierarchical, matching, transmission, and agglomeration. We compare the changes across two time periods and ultimately present optimization recommendations (Hou and Sun, 2022). Current research primarily adopts a singular perspective, focusing on aspects such as information, transportation, economy, ecology, or innovation, and is deficient in a comprehensive approach. The study data mostly depend on static panel data, such as the social statistics yearbook, and are devoid of dynamic flow element data. In conclusion, while evaluating the resilience of network structure, pertinent academic research typically depends on indicators that illustrate the properties of network structure within the framework of complex networks theory. Nevertheless, they have yet to establish a cohesive evaluation system. Few instances of comprehensive assessment mostly concentrate on metropolitan networks, detailing their static attributes with a very restricted set of measuring indicators. Nonetheless, there is a significant deficiency of study concerning rural networks, their dynamic attributes, and complete measuring tools for indicators (Yu et al., 2024).

Rural environments are intricate systems composed of various elements and sophisticated procedures. Complex network theory is a research framework that examines the intensity of interactions among the components of the study topic and the attributes of the network from a systematic viewpoint. It offers multiple metrics for evaluating network structural resilience and simulates the spatial and temporal development of network structural resilience. It integrates and presents multidimensional and diverse data as a "graph", offering an accessible and interactive analytical instrument for evaluating network structural resilience. Rural networks can be examined through the lens of complex network theory as intricate systems.

This paper utilizes Shiba Township of Mingguang City as a case study to accurately represent the complexities of villages. It identifies four primary dimensions—living environment, location conditions, facility systems, and farmer characteristics—along with 20 specific indicators to develop a village quality evaluation system. This system is employed to refine the gravity model, which subsequently facilitates the construction of a rural network. The spatial configuration of this network is analyzed through complex network theory, focusing on the network's structural robustness and its variations under disruption simulations to elucidate the characteristics of the rural network's structural resilience. This paper proposes recommendations to enhance the structural resilience of rural networks, intending to offer theoretical insights for the examination of rural network resilience and the decision-making processes in rural planning and development.

2 Research methods

2.1 Study area

Shiba Town is located in the center of Mingguang City, Chuzhou City, Anhui Province. It administers 13 communities and encompasses an area of 249.280 km^2. The town's population is 50.61 million individuals. Shiba Street serves as the socio-economic hub of the town, while Jinli Village, Su Ying Village, and San Guan Village have established their markets, considerably enhancing the region's socio-economic activities. Nonetheless, the town's transportation infrastructure is somewhat inadequate, with Provincial Highway 309 serving as the primary transportation conduit. The rural roads are inadequately maintained and have low road density. The town possesses ample arable and forested territory, together with relatively scattered settlements (Fig. 1). This study regards the administrative village as the fundamental unit of evaluation. Owing to the distinct geographical characteristics of Shiba Reservoir, Lindong Reservoir, and Laojiashan Forestry, coupled with the absence of pertinent data, these locations are provisionally omitted from the study's scope. Consequently, 13 evaluation units corresponding to the village areas are incorporated in the study.

2.2 Data sources

This study utilizes time-distance data, questionnaire interview data, and map vector data. The time-distance data is sourced from the Baidu Data Platform's Route Planning Service Module, which offers the least time distance for all driving route planning options based on the coordinates of the villages' starting and ending sites. The interview data was obtained from 13 surveys administered to the government. These questionnaires encompass several elements including demographics, per capita income, major industries, geographical resources, public service infrastructure, and construction quality. The vector map data is derived from the Third National Land Survey database, encompassing details on land classifications, topography, administrative regions, and additional information.

2.3 Research framework

This study employs complex network theory to establish a framework for assessing the robustness of rural network structures. The structure has three primary steps. Firstly, the rural connection network is established with the modified gravity model, which incorporates rural quality and temporal distance data. This network illustrates the interconnections among several rural regions in Shiba Town. Secondly, the structural resilience of the rural network is examined via the lens of complex network theory. The toughness perspective is employed to examine the resilience and susceptibility of the network structure. Ultimately, computer-simulated attacks assess the variations in the resilience of the network structure during disruption simulations to pinpoint the critical

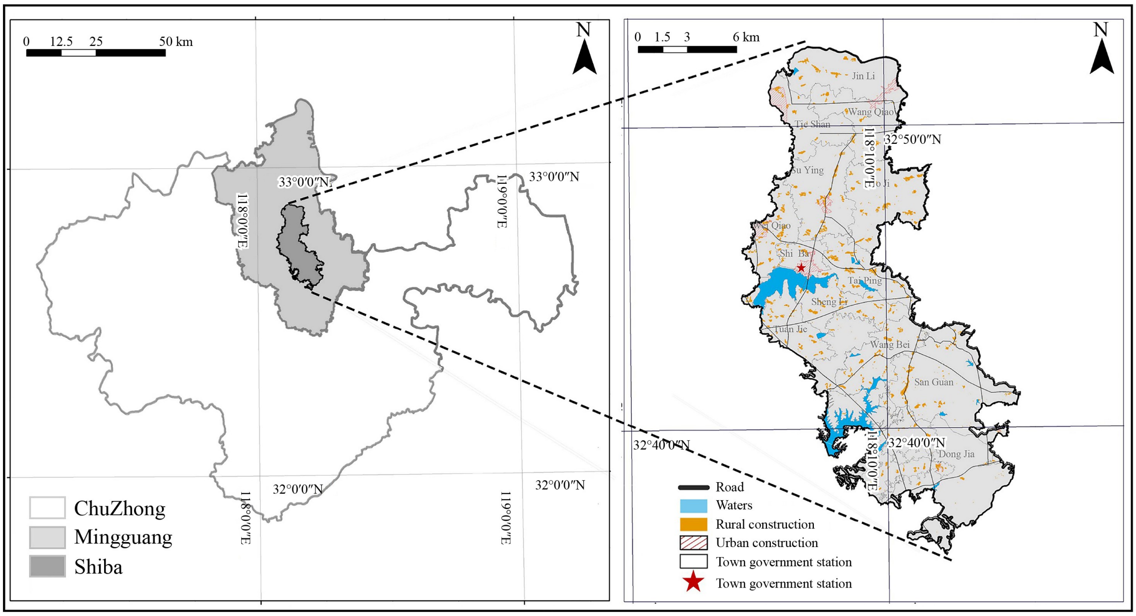


Fig. 1 Geographical location of the study area.

