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RESEARCH

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Elemental evolution characteristics and influencing factors of green infrastructure network in karst mountain cities: a case study of Qianzhong urban agglomeration in Southwest China

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Abstract

Background The urban green infrastructure (GI) network is an important conduit for ecological flows and plays a crucial role in improving regional habitats, especially in karst areas that are highly ecologically fragile and sensitive. However, the existing research only focuses on the construction of GI network in karst mountain cities, and the evolution characteristics of its elements and driving mechanism are not clear, which is of great significance for guiding urban land use planning and comprehensively improving the quality of the ecological environment. In view of this, this study took Qianzhong urban agglomeration as the study area, based on multi-source data, and identified ecological sources through ecological resilience analysis. Considering the special geographic environment, the rock exposure rate factor was added to correct the resistance surface, and the minimum cumulative resistance (MCR) and gravity model were coupled to extract the GI network. The complex network topology characterization parameter was introduced to assess the spatial and temporal variations of ecological sources and corridors. Finally, the geographical detector was used to identify the dominant influencing factors and interactions of the spatial distribution of the GI network.

Results The results showed that from 2000 to 2020, the condition of GI network elements in the study area presented a decreasing and then an increasing trend. The ecological sources or corridors in highly urbanized areas were critical for ecological flow transport and the overall structural stability of the GI network. The influence of natural factors on the spatial distribution of the GI network gradually weakened, and the influence of human factors continuously increased. The spatial distribution of the GI network was influenced by multiple factors, and the interaction between all the factors was enhanced, which gradually changed from the interaction of natural factors to the interaction of human factors during the study period.

Conclusions The research results will provide scientific references for the construction of an ecologically safe environment and sustainable development of karst mountain cities.

Keywords Karst, Ecological resilience, Complex network, Geographical detector, Qianzhong urban agglomeration

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Introduction

Rapid socio-economic development has led to a further escalation of the already tense contradiction between the supply and demand of land resources, and the contradiction between human beings and the environment has been increasingly aggravated, seriously affecting regional ecological security and sustainable social development (Dai et al. 2021). The green infrastructure (GI) network is recognized as an effective means of connecting fragmented urban patches and integrating ecological landscapes. As connectivity structures that can be naturally occurring or artificially constructed, the GI network serves as a pathway for species migration and plays an important role in facilitating species exchange and building ecological security patterns (Nie et al. 2021; Song et al. 2022).

In 1986, Forman systematically summarized two conceptual models of "irreplaceable pattern" and "segregation between agglomerations", which laid an important foundation for the construction model of urban GI of "ecological source identification-comprehensive resistance surface construction-corridor extraction" (Lopes et al. 2023). Along with the gradual deepening of related research, methods from various disciplines, such as typology, landscape ecology, and operations research, have been applied to various core aspects of infrastructure network construction. And "sources-sinks" landscape patch identification, network index, effective cost distance model (ECDM), geographic approach to protect biological diversity (GAP) and other modeling methods have appeared one after another (Bo et al. 2016; Derolez et al. 2020; Li et al. 2017). Although the research methods are increasingly rich and diversified, and effective explorations have been made in identifying GI network, previous studies have neglected the influence of special geographic environmental factors on GI network construction, which is particularly important in heterogeneous karst areas and cannot be ignored.

Urbanization is an inevitable trend in current social development, and while it promotes social progress and economic prosperity, it is also considered a key factor threatening regional ecological and environmental security (Wu et al. 2020; Xie et al. 2020). As one of the three most fragile ecosystems, karst areas play a crucial role in achieving urban ecological security in the process of urbanization. Understanding the spatial and temporal characteristics of GI network in karst areas and the influencing factors in the process of urbanization is of more reference value for the formulation of urban ecosystem protection measures, which can better promote the effective coordination of socio-economic development and fragile ecological environment protection (Zhang et al. 2019). The existing research only stays on the assessment of ecosystem structure, service function, and evolutionary drivers in the karst region under the action of human-land coupling, but there is a lack of research on the assessment of the elements of the GI network and the influencing factors (Wang et al. 2020). Additionally, current research generally focuses on internal studies at the city scale, with less attention paid to existing urbanization differences within urban agglomerations as a whole, yet quantifying differences in the development of GI network within urban agglomerations is particularly important for sustainable regional development.

In this study, we took Qianzhong urban agglomeration, a highly urbanized karst area in Southwest China, as an example, and quantitatively analyzed the ecological resilience of the study area in 2000, 2010, and 2020 to realize the scientific identification of GI network sources. Using minimum cumulative resistance (MCR), gravity modeling, complex network theory, and geographical detector to explore the elemental evolution characteristics and influencing factors of GI network in karst mountain cities. The results will provide a valuable reference for effectively improving the quality of the GI network, alleviating the contradiction between socio-economic development and ecological environment, and realizing the construction of regional ecological security patterns. Specifically, this study aims to achieve the following objectives: (1) Explore the distribution of GI network in karst mountain urban agglomerations in the past two decades; (2) Assess and analyze the spatial and temporal variations of the GI network elements; (3) Identify the influencing factors and interactions in the spatial distribution of the GI network; (4) Put forward optimization proposals for the GI network in karst mountain cities. Figure 1 presents the flowchart of this study.

Materials and methods

Study area and data sources

The Qianzhong urban agglomeration is located in the central region of Guizhou Province in China, covering six cities (states), including Guiyang, Zunyi, Bijie, Anshun, Qiandongnan, and Qiannan, and involving 33 counties (cities and districts), including Guian New District, with a total area of 53,800 km^2, accounting for 30.6% of the total area of Guizhou Province (Fig. 2). It belongs to the subtropical monsoon climate, warm and humid, with an average annual temperature of 10–20 °C and an average annual precipitation of 1100–1300 mm, which is mainly concentrated from May to October and unevenly distributed throughout the year (Chen et al. 2018). It has 43.91% of the surface soil erosion, with typical karst landform characteristics. The average altitude is 1197.6 m, and the terrain decreases from west to east (Huang et al. 2021a, b). At the end of