(dominant) and vulnerable nodes within Shiba Town's rural network, and optimization measures are suggested to improve its resilience accordingly. Figure 2 provides a visual representation of the framework and its components.

2.4 Construction of network structure

2.4.1 Modified gravitational model construction

The gravity model is widely utilized to forecast the intensity of connections between places based on gravitational principles. It evaluates factors such as quality and distance to ascertain regional connection (Wang et al., 2014). Nevertheless, current research frequently depends on singular variables such as population size and economic aggregates to signify the quality of communities (Su et al., 2018a). Furthermore, they employ Euclidean distance or raster analysis to determine the distance between villages, which may not adequately represent the true conditions of the communities (Su et al., 2018a, 2018b; Su and Wang, 2018). This work presents a revised gravity model that integrates quality enhancements and distance measurement to overcome these constraints and more accurately reflect the realities of villages. The evaluation of villages is based on four criteria: the living environment, locational conditions, infrastructure, and the attributes of the farmers. This thorough technique offers a more complete knowledge of village quality. Moreover, the distance between villages is converted into a time distance through the concept of spatial accessibility. This method considers elements such as transportation infrastructure and journey duration, which are essential for assessing connectedness among communities. Through the integration of these adjustments, the revised gravity model offers a more precise depiction of the interconnectivity across villages and improves comprehension of the rural network framework. The enhanced gravity model can be articulated as follows:

$$R_{ij} = G\frac{M_i M_j}{{D_{ij}}^k}, \tag{1}$$

where G is the medium constant, usually taken as 1; $M_i$and M_j is the mass of i and j villages; D_{ij} is the commuting time between villages obtained through the Python language based on the Baidu map data platform; k is the friction coefficient of the commuting time, which denotes the speed of gravitational decay, and concerning the existing relevant studies, k is taken as 2.

2.4.2 Measurement of village node quality

The quality of village nodes is influenced by environmental, economic, cultural, and various other factors. This study, grounded in the present circumstances of Shiba Township and adhering to the principles of scientific rigor, systematic methodology, accessibility, and comparability, along with the index frameworks of prior research (Su et al., 2018a, 2018b; Su and Wang, 2018), ultimately identifies four target dimensions: living environment, locational attributes, facility infrastructure, and characteristics of farming households, as well as 20 index metrics to develop the village quality assessment system (Tables 1–4). The residential setting mirrors the village's natural surroundings. The living environment

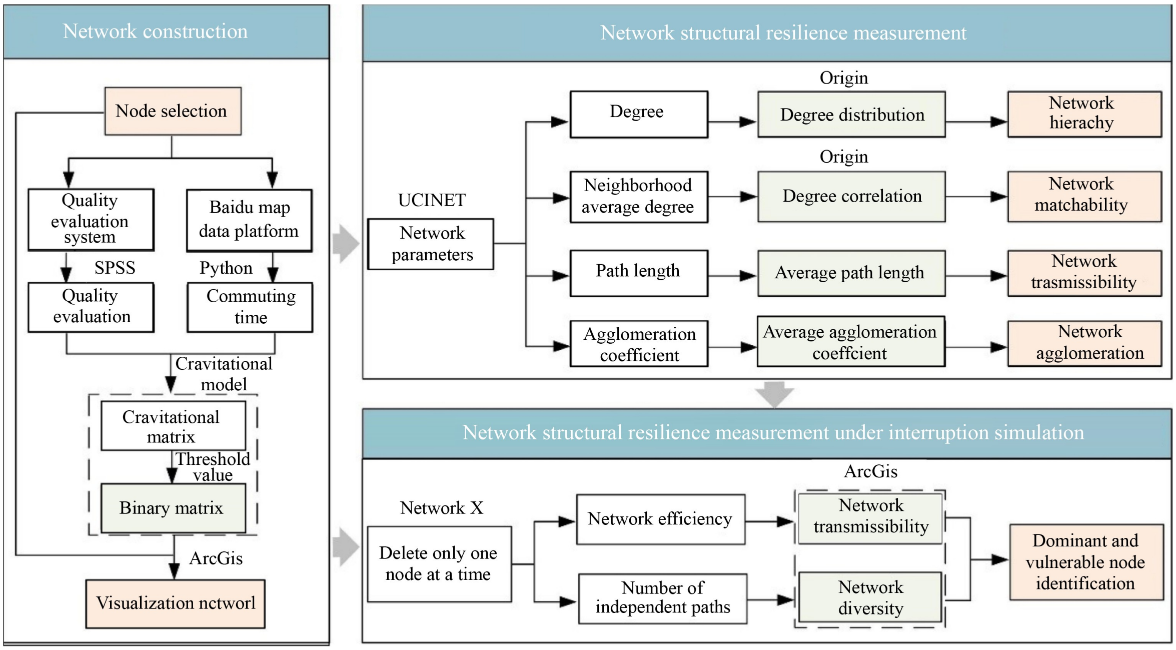


Fig. 2 Research framework.

Table 1 Indicator system for measuring village quality (living conditions)

Index layer	Index content	Weight value
Administrative village scale	Administrative village jurisdiction area/hm^2	0.0148
Topographic position	Reflect two terrain factors: elevation and slope	0.0137
Building quality	Reflect the building structure: concrete = 1, brick-concrete = 0.75, Brick = 0.5, adobe = 0.25	0.0048
Water area ratio	The ratio of water area to administrative village area	0.0089
Proportion of forest and grass area	The ratio of forest and grass area to the administrative village area	0.1270

Table 2 Indicator system for measuring village quality (location condition)

Index layer	Index content	Weight value
Distance from industrial park	Average nearest distance to all industrial parks in the township /km	0.0098
Distance from the town center	The nearest distance from the center of the township /km	0.0290
Distance from school	Average nearest distance to all schools in the township /km	0.0048
Distance from hospital	Distance from all medical and health institutions in the town. Average nearest distance /km	0.0267

Table 3 Indicator system for measuring village quality (facility system)

Index layer	Index content	Weight value
Proportion of area of public activity places	The ratio of the area of public activity places to the area of administrative villages	0.2613
Road area ratio	The ratio of the road area to the administrative village area	0.0080
Level of provision of municipal facilities	Reflect the configuration of water and electricity facilities: Water/electricity/ventilation = 1; Two supply facilities are available = 2; Three supply facilities are available = 3	0.0000
Quantity of garbage disposal	Number of garbage disposal facilities within the administrative village/unit	0.4273
Fitness and entertainment facilities	Number of leisure and entertainment facilities within the administrative village/unit	0.0222

Table 4 Indicator system for measuring village quality (characteristics of farmers)

Index layer	Index content	Weight value
Number of households	The sum/household of all households gathered in the administrative village.	0.0101
Human population	The sum of the number of all farmers in the administrative village/person	0.0076
The population of the labor force	Total labor force population in the administrative village/person	0.0140
Average annual income per household	The average annual income of farmers' families in administrative villages/yuan	0.0028
Source of livelihood	Reflect the number of farmers' livelihood sources: agricultural cultivation, large-scale production, non-agricultural operation, migrant workers and other income. (Each livelihood source is assigned a value of 1, and accumulated statistics)	0.0073
Villager satisfaction	Reflecting farmers' satisfaction level with their village: Satisfied = 1, Fairly Satisfied = 0.75, Average = 0.5, Unsatisfied = 0.25.	0.0000

embodies the village's natural endowment, serving as the fundamental basis for its development; the locational attributes denote the village's geographical position, facilitating resource acquisition, which is essential for development; the infrastructure system indicates the functionality of the village, representing an inherent advantage; and the traits of the farming households illustrate their living conditions, providing an accurate depiction of the village's development. The attributes of farmers reflect their living conditions in the hamlet, which accurately represents the village's progress. This work used the Delphi technique, sometimes referred to as the expert opinion survey or expert correspondence method, to gather the insights of six academics and specialists in rural resilience research (Wang et al., 2016). The scientific allocation of indicators is integrated with the hierarchical analysis method to ensure that the principal indicators receive more weights. This study employs the entropy method to rectify the potential subjectivity and bias in the assignment of indicator weights, wherein the accessibility to water, electricity, and gas in each village corresponds to the residents' satisfaction level, initially assigned a weight of 0.0000. By employing relative standardization, we eradicated scale discrepancies among several indicators and attained consistency in their directional alignment. This study employed the composite index method to thoroughly and precisely evaluate the quality of village nodes.

2.4.3 Village network construction

In complex network theory, villages are represented as nodes, while the connections between them are represented as edges, creating a village network. The establishment of this network entails multiple phases. Initially, the network nodes are identified and positioned near the centroid of the village's population density (Wang et al., 2016). This phase assists in establishing the initial locations of the nodes inside the network. The network edges are subsequently computed. The quality measurement data of villages and the inter-village distances are incorporated into the enhanced gravity model to derive the gravity matrix. The gravity matrix denotes the intensity of links among settlements, determined by quality and distance. The gravity matrix is subsequently symmetrized utilizing UCINET6.0 software, guaranteeing that village connections are bidirectional. The network has been constructed. Several sensitivity tests are performed to analyze the complexity features of the network and identify a suitable cutoff threshold. The gravity matrix is subsequently binarized according to this threshold, yielding a binary matrix (Albert et al., 2000). The spatial configuration of the rural network is depicted utilizing the ArcGIS 10.8 software platform. This approach facilitates the examination of the complexity and spatial patterns of the rural network, yielding insights into the connectedness and interrelations across villages.

2.5 Network structural toughness measurement

Relevant literature identifies four indicators (Chu et al., 2010; Yan et al., 2021; Guo et al., 2022): network hierarchy, network matching, network transmission, and network agglomeration, as appropriately selected (Tables 5−8). UCINET 6.0 is a network analysis tool that quantifies the structural toughness index of networks. The indicators assess the network's structural characteristics across various dimensions, providing a comprehensive reflection of its structural resilience. They serve as the foundation for optimizing the network structure and improving its resilience.

2.6 Changes in network structural toughness under disruption simulation

The network disruption simulation seeks to evaluate the resilience of a network by analyzing the effects of node failures during unforeseen occurrences. The designated design methodology for the disruption simulation entails the construction and simulation of a network model utilizing Network X, predicated on a binary value matrix. The village nodes in the network are designated as targets for assault. A simulated network disruption scenario involves the sequential attack of 13 nodes, resulting in the failure of one node at a time. The nodes fail instantaneously upon attack, and all associated edges are concurrently eliminated.

Table 5 Indicator system for measuring the structural resilience of rural networks (network hierarchical)

Norm	Exponents	Formula	Interpretation of the calculation formula	Significance
Hierarchy	Degree	——	——	Node External Connectivity
	Degree distribution	$K_m = C \times (K_m^*)^a$	K_m is the degree of node m; C is a constant; K_m^* is the ranking of the degree of node m in the network; a reflects the slope of the degree distribution curve.	Distribution Characteristics of Node Degree Values

Table 6 Indicator system for measuring the structural resilience of rural networks (network compatibility)

Norm	Exponents	Formula	Interpretation of the calculation formula	Significance
Matching	Neighborhood average degree	$\overline{K_m} = \sum_{i \in V} \frac{K_i}{K_m}$	$\overline{K_m}$ is the average of the degrees of all neighboring nodes directly connected to node m; K_m is the degree of node m; $v$is the degree of node m and is the set of all neighboring nodes of node m; K_i is the degree of the neighboring node i directly connected to node m	Connectivity of Neighbor Nodes
	Degree correlation	$\overline{K_m} = D + bK_m$	$\overline{K_m}$ is the average degree value of the connected nodes of node m; D is a constant; b is the slope of the degree correlation curve.	Correlation of Node Connections

Table 7 Indicator system for measuring the structural resilience of rural networks (network transportability)

Norm	Exponents	Formula	Interpretation of the calculation formula	Significance
Transmission	Average path length	$L = \frac{2\sum_{i>j} d_{ij}}{n(n-1)}$	L is the average path length; n is the number of nodes in the network; i, j are nodes; d_{ij} denotes the shortest path length between i, j	Network Connectivity and Diffusion Efficiency

Table 8 Indicator system for measuring the structural resilience of rural networks (network agglomeration)

Norm	Exponents	Formula	Interpretation of the calculation formula	Significance
Agglomeration	Average coefficient of agglomeration	$C = \frac{1}{n}\sum_i^n \frac{2e}{k_i(k_i-1)}$	C is the average clustering coefficient, n refers to the number of nodes; k_i denotes the number of neighboring nodes of node i; e denotes the number of actual connections that node i generates with neighboring nodes	Clustering Coefficient of Node Connections

This study utilizes two variables, network transmissibility and diversity, to evaluate alterations in network structural resilience during the disruption simulation (Wei and Pan, 2021b; Yang and Liu, 2022), as outlined in Table 9. The objective is to assess the differing significance of each node in enhancing the network's overall resilience. The alterations in network efficiency and diversity are further classified to designate node levels, illustrated by the ArcGIS natural breakpoint approach. Nodes in the initial level are designated as dominant nodes, while nodes at the last level are classified as vulnerable (Yang and Liu, 2022).