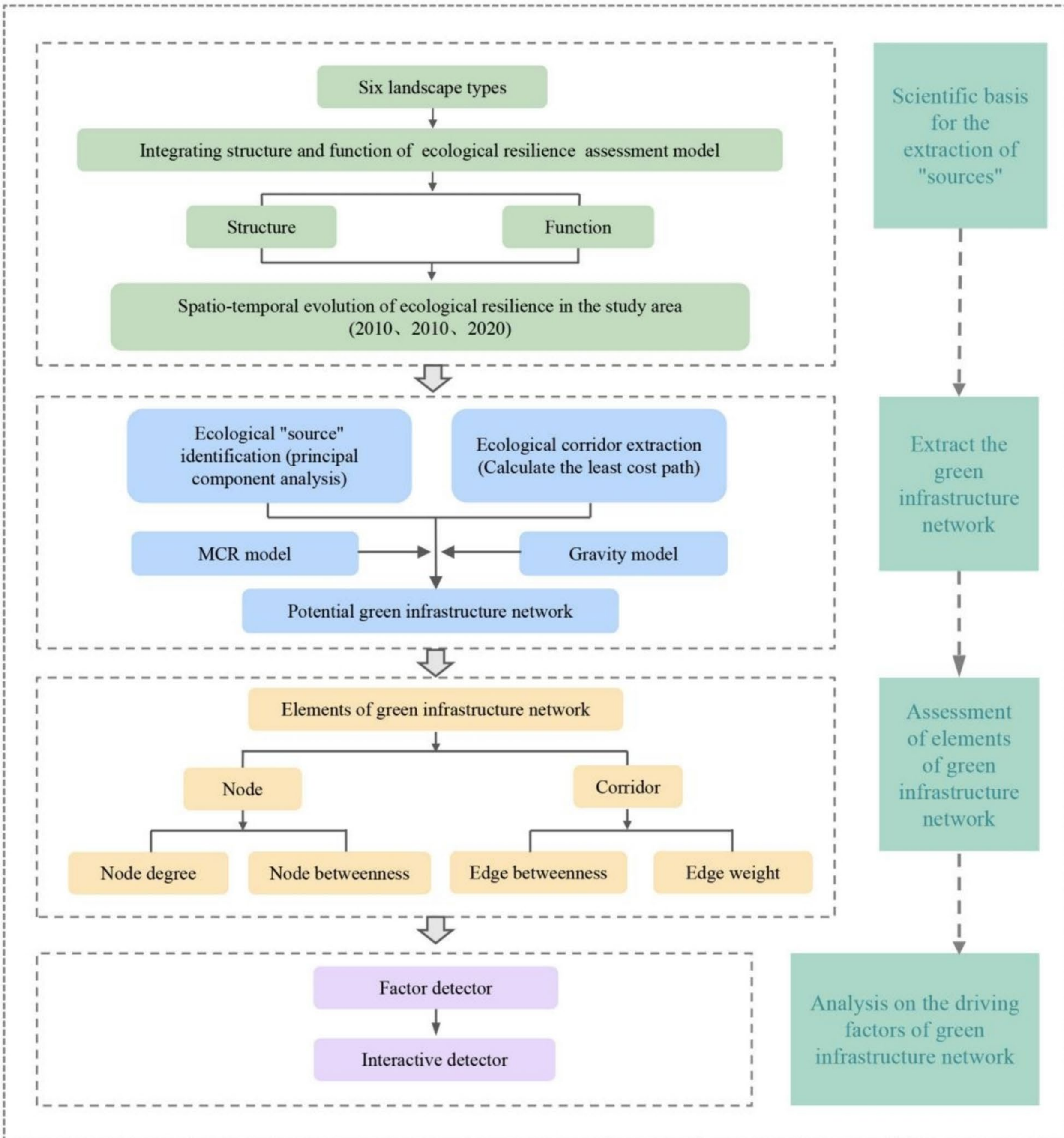

Fig. 1 Flowchart of the study

2020, the urban agglomeration had a resident population of 18.7 million and a GDP of 1002.8 billion yuan, accounting for 49.5% and 56.0% of Guizhou Province, respectively (Li and Geng 2022; Huang et al. 2021a, b). Due to frequent human activities and urban expansion, the GI network structure of urban agglomerations is unbalanced, land use is unreasonable, soil erosion is intensified, and ecological environment security is facing continuous challenges.

Our data mainly included 2000, 2010, and 2020 remote sensing data (30 m), after a range of procedures such as radiation correction, FLAASH atmospheric calibration, fusion, and masking, and using support vector machine combined with visual interpretation to

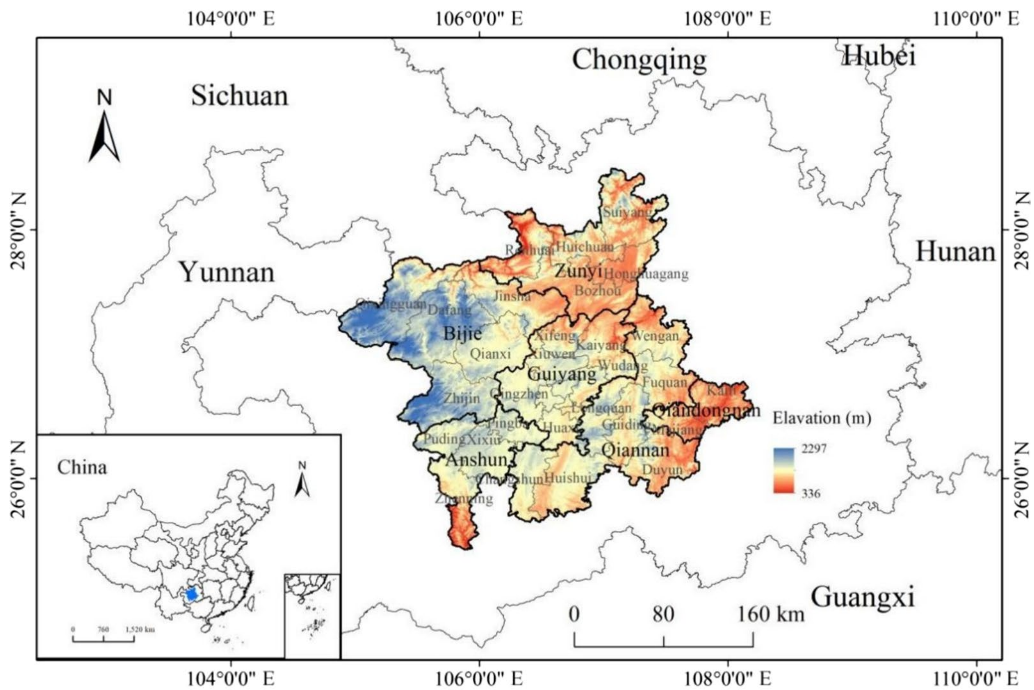

Fig. 2 Schematic of study area

obtain land use classification. Referring to the Classification of Land Use Status in China (GB/21010-2007), the study classified the land use of urban agglomerations into 6 categories and 22 subcategories (Table 1), with the overall classification accuracy is 92.4% (Fig. 3). The climate and environmental data include average annual precipitation, average annual temperature, normalized difference vegetation index (NDVI), modified normalized difference water index (MNDWI) data, soil data, degree of rocky desertification data, digital elevation model (DEM) data and extract elevation and slope data from it. Socioeconomic data include highways, railroads, and roads, water bodies, population, and gross domestic product (GDP). The details of the data sources are as follows (Table 2).