3 Analysis of results

3.1 Network spatial pattern

In Shiba Town, the villages function as network nodes, while the gravity matrix between them acts as the connecting edges within the network. The Shiba Town village network is constructed and visualized using ArcGIS 10.8 software (Fig. 3). The network comprises 13 nodes and 78 edges. Edge weights are classified into five levels utilizing the natural breakpoint method. Of these, 46 edges exhibit a connection strength below 17.977841/105, representing 58.974% of the total edges. The current assessment of rural development in Shiba Town indicates that the weakly connected edges are inadequate for facilitating the flow of elements within the network. The gravity matrix is binarized to further analyze the complexity characteristics of the network.

Initially, a suitable cutoff value is determined via sensitivity analyses. A cutoff value of 17.978/105 has been selected. If the strength of inter-village connections surpasses this threshold, the corresponding matrix cell is assigned a value of 1; if not, it is assigned a value of 0. This facilitates the development of a binary matrix for the

Table 9 Indicator system for measuring changes in the structural resilience of rural networks

Norm	Exponents	Formula	Interpretation of the calculation formula	Significance
Network transportability	Network efficiency	$E = \sum_{i \neq j \in G} \frac{2}{D_{ij} n(n-1)}$	E denotes the network efficiency; n is the number of nodes in the network, and G is the set of nodes in the network after removing a particular node; D_{ij} denotes the shortest path between node i and node j	Network efficiency reflects the diffusion capacity of elements in a network
Network variegation	Number of independent paths	$V = \sum_{i \neq j \in G} \frac{2N_{ij}}{n(n-1)}$	V denotes the number of independent paths; n is the number of nodes in the network, and G is the set of nodes in the network after removing a particular node; N_{ij} denotes the number of independent paths between node i and node j	The number of independent paths reflects the fault tolerance of the network

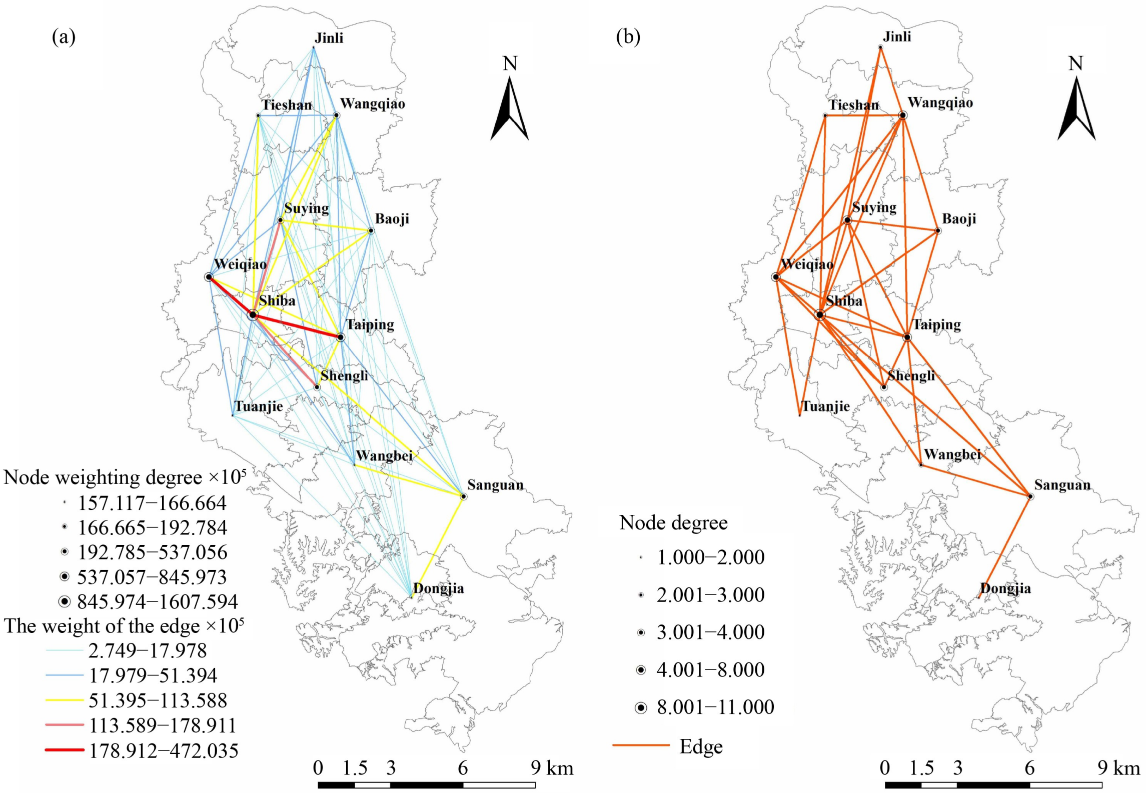


Fig. 3 Original network space structure (a) and binarisation processed network space structure (b).

analysis of complex networks. In the gravity matrix, 32 out of the original 78 connecting edges are assigned a value of 1 following binarisation, with the remaining edges assigned a value of 0.

Secondly, the spatial structure of the rural network in Shiba Town post-binarisation is visualized using ArcGIS 10.8 software (Fig. 3). The connecting lines demonstrate that the gravitational strength between a specific village and its associated villages surpasses the cutoff value, establishing a connection of defined strength. The rural network of Shiba Town consists of 32 connecting edges and demonstrates a configuration characterized by density in the center, sparsity in the north, and a lack of connections in the south. Shiba village, characterized by a high node degree, is situated at the core of the central region of the network. The connecting nodes are evenly distributed, leveraging an advantageous geographical location and accessible transportation. Consequently, it constitutes the foundation of the rural network. Villages with medium node degrees are predominantly located near the core of the northern section of the network. The villages exhibit average locational conditions and restricted connectivity. They demonstrate a greater degree of interconnection, increased sharing of facilities, and proximity to rural roads, which enhances traffic conditions. They function as essential hubs for neighboring villages, acting as a connection between those with high and low node degrees. Villages with low node degrees are situated on the southern edge of the network. The villages exhibit a reduced level of connectivity among nodes. Due to suboptimal location conditions or restricted facility coverage, these areas demonstrate reduced interconnectivity with neighboring villages and possess a lower node degree.

3.2 Network structural resilience assessment

3.2.1 Network hierarchy

The network nodes in Shiba Town’s rural network are classified into five tiers, exhibiting a spatial distribution described as “dense in the centre, sparse in the north, and disconnected in the south” (Fig. 4). The study indicates that Shiba village occupies the fifth tier and maintains the most proximate linkages with other villages in the network. It is directly linked to a total of 11 communities, representing the greatest network level. Shiba village serves as a significant hub within the network. Conversely, Tuanjie Village and Dongjia Village are classified at the primary level and possess minimal direct ties with neighboring villages. They possess the lowest network tier and are comparatively isolated nodes inside the network. The network hierarchy of the rural network in Shiba Town is inconsistent. Nevertheless, within the network, communities such as Taiping Village, Wangqiao Village, Su Ying Village, and Weiqiao Village exhibit closer interconnections and generally elevated network levels. These settlements demonstrate superior local

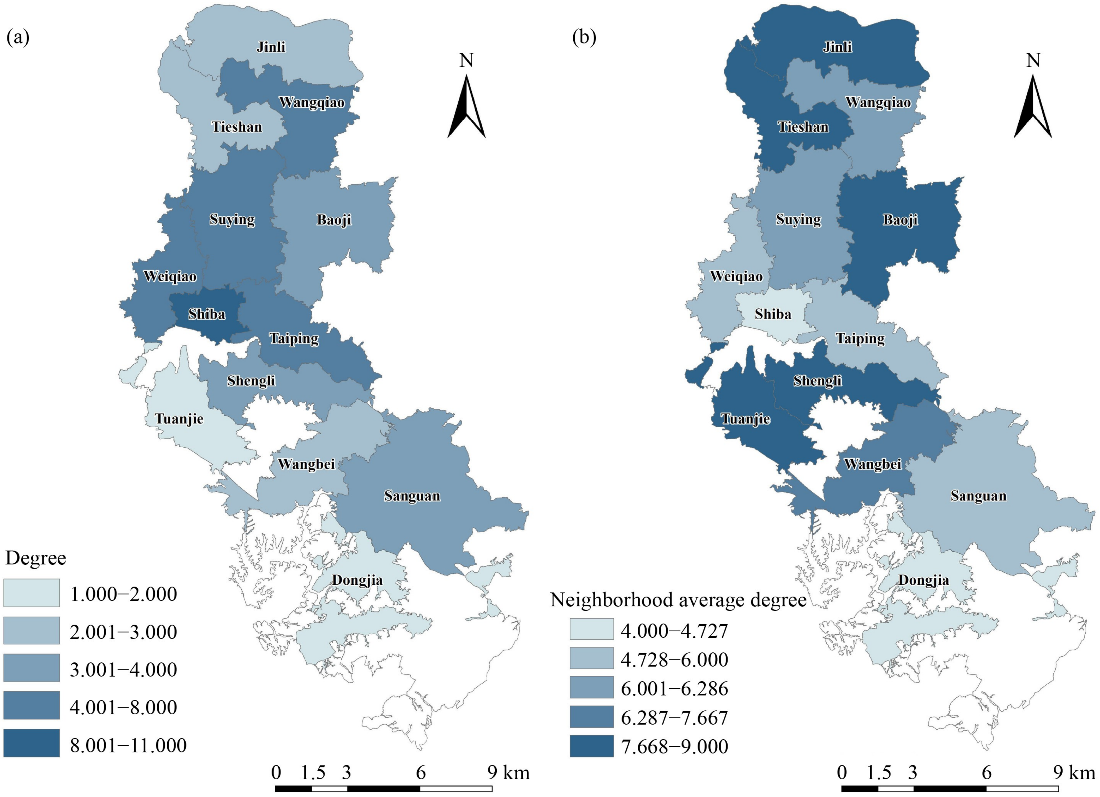


Fig. 4 Spatial pattern of network node degree (a) and spatial pattern of average neighbor degree (b).

structural resilience within the network.

The degrees of all nodes in the network are sorted, and a power-law curve fitting is employed to examine the overall hierarchy (Fig. 5). The absolute value of the index of the degree distribution curve for the rural network in Shiba Town is 0.545. Guo Weidong's research on the network hierarchy of China's high-speed rail cities revealed an index of 0.8497 (Guo et al., 2022). This suggests that the rural network hierarchy in Shiba Town is minimal, resulting in a greater homogeneity among the network nodes. From the standpoint of local curve slope, the highest node, Shiba village, exhibits a greater absolute slope value of 3.000. This indicates that while the network overall lacks substantial hierarchy, it possesses considerable control through the center node. Consequently, the failure or interruption of the core node can readily result in network paralysis, although the failure or disappearance of other nodes has a minimal effect on the network's normal operation.

3.2.2 Network matching

The average neighborhood degree of rural network nodes in Shiba Township is categorized into five distinct levels. The spatial distribution of the average neighborhood degree exhibits a pattern characterized by lower values in the center and higher values on the periphery (Fig. 4). This stands in contrast to the spatial distribution of node degree, which displays higher values in the center and lower values around it. This phenomenon can be explained by the presence of a multi-core pattern within the study area, where the hierarchical differentiation among core nodes is not sufficiently pronounced. A significant correlation exists with the edge villages. The degree correlation index for the rural network in Shiba Township is −0.250, which suggests that the network exhibits heterogeneity and qualifies as a heterogeneous network (Fig. 5). Villages exhibiting elevated node degrees within the network facilitate connections not only among villages at equivalent levels but also tend to establish links with villages possessing lower node degrees. This enhances the network's connectivity options and facilitates a more streamlined development process. The heterogeneity and diversity of connectivity paths facilitate factor mobility between villages and strengthen the structural resilience of the network.