Extraction of GI network

As an important part of urban resilience and a basic guarantee, the quantitative assessment of ecological resilience could provide a scientific cognitive basis for the urban ecological security state, and offer a reference for urban ecosystem protection and management decision-making (Hong et al. 2022; Wang et al. 2021). This study synthesized the theory of the human-land relationship, sustainable development, and other related theories, and constructed an ecological resilience (ERS) assessment index system based on the "structure–function" perspective, from the internal operation of the ecosystem and the external development needs, respectively. After that, through the integrated subjective–objective assignment of the analytic hierarchy process (AHP) and entropy

Table 1 Land use classification in the study area

Reorganization number	Type after reorganization	Types of classification of land use status	Corresponding number
1	Arable land	Paddy field, Dryland	11, 12
2	Woodland	Forestland, Bush, Sparse forest, Other woodland	21, 22, 23, 24
3	Grassland	High coverage grassland, Medium coverage grassland, Low coverage grassland	31, 32, 33
4	Water area	Canal, Lake, Reservoir, Shoal, Beach, Marsh	41, 42, 43, 45, 46, 64
5	Construction land	Urban land, Rural settlement, Other construction land	51, 52, 53
6	Unused land	Permanent ice and snow, Saline-alkali land, Bare land, Bare rock and gravel	44, 63, 65, 66

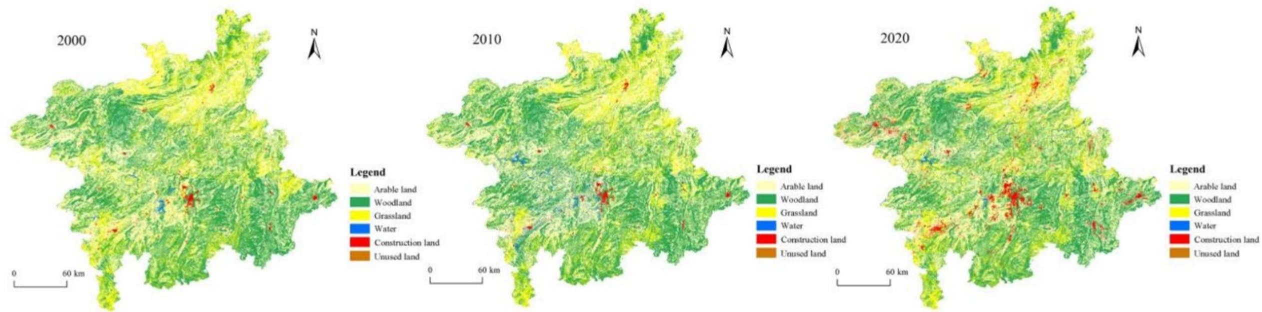

Fig. 3 Land use of the study area

Table 2 Details of the data

Data type	Source	Remark
Remote sensing data (30 m)	Geospatial Data Cloud	https://www.gscloud.cn/
DEM (30 m)		
Net primary productivity (NPP)	Resource and Environmental Science Data Center, Chinese Academy of Sciences	http://www.resdc.cn
Modified normalized difference water index (MNDWI) data		
GDP		
Population density data		
DMSP-OLS night light data		
Degree of rocky desertification	Guizhou Province Stone Desertification Survey Database	Guizhou Provincial Forestry Bureau
Soil data	Harmonized World Soil Database (HWSD)	https://data.tpdc.ac.cn/zh-hans/
Hydrological data	National Meteorological Science Data Center	https://data.cma.cn/
Road data	Open Street Map	http://www.Openstreetmap.org/

weight method (EWM), which can not only reflect the importance of the indicators, but also reflect their differences, making the research results more accurate and scientific (Song et al. 2022). The ecological resilience comprehensive assessment model was finally obtained (Fig. 4).

Considering the actual status of karst mountain cities, the woodland and water patches with the principal component level of I in the ecological resilience assessment results were selected as the sources of the GI network in the study area. Patches that are larger in size, higher in quality, and closer together are more conducive to species migration and biodiversity conservation. In the process of source identification, the setting of the minimum area of the patches will directly affect the number of sources. With the increasing of the minimum area threshold, the number of patches of the source decreases rapidly. The study explored the optimal scale of the minimum area threshold for sources from the perspective of the landscape pattern of urban agglomerations (Wu et al. 2019). The results of the analysis showed that after the minimum area threshold was increased to 10 km^2, the decrease in the number of patches and the proportion of total area tended to level off, and the overall pattern stabilized (Fig. 5). Therefore, this study removed smaller and more fragmented patches, finally identifying sources of the GI network with a threshold value of 10 km^2.

Ecological flows from the source to the outflow need to overcome ecological resistance which is influenced by a variety of resistance factors (Li et al. 2020; Song et al. 2021). Scientific selection of resistance factors to construct a comprehensive resistance surface can more accurately reflect the degree of obstruction of ecological flows in the process of intra-regional circulation (Ye et al. 2020). In this study, the resistance factors were selected from both natural and anthropogenic factors as well as the actual situation of karst mountain cities. While integrating several typical natural and human factors, this study also incorporated the rock exposure rate to construct resistance surfaces based on the natural geographical environment of the karst mountain city. 12 factors were selected comprehensively, and the resistance of each factor was set according to the assessment system (Table 3). The corridors of the GI network are the least-cost pathways for ecological flows from one source to another via ecological resistance surfaces (Song et al.

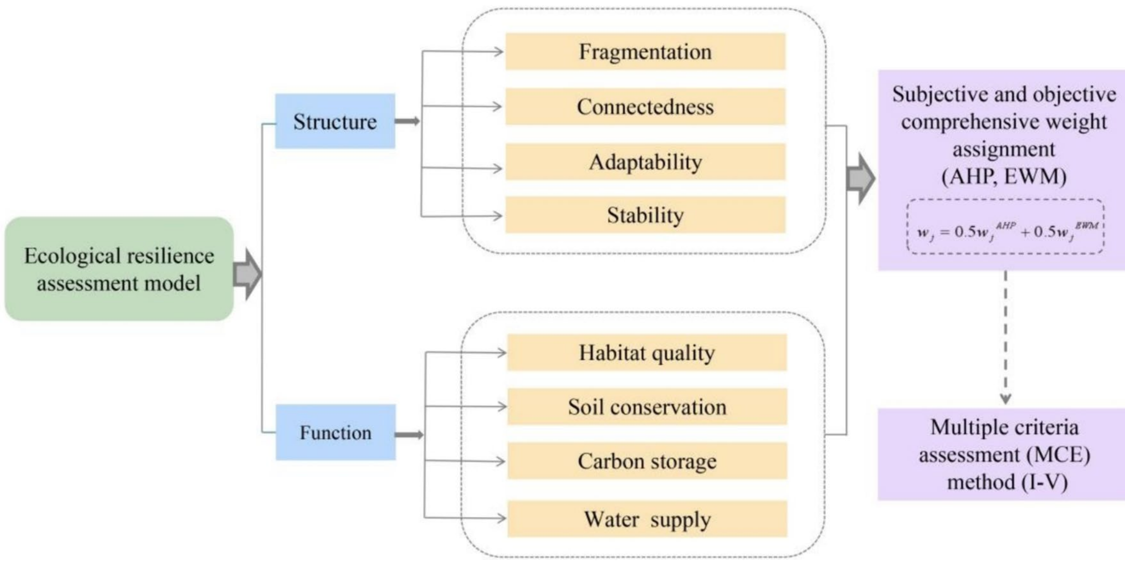

Fig. 4 Urban ecosystem resilience assessment model

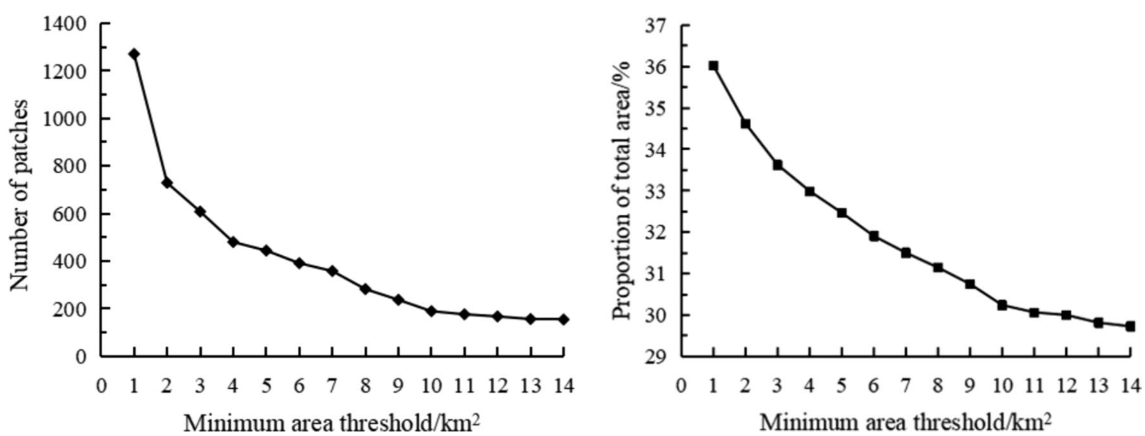

Fig.5 Impact of the minimum size threshold of ecological source patches

2021). At the same time, there is gravity between ecological sources. In this study, the corridor was extracted by MCR model and gravity model.

Complex network theory

Complex network theory combines system science, sociology, and other theories. It is a new perspective and method to study complex systems by analyzing the topological structure of individual interactions in the system (Slota et al. 2016; Zhao et al. 2019). It aims to clarify the functions of different kinds of realistic network systems, and then provide guidance for network system design and optimization (Wang et al. 2015; Zhang et al. 2015). Four typical statistical indicators of complex network theory (Jiang et al. 2011) are selected to analyze and evaluate the spatial and temporal variations of nodes and corridors: node degree, node betweenness, edge betweenness, and edge weight. Node degree and node betweenness indicate the importance of nodes from connectivity and structural support, respectively. The edge betweenness and edge weight assess the importance of the corridor in terms of flow efficiency to ecological flows and structural stability, respectively. These metrics are calculated as follows (Song et al. 2021):

$$D_i = \sum_i d_{ij} \tag{1}$$

Table 3 Ecological resistance factor system

Factors	Grade	Resistance	Factors	Grade	Resistance
DEM (m)	> 250	9	Distance from water (m)	> 400	9
	200–250	7		300–400	7
	150–200	5		200–300	5
	100–150	3		100–200	3
	< 100	1		< 100	1
Slope (°)	> 30	9	Rock exposure rate (%)	< 15	9
	25–30	7		15–30	7
	20–25	5		30–45	5
	15–20	3		45–60	3
	< 15	1		> 60	1
NPP	< 0.1	9	Soil thickness (cm)	< 15	9
	0.1–0.2	7		15–30	7
	0.2–0.3	5		30–45	5
	0.3–0.6	3		45–60	3
	> 0.6	1		> 60	1
MNDWI	< 0.1	9	Land use	Construction land	9
	0.1–0.3	7		Unused land	7
	0.3–0.5	5		Arable land	5
	0.5–0.8	3		Grassland	3
	> 0.8	1		Woodland, water	1
Rainfall (m)	> 0.056	9	Road network density	> 1.25	9
	0.054–0.056	7		0.85–1.25	7
	0.052–0.054	5		0.52–0.85	5
	0.050–0.052	3		0.20–0.52	3
	< 0.050	1		0–0.20	1
Temperature (°C)	< 14	9	Population density	> 425	9
	14–15	7		300–425	7
	15–16	5		175–300	5
	16–17	3		50–175	3
	> 17	1		< 50	1
Biodiversity index	< 0.3	9	GDP	> 250	9
	0.3–0.4	7		200–250	7
	0.4–0.5	5		150–200	5
	0.5–0.6	3		100–150	3
	> 0.6	1		< 100	1
Distance from green space (m)	> 800	9	Night light intensity index	< 0.2	9
	600–800	7		0.2–0.35	7
	400–600	5		0.35–0.5	5
	200–400	3		0.5–0.65	3
	< 200	1		> 0.65	1

$$B_v = \sum_{i \neq j \in V} \frac{\delta_{ij}(v)}{\delta_{ij}} \quad (2)$$

$$B(e) = \sum_{i \neq j} \frac{\delta_{ij}^{e}}{\delta_{ij}} \quad (3)$$

$$D(e) = w_{ij} = D_i D_j \quad (4)$$

where D_i is the degree of node i, d_{ij} is the connection relationship between node i and node j. B_v is the betweenness of node v, V is the set of all nodes in the network, $\delta_{ij}(v)$ is the number of node v passing through the shortest path of node i and j, δ_{ij} is the shortest path number between nodes i and j. $B(e)$ is the betweenness of edge e. δ_{ij}^{e} denotes the number of shortest paths through edge e. $D(e)$ is the weight of the edge e, D_i and D_j denote the degree values of nodes i and j, respectively.

Analysis of influencing factors

The geographical detector model is a statistical approach of spatial variability, which can solve the problem of multicollinearity of factors that many mathematical models can not overcome (Xu et al. 2022). Meanwhile, it is possible to interconnect digital maps and economic statistics to realize the detection of the influence of a single factor on the dependent variable as well as the interaction of two factors on the dependent variable, making it extremely useful in studies of geospatial similarity and dissimilarity (Ren and Cao 2022; Yao et al. 2023). In this study, factor detector and interaction detector were specifically chosen to explore the main influencing factors and their interactions on the spatial and temporal changes of the GI network of the study area.

By using the factor detector, the explanatory power q of the independent variable X with statistical significance to its dependent variable Y can be clarified (Xu et al. 2022; Zhang et al. 2022a). The formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} n_h \sigma_h^2}{n\sigma^2} \quad (5)$$

where σ^2 is the variance of the dependent variable Y, σ_σ^2 is the variance of the dependent variable of each grid, n is the number of samples in the study area, n_h is the number of samples of grid h, L is the number of grids in the study area.

The interaction detector can calculate and compare the relationship between the explanatory power $q(\text{X1})$, $q(\text{X2})$ of the independent variables X1 and X2 to the dependent variable Y and the explanatory power $q(\text{X1}\cap\text{X2})$ of the interaction between X1 and X2, and analyze whether the explanatory power of the two independent variables X1 and X2 to the dependent variable Y has an interaction enhancement or weakening trend, or is independent of each other (Ni et al. 2022; Zhang et al. 2022b). The types of interaction relationships are shown in Table 4.

Table 4 Types of two-factor interaction results

Condition	Interaction relationship
$q(\text{X1}\cap\text{X2}) < \text{Min}(q(\text{X1}),q(\text{X2}))$	Nonlinearity attenuation
$\text{Min}(q(\text{X1}),q(\text{X2})) < q(\text{X1}\cap\text{X2}) < \text{Max}(q(\text{X1}),q(\text{X2}))$	Single-factor nonlinearity attenuation
$q(\text{X1}\cap\text{X2}) > \text{Max}(q(\text{X1}),q(\text{X2}))$	Two-factor enhancement
$q(\text{X1}\cap\text{X2}) = q(\text{X1}) + q(\text{X2})$	Independence
$q(\text{X1}\cap\text{X2}) > q(\text{X1}) + q(\text{X2})$	Nonlinearity enhancement

Results

Ecological resilience

The overall spatial distribution pattern of ecological resilience in the study area can be summarized as "high in the west and low in the east", and the spatial differentiation characteristics are significant (Fig. 6). The high value areas were mainly distributed in Bijie and Anshun in the northwestern part of the study area, mainly composed of nature reserves, forest parks, water sources, and wetlands. The low value areas were clustered in Zunyi and Guiyang in the northeastern part of the study area, mainly composed of construction land and bare rock gravel land. Among them, from 2000 to 2010, the high value area increased slightly in the northeast of the study area, and there was obvious degradation in the western part of the study area. At the same time, the low value area degraded obviously in the southeastern part of the study area, and a large number of scattered new areas appeared in the middle of the study area. From 2010 to 2020, the high value area continued to degenerate in the eastern part of the study area, and the low value area had a significant trend of spreading expansion in the southeast and central parts.