3.2.3 Network transmissibility

The mean path length of the rural network in Shiba Town, as determined by the network transmissibility index, is 1.692. This is below the average path length of China's high-speed rail urban network, which is 1.916 (Guo et al., 2022). The reduced average path length signifies that the routes inside the rural network of Shiba Town exhibit more transmissibility, requiring elements to traverse between village nodes fewer than twice. According to Fig. 6, there are 32 direct paths in the network that do not necessitate intermediaries, representing 41.0% of the total. One transit can connect 38 pathways, constituting 48.7% of the total. Eight routes, or 10.3%, necessitate two transits for connection. This analysis indicates that a maximum of one transit can directly link approximately 90% of communities. The extensive accessibility and dissemination of elements inside the network enhance the transmission and distribution of elements throughout villages. A network exhibiting elevated transmission efficiency possesses superior adaptive and restorative capabilities during crises. Nonetheless, over 10% of villages exhibit limited accessibility and diffusivity, rendering them vulnerable components in the structural resilience of the rural network. Should one or more of the intermediate medium-node villages collapse, the local network in those villages may cease to function. This may diminish the network's overall structural integrity.

3.2.4 Network agglomeration

The average agglomeration coefficient of the village network in Shiba Town is 0.771, surpassing the average agglomeration coefficient of China's high-speed rail city

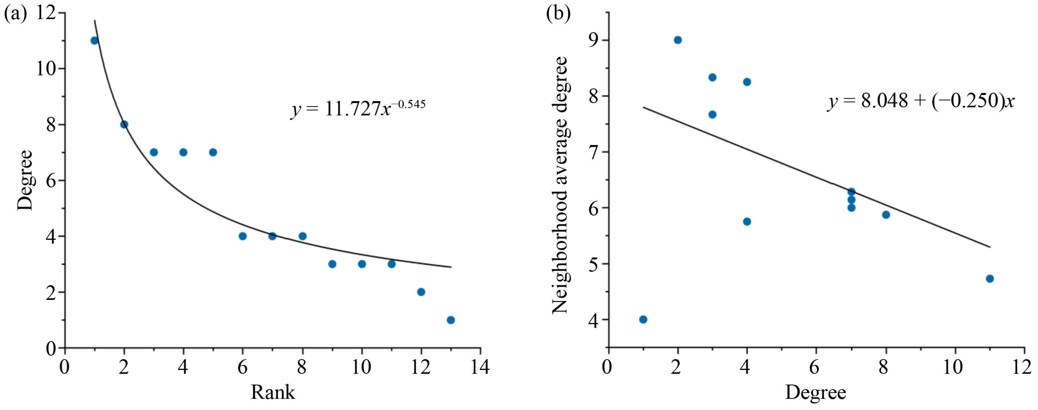
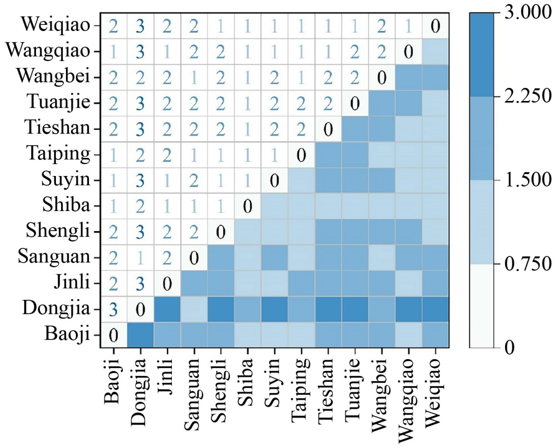


Fig. 5 Network degree distribution (a) and network degree correlation (b).



	Baoji	Dongjia	Jinli	Sanguan	Shengli	Shiba	Suyin	Taiping	Tieshan	Tuanjie	Wangbei	Wangqiao	Weiqiao
Weiqiao	2	3	2	2	1	1	1	1	1	1	2	1	0
Wangqiao	1	3	1	2	2	1	1	1	1	2	2	0	
Wangbei	2	2	2	1	2	1	2	1	2	2	0		
Tuanjie	2	3	2	2	2	1	2	2	2	0			
Tieshan	2	3	2	2	2	1	2	2	0				
Taiping	1	2	2	1	1	1	1	0					
Suyin	1	3	1	2	1	1	0						
Shiba	1	2	1	1	1	0							
Shengli	2	3	2	2	0								
Sanguan	2	1	2	0									
Jinli	2	3	0										
Dongjia	3	0											
Baoji	0												

Fig. 6 Shortest path length between network nodes.

network, which is 0.703, as reported by Guo et al. (2022). This suggests a strong interconnection among the villages in the network, with a reduced number of isolated nodes. The network demonstrates a notable agglomeration effect alongside high transmittance, suggesting a pronounced small-world effect. Figure 7 illustrates a negative correlation between the agglomeration coefficient and the degree value of village nodes. Baoji, Shengli, Zinli, Unity, Wangbei, and Dongjia villages exhibit agglomeration coefficients below 0.6 and node degree values not exceeding 4, signifying low node degrees.The villages of Shiba and Taiping exhibit higher node degree values and agglomeration coefficients below 0.6, suggesting substantial interconnections among the core villages. The core villages exhibit increased connectivity with other villages in the network, leading to enhanced network transmittance and a notable small-world effect. Nonetheless, there are limited close interactions among the edge villages, resulting in an absence of local area agglomeration effects in these communities. The agglomeration of the rural network in Shiba Town indicates that core villages exhibit a lower degree of agglomeration, highlighting characteristics of openness, flexibility, and network resilience regarding overall connectivity. This enhances the correlation effect of the overall network and improves its structural resilience.

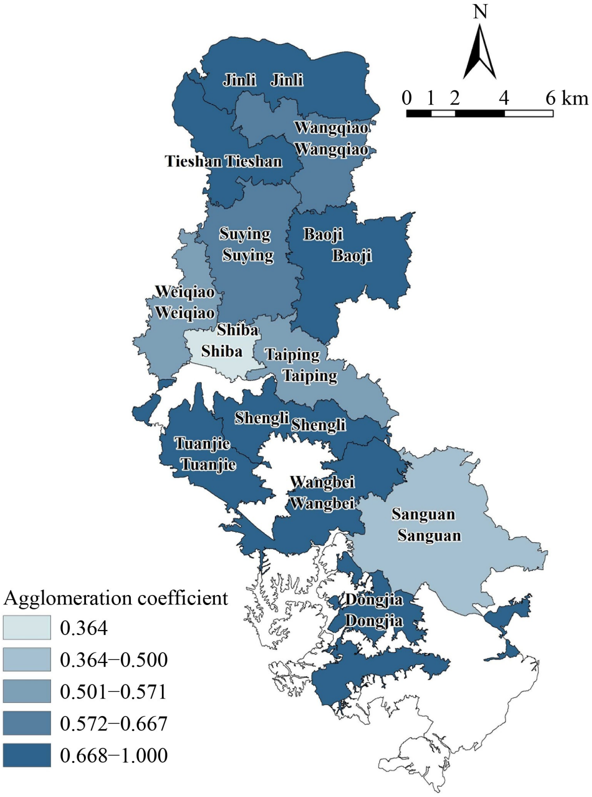


Fig. 7 Spatial pattern of network node agglomeration coefficients.

3.3 Assessment of network structural toughness under disruption simulation

Analysis of the alterations in network structural toughness indicators during interruption simulations (Fig. 8) reveals that the overall network transmissibility and diversity display markedly regionally varied characteristics following the failure of various nodes. The natural breakpoint technique classifies the nodes into five levels according to variations in network transmissibility and diversity. The primary level comprises the dominant nodes, specifically Sanguan and Shiba villages, while the fifth level includes the weak node, Dongjia village.

Sanguan and Shiba villages are pivotal nodes in the rural network of Shiba Town, ensuring the stability of the network structure. These settlements have superior infrastructure, enhanced economic development, and notable geographical advantages in resource distribution and allocation. Their effect encompasses the neighboring settlements. Disruptions in these communities will substantially affect the network's overall resilience. Consequently, future advancements in the rural network of Shiba Town should prioritize the enhancement of Sanguan and Shiba villages' quality and their resilience to hazards. This will mitigate the likelihood of their failure. Furthermore, it is essential to enhance the inherent cyclic dynamics of elements in Dongjia village and fortify its links with other communities. This will augment its resilience to threats and aid in preserving the network's overall robustness.

4 Discussion

4.1 Research significance and characteristics of village network structural resilience

Most prior research is confined to unidimensional analysis of extensive regions or evaluations of urban network resilience. Simultaneously, there is a dearth of

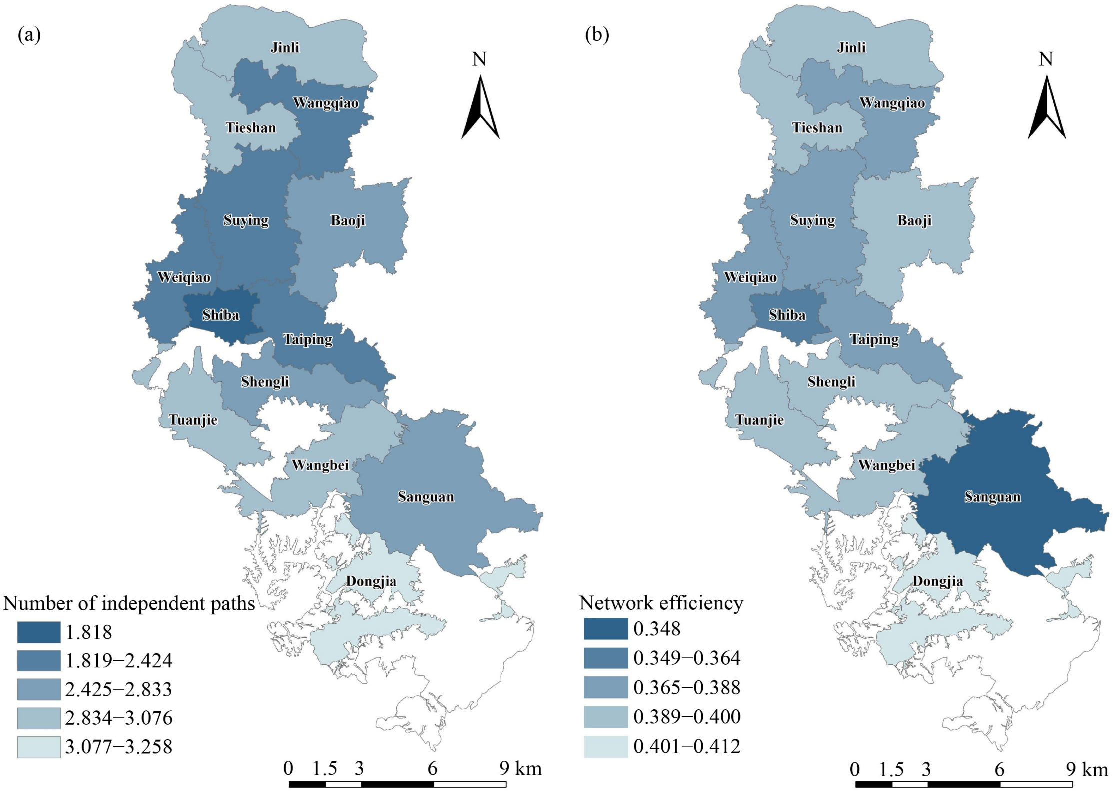


Fig. 8 Network diversity (a) and network transmissibility (b) after attack on different village nodes.

discourse regarding the development of micro-level networks, particularly those pertaining to villages and towns, and their resilience attributes. This study analyzes the multifaceted condition of town and village regions and develops a set of indicators to thoroughly assess the quality of villages, considering essential factors such as demographics, locational and transportation benefits, facility comprehensiveness, natural resource status, and economic vitality. The gravity model is revised to incorporate village quality and commuting distance to inform the development of the village network. This method precisely encapsulates the intricate diversity and distinctiveness of villages. It exhibits robust generalizability, offering a reference and motivation for the establishment of village networks in other towns and villages.