Combining ecological resilience with land use types, with concentrated, large areas (>10 km^2 patches) of woodland and waters as ecological sources. The number of ecological sources in the three periods of 2000, 2010, and 2020 were 115, 108, and 105, with a total area of 10,674.96 km^2, 9788.93 km^2, and 10,256.98 km^2, respectively. During the study period, the area where the number of ecological sources decreased was mainly concentrated in the southern part of Qiannan Prefecture, and the number of ecological sources in Zunyi and the northern part of Bijie increased. Among them, the number of ecological sources in the eastern part of Qiannan Prefecture increased in 2010 but decreased in 2020.

The GI network in the study area

The spatial and temporal changes of the ecological resistance surface were significant during the study period. Overall, the ecological resistance value showed an upward trend from 2000 to 2020 (Fig. 7). The areas with high resistance values were mainly distributed along Zunyi-Guizhou-Qiannan-Qiandongnan, and the areas with low resistance values were mainly concentrated in the Bijie. From 2000 to 2010, the areas of growth in ecological resistance values were mainly concentrated in the southern part of Zunyi and the northern part of Qiannan. From 2010 to 2020, the areas of growth in ecological resistance values shifted to the western and northern parts of the study area. Among them, the resistance values in most of Bijie showed a continuous upward trend, and only the ecological resistance values in the northern part of Zunyi showed a relatively significant decrease.

In 2000, there were 217 corridors in the GI network of Qianzhong urban agglomeration, with lengths ranging from 1.65 to 131.16 km, and a total length of 4969.86 km (Fig. 8). The number of corridors decreased significantly in 2010, with 183 and a total length of 4284.83 km. The degraded areas of corridors were mainly concentrated in the southern part of Zunyi and the western part of Guiyang, with a few growth occurring in the northern part of Zunyi. In 2020, the total number of corridors was 190 with a total length of 4395.01 km, a slight increase from 2010. The number of corridors in the northern part of Zunyi, the northern part of Bijie, and the southeastern part of Qiannan increased slightly, and decreased in other areas, with the most obvious decrease in the number of corridors in the western and northern parts of Zunyi.

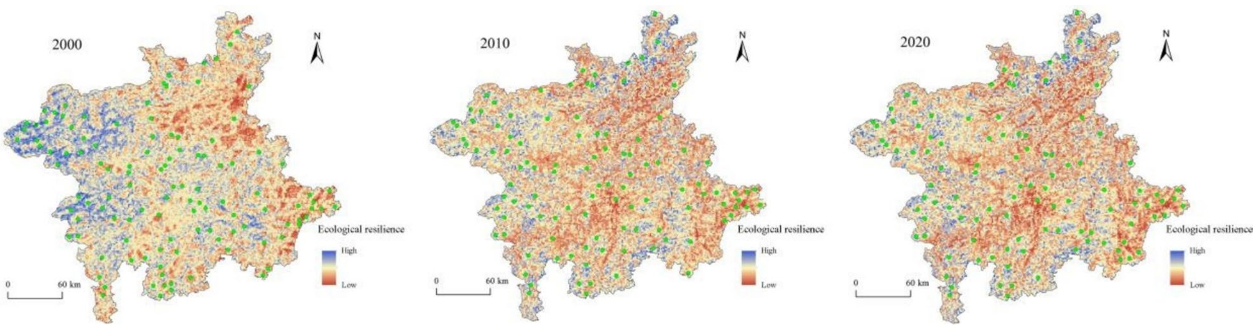

Fig. 6 Distribution of ecological source

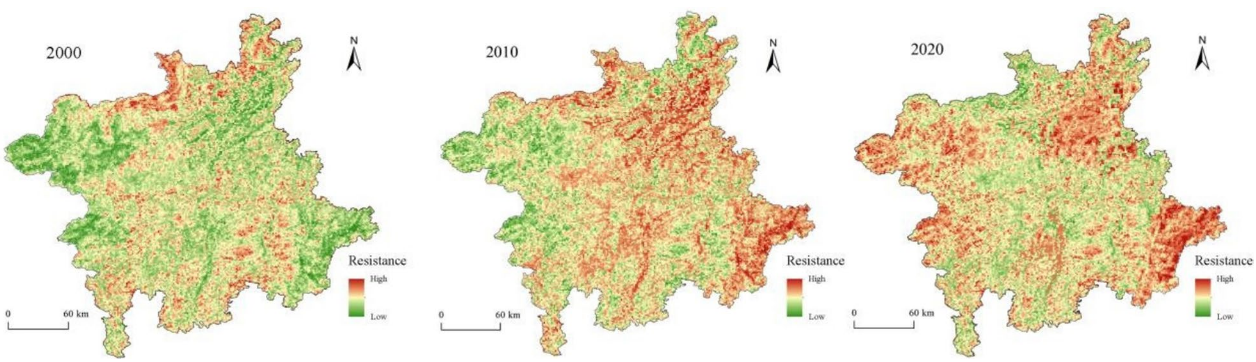

Fig. 7 Distribution of ecological resistance

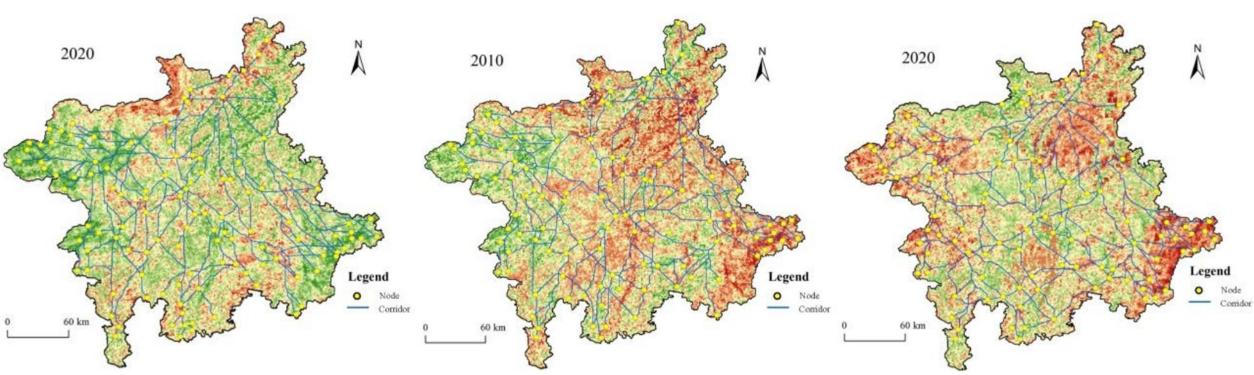

Fig. 8 Distribution of GI network

Spatial distribution characteristics of GI network elements

According to the spatial distribution characteristics of node degree and node betweenness of GI network, it was shown that the node degree and betweenness of high urbanization area were higher than those of low urbanization area (Fig. 9). Although the northern part of Guiyang has fewer nodes, it plays a vital role. Moreover, from 2000 to 2020, with the decrease in the number of nodes, the number of nodes with high node degree and betweenness in the study area also decreased, and the ecological value decreased. In 2000, the nodes with high degree and betweenness were mainly located in the central and northwestern parts of the study area, and these nodes corresponded to generally larger source areas with higher ecological resilience. Some of the nodes in the central part of the study area decreased in degree or betweenness in 2010 and were less capable of ecological flow transfer or structural support for the network. In 2020, the degree of ecological nodes in the northwestern part of the study area generally decreased, and the ability to circulate ecological flows generally declined, while the degree and betweenness of some nodes in the southeastern part of the study area increased, and the structural stability of the network was improved.

The spatial distribution of corridor betweenness and weight of the GI network is as follows: in the central part of the study area, that is, the corridor betweenness or weight of the high urbanization area was generally higher, which had a greater effect on the overall structural stability of the network (Fig. 10). Especially in the north of Zunyi and southwest of Guiyang, although there were fewer corridors, they played a crucial role. From 2000 to 2010, corridors with high betweenness and weight generally shifted to the southeastern part of the study area, and the corridors in the southeastern part of Zunyi showed a significant decrease in betweenness and weight and a significant decrease in the transmission capacity for ecological flows. The weights of corridors in the northeastern part of the study area also showed a decreasing trend, contributing less to the structural stability of the network. From 2010 to 2020, the spatial distribution of corridor betweenness and weight in the study area was more balanced. The corridor betweenness and weight in northern Bijie and southern Zunyi were improved, and the ecological flow transmission capacity was significantly improved.

Influencing factors and interactions

The factor detector results of the spatial distribution of infrastructure networks in karst mountain urban agglomerations showed that the influence of natural factors was decreasing during the study period, while the influence of human factors continued to increase (Fig. 11). Specifically, DEM and NPP had significant driving effects on network distribution in 2000 and were the key natural influencing factors. In 2010, the influence of DEM and NPP on the spatial distribution of the network decreased significantly, and the GDP became the most dominant

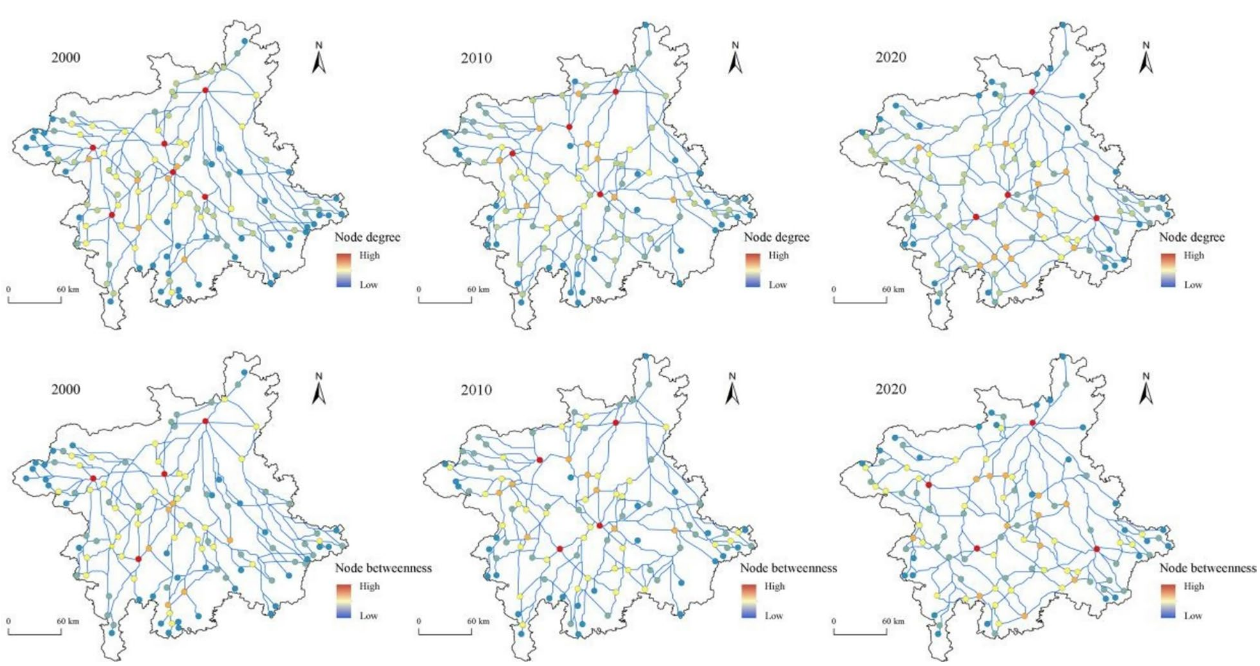

Fig. 9 Node characteristics analysis of GI network based on complex network theory

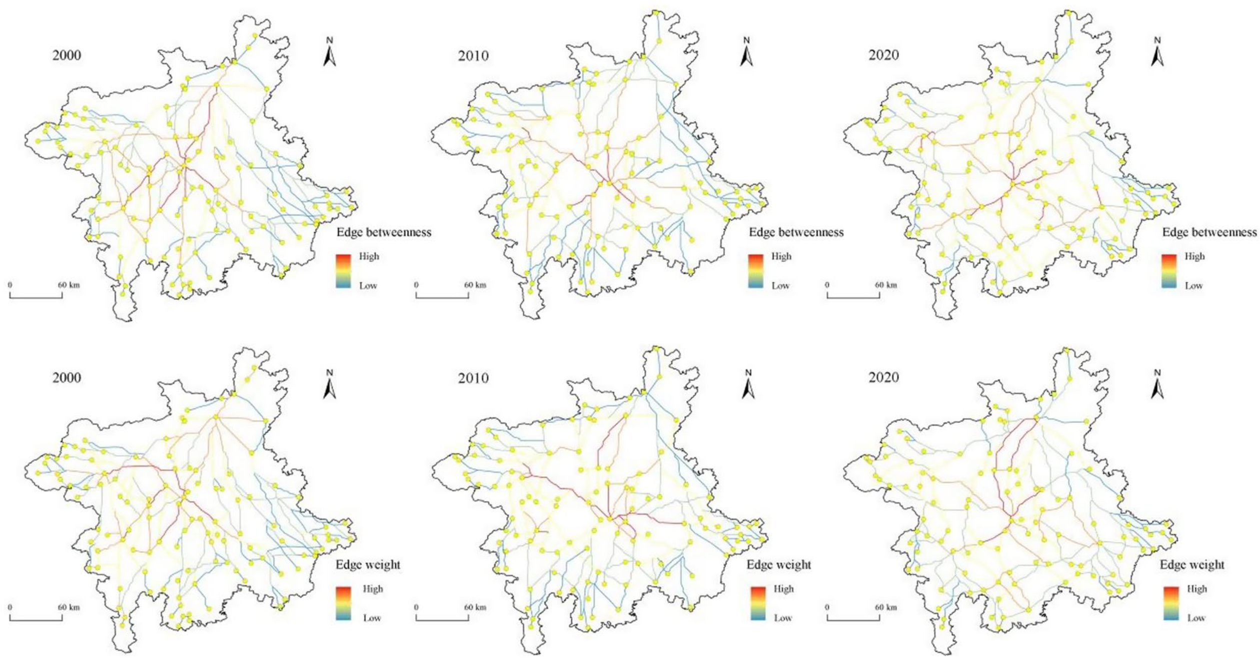

Fig. 10 Corridor characteristics analysis of GI network based on complex network theory