The spatial configuration of the rural network in Shiba Town exhibits a pattern characterized by density in the center, sparsity in the north, and a lack of connectivity in the south, consistent with pertinent research findings (Wang et al., 2016). This trend can be ascribed to the influence of villages with advantageous geographical locations, accessible transportation, and comprehensive services, which significantly impact adjacent villages and function as the nucleus of the rural network. Conversely, settlements situated in unfavorable geographical positions, with restricted transportation and insufficient infrastructure, exhibit poorer linkages to other villages and are positioned on the outskirts of the rural network (Liu et al., 2009). The rural network in Shiba Town exhibits minimal hierarchical structure, characterized by relatively homogeneous network nodes. Nonetheless, as a central node, Shiba Village has greater control on the network, akin to the conclusions of pertinent studies (Wang et al., 2014; Su et al., 2018a, 2018b; Su and Wang, 2018). This can be ascribed to the generally low level of growth in rural regions, leading to insufficient network advancement. Notwithstanding this, the central nodes, including the municipal government seat, signify elevated levels of social and economic development. The primary cause of this issue is the relatively low degree of development in rural regions, resulting in inefficient factor flows and an archaic development paradigm (Jia, 2018; Wei and Pan, 2021b).The spatial configuration of the rural network in Shiba Town demonstrates a core-edge structure, wherein villages in advantageous positions constitute the core, while those in less favorable places are situated on the perimeter. The network's hierarchical structure is not critical; nonetheless, certain central nodes, like Shiba Village, exert a greater influence. This trend is shaped by the generally low degree of development in rural regions and the corresponding underdevelopment of networks.

The outcomes of the disruption scenario analysis, namely the metrics of transmissibility and variety, elucidate the differential effects of village failure on the overall structural resilience of the network at various nodes, aligning with conclusions from pertinent studies

(Peng et al., 2018). In the presence of hazards, various node communities demonstrate considerable disparities in their impact on the network's overall resilience level. The disparities can be ascribed to hierarchy, matching, local transmissibility, and variances in local agglomeration (Guo et al., 2022). Consequently, it is essential to establish distinct risk prevention measures for various node communities.

4.2 Recommendations for improving the structural resilience of rural networks

This research establishes a framework for the quantitative assessment of structural resilience in rural networks, with a particular emphasis on the networks in Shiba Township. This framework seeks to enhance sustainable and healthy rural development in Shiba Township and is applicable for assessing other rural networks as well. Based on the analysis of the structural resilience of rural networks in Shiba Town and informed by relevant literature (Wei and Pan, 2021a; Guo et al., 2022; Zhang et al., 2022), we propose several strategies and recommendations for enhancing network structural resilience. 1) Enhance the quality of villages and maintain the stability of village nodes. Village nodes are essential components of the rural network. Future planning and development should utilize the existing strengths of villages while addressing deficiencies in accordance with the residents' actual production and living requirements. This includes upgrading transportation infrastructure, constructing department store markets, establishing medical institutions, and improving social welfare and security systems. Improving village quality will enhance the overall resilience of the network. 2) Optimize the village linkage structure to enhance the resilience of the village network. It is essential to strengthen the development of township enterprises and attract surplus labor from surrounding villages by leveraging the strengths of leading nodes like Sanguan Village and Shiba Village. This can foster development in surrounding villages through point-to-point connections, thereby enhancing the linkage and exchange between less-connected villages and others. The objective is to attain coordinated and balanced development of rural regions in Shiba Township, thereby improving the overall resilience of the network. 3) Enhance the prevention and control of rural network risks and improve network security by continuously refining the risk supervision and emergency management system and mechanisms. This involves expediting the development of a robust network risk prevention information system, improving regional cooperation, and establishing emergency protocols. The measures are designed to mitigate damage to the village network during natural disasters or human-induced events, thereby safeguarding village nodes and the network as a whole. In conclusion, the implementation of these strategies and recommendations can enhance the structural resilience of networks in rural areas, thereby fostering sustainable and healthy rural development.

4.3 Research shortcomings and prospects

There are still some limitations in this study. For example, the study constructed an undirected, unweighted network. What are the characteristics of the resilience of rural network structures reflected in directed weighted networks? The study is still limited to the relatively micro-scale town and village networks. What are the characteristics of the resilience of town and village community network structures in a larger county? The study only analyzed the resilience of rural network structures at a single time point, lacking dynamic comparisons of the resilience of rural network structures at different periods. These limitations will be the focus of future research.

5 Conclusions

This study evaluates the structural resilience of the rural network in Shiba Town by establishing the network and employing six static evaluation indicators alongside two dynamic indicators, thereby analyzing its changes from a structural resilience standpoint. The principal conclusions are as follows.

1) The network has a configuration defined by density in the central region, sparsity in the northern region, and an absence of connections in the southern region. The network lacks a pronounced hierarchy at the aggregate level; yet, a central node, Shiba Village, wields considerable influence over the network. The network nodes exhibit a degree of homogeneity. The network exhibits considerable variety, characterized as a heterogeneous network, wherein villages with elevated node degrees are inclined to interact with villages possessing lower node degrees, signifying different interconnections within the network. The network exhibits a high local transmission efficiency, with approximately 90% of villages need only one intermediate link to achieve direct communication, hence enabling the transfer and spread of elements among communities. Nevertheless, certain communities continue to exhibit low network transmission efficiency, indicating vulnerabilities inside the network. The network demonstrates considerable clustering effects, with the majority of villages maintaining close links and only a limited number of isolated node communities. Nevertheless, the proximity among communities with elevated node degrees is not substantial.

2) During a network attack, the spatial transmission pattern and diversity exhibit considerable spatial difference. The nodes are categorized into five tiers, with

San Guan Village and Shiba Village as primary (level one) and Dong Jia Village as tertiary (level five). It is essential to concentrate on augmenting the quality of the dominating nodes, bolstering their resilience to threats, and minimizing the probability of failure. Enhancing the internal cyclic dynamics of elements and fortifying their links with adjacent communities for vulnerable nodes can improve their resilience to threats. Implementing these techniques will safeguard the overall resilience of the rural network in Shiba Township.

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