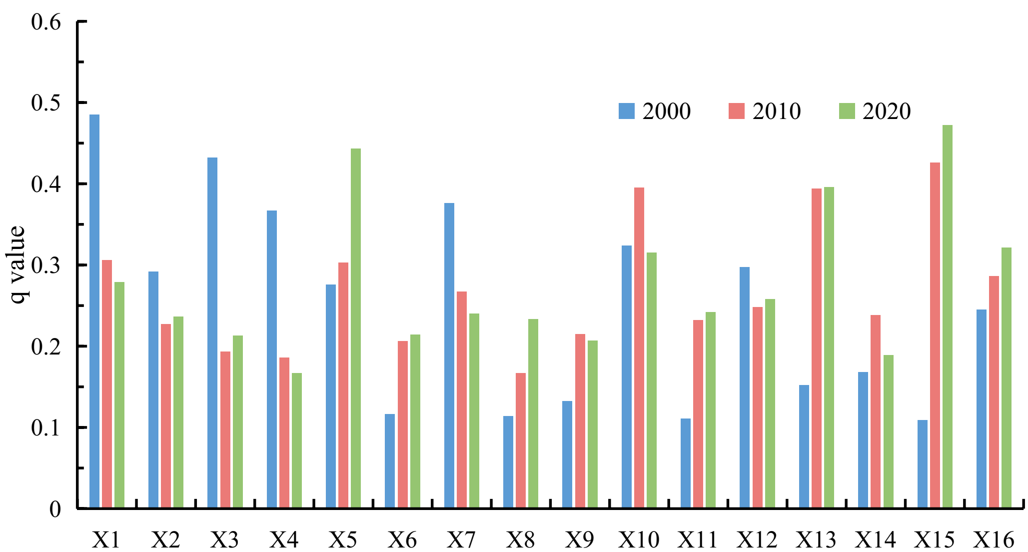

Fig. 11 The factor detector of GI network in the study area. X1 DEM; X2 Slope; X3 NPP; X4 MNDWI; X5 Rainfall; X6 Temperature; X7 Biodiversity index; X8 Distance from green space; X9 Distance from water; X10 Rock exposure rate; X11 Soil thickness; X12 Land use; X13 Road network density; X14 Population density; X15 GDP; X16 Night light intensity index.

human influencing factor, while at the same time, the influence of rock exposure rate increased rapidly and became the most dominant natural influencing factor. The influence of rainfall on the spatial distribution of the network was significantly higher in 2020, while GDP and night light intensity index became the main human influencing factor.

The results of the interaction detector showed that the spatial distribution of the GI network in the study area was influenced by multiple factors, and the interaction between the factors was enhanced (Fig. 12). From 2000 to 2020, the spatial distribution of the GI network in the study area gradually shifted from the interaction-enhancing influence of natural factors to the

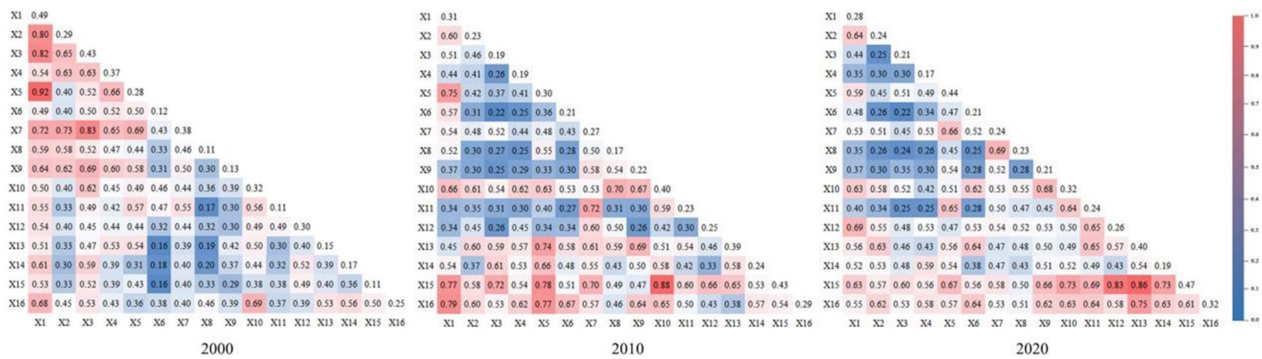

Fig. 12 The interaction detector of GI network in the study area. X1 DEM; X2 Slope; X3 NPP; X4 MNDWI; X5 Rainfall; X6 Temperature; X7 Biodiversity index; X8 Distance from green space; X9 Distance from water; X10 Rock exposure rate; X11 Soil thickness; X12 Land use; X13 Road network density; X14 Population density; X15 GDP; X16 Night light intensity index.

interaction-enhancing influence of human factors. The interaction between natural factors was particularly significant for the spatial distribution of the GI network in the study area in 2000. The strongest explanatory power was the interaction between DEM and rainfall. The interaction of natural and human factors in 2010 had strong explanatory power for the spatial distribution of the GI network in the study area, and the strongest explanatory power was the interaction between road network density and rock exposure rate, the interaction between DEM and night light intensity index was the second. In 2020 the interaction between human factors had a particularly significant influence on the spatial distribution of the GI network in the study area, and the interaction between human factors and natural factors also had a strong explanatory power. Among them, the interaction between GDP and road network density had a strong explanatory power and was the decisive condition for the spatial distribution of the GI network.

Discussion

The spatial distribution changes of GI network elements

Through the analysis of the spatial distribution characterization of GI network elements, we found that there was a close correlation between corridors and sources, and that the corridor between nodes with high degree and betweenness tends to have higher corridor betweenness and weights as well. Therefore, the ecological management focusing only on corridor protection and construction is unscientific. Meanwhile, we found that the areas with higher levels of urbanization have a small number of nodes and relatively sparse corridors, but play an important role in the ecological flow transfer efficacy and structural stability of the network. This is related to the better development of the regional economy, and the government may invest more funds in land use adjustment (Chen et al. 2018). Compared with the surrounding cities, Guiyang in the central part of the study area is more economically developed and has more financial support for environmental construction, so the quality of GI elements was relatively good. While Qiannan and Qiandongnan, which have lower urbanization levels in the study area, have a relatively dense distribution of ecological nodes and ecological corridors, the corresponding ecological sources of the nodes were generally less resilient or the width of the corridors was narrower. At the same time, due to the influence of geomorphological factors, the habitat quality of blue-green landscape patches in Qiannan and Qiandongnan is poor and the fragmentation is serious. Therefore, for the construction of the regional GI network with a low urbanization level and poor ecological matrix, the number, location, and cost of adjusting land should be considered as a whole, and the ecologically unsuitable land should be adjusted and restored to ecological land as soon as possible (Chatzimentor et al. 2020). In recent years, the Guizhou government has designated several different levels of nature reserves in the surrounding areas of the study area (Ji et al. 2023), which provides corresponding policy support for the protection of GI network elements with low urbanization level and helps the self-healing of ecological source patches. Therefore, in the face of the imbalance of the internal development of urban agglomerations and the differences in the ecological basis, the government should formulate corresponding measures differently, clarify the key points, and implement policy measures according to local conditions.

The positive influence of human factors on GI network is emerging

With the continuous improvement of urbanization level and the coupling of human activities and natural factors, the overall spatial distribution of the GI network in the study area from 2000 to 2020 showed a trend of degradation first and then improvement. Previous studies have shown that large-scale urban development has not only changed the original natural environment, resulting in significant changes in the ecological environment, causing soil erosion, landslides, debris flows, and other geological disasters but also caused the urban heat island effect, which has different degrees of impact on the surrounding natural environment (Chi et al. 2018). However, it is worth noting that with the rapid development of the regional economy, human factors as the main influencing factors in 2020 have driven the overall situation of the GI network to improve, and the positive impact of human factors is emerging.

Combined with the actual situation of the study area, in 2005, the Guizhou provincial government put forward the strategic goal of "accelerating the construction of ecological civilization and building an ecologically beautiful Guizhou", which started the course of ecological civilization construction in Qianzhong urban agglomeration (Li and Geng 2022). Since then, the government has formulated a series of plans and policies for the construction of ecological civilization, such as the "Guizhou Provincial Plan for the Construction of Ecological Civilization" and the "Guizhou Provincial Regulations on Ecological Environmental Protection" (Wang et al. 2020), which have laid down the legal foundation for ecological construction in the study area. At the same time, many ecological initiatives have been implemented (Zhang et al. 2019). Firstly, the efforts of re-greening abandoned land and ecological land restoration and reconstruction were increased, and ecosystem pollution problems were mitigated with the help of biocontrol and other technologies, focusing on increasing pollution monitoring and prevention of phosphorus mines and coal mines. This led to a significant enhancement of ecological environments, especially Guiyang, in the central part of the study area. Secondly, it optimized the planting structure of urban agglomerations and increased the beneficial interaction between human and natural elements (Li and Geng 2022), thus reducing human inputs. This led to an effective increase in the ecological benefits of vegetation, especially in the Qiannan and Qiandongnan, where the quality of ecological sources improved significantly. Addition, in the northeastern part of the study area, combined with ecological conservation means to utilize the natural landscape in the area to create scenic ecological corridors, ecological transition zones, and so on, to strengthen the protection of mountain slopes, and to restore natural forests. The above measures have greatly promoted the addition of GI network corridors in Guiyang and Zunyi.

Natural factors continue to have a significant influence on GI network

The results showed that DEM was the main factor influencing the spatial distribution of the GI network in the study area in 2000, and the interaction with NDVI has the strongest explanatory power. The DEM in the karst area is generally high, and the problem of soil and water loss is often more serious. It is easy to cause soil corrosion, destroy surface vegetation, and eventually lead to the degradation of the GI network. This may be the reason why the interaction between DEM and NDVI has such a strong explanatory power. This phenomenon is especially obvious in Zunyi in the southern part of the study area. Therefore, to mitigate the negative impacts of DEM on the GI network in karst areas, more attention should be paid to the status of vegetation restoration. Relevant studies have shown that artificial vegetation restoration is more resilient than natural vegetation (Li and Geng 2022).

As an area of highly developed karst, the rock exposure rate has always played a large role in influencing the GI network in the study area, especially along the Anshun-Guiyang-Qiannan-Qiandongnan route, where the rocky desertification landscape constitutes a major influence on the survival and development of the local inhabitants and species, and the overall ecological security is threatened by special geomorphological factors. But thankfully the results of the study showed that the influence of rock exposure rate in the later stages of the study area was reduced, which was due to the comprehensive launch of the special action of rocky desertification control (Huang et al. 2021a). The GI network in the karst landscape development area mainly faces three problems: first, the ecological source patches are fragmented and the ecological service functions are limited due to the impacts of production and construction and rock desertification erosion. Second, the ecological corridors are discontinuous or too narrow, they are subjected to rocky desertification erosion and the ecological environment is extremely fragile (Li and Geng 2022). And third, the ecological barriers are more seriously degraded due to the influence of rock desertification. Therefore, curbing the influence of rocky desertification on the GI network in karst areas is a long-term systematic and comprehensive project.

Additionally, extreme weather events such as frequent rainstorms and droughts have occurred frequently in karst regions in recent years, which is consistent with the current global warming trend. The results of the study also showed a gradual increase in the influence of rainfall on the spatial distribution of the GI network. Qianzhong urban agglomeration is located in the southern subtropical region, rainfall is generally abundant, but due to the unique karst geological environment, rainwater infiltration is rapid, there are many bare rocks on the surface, and the water storage capacity is weak, which makes it easy to effectively utilize the surface water resources that are extremely limited (Wang et al. 2020; Zhang et al. 2019). Meanwhile, the region is also facing a serious lag in the development of water infrastructure. How to enhance the resilience of GI networks in the face of frequent extreme weather events is worthy of further discussion.

Implications for GI networking in karst areas in the process of urbanization

The spatial distribution of the GI network in the study area showed that the highly urbanized central region has fewer sources but plays a significant role in the network performance. Comprehensive adjustment of land use in these areas will bring huge economic pressure to the government (Zhao et al. 2019). For this reason, in practice, it is possible to combine "organic renewal", "smart growth" and "urban transformation" (Jiang et al. 2015). It could strengthen the control of construction land in the study area, make full use of scattered green space, adjust the number and form of various landscape patches, and organize and integrate ecological patches such as blue-green space channels and green corridors (Yang et al. 2020), to enhance the performance of ecological source and curb the impact of polarization effects. For the areas around the study area with low urbanization level, the ecological sources are mostly located in forest parks, nature reserves, scenic spots, and so on, with relatively good substrate conditions and less human disturbance, such as Bijie, Qiannan, and Qiandongnan. This is largely attributed to the relative stability of land use in the region as a result of the Government's enhanced conservation measures. Meanwhile, as an ecological barrier in the study area, the above area should be further strengthened with its woodland and grassland connectivity, to form a continuous and stable ecological functional area, and continuously amplify the diffusion effect of the regional infrastructure network.

Corridors of the GI network are bridges between ecological patches and play a crucial role in species migration (Huang et al. 2020). Constructing these corridors effectively, with a focus on enhancing the betweenness and weights of the corridors, will help to balance the relationship between human activities and natural habitats. In contrast, the betweenness and weight of corridors in highly urbanized areas are generally high. Strengthening the maintenance of corridors in these areas is a necessary condition for enhancing the integration of corridors in the karst area. Less urbanized areas are generally more ecologically sound and have more ecological land, so the corridors of the GI network are easier to maintain. In the process of urbanization, the designation of priority restoration areas is important for the effective construction of ecological corridors (Huang et al. 2021a). The low urbanization area requires relatively low financial investment to change the nature of land use, which is very suitable as a priority area for ecological restoration, so it can be used as an important part of corridor construction.

Limitations of the study and directions for future research

Considering the actual situation of karst mountain cities, the study constructed a resistance surface system consisting of 12 factors, including rock exposure rate, which improved the accuracy to a certain extent, but there are still biases with the actual situation, and it is necessary to incorporate more regional characteristic factors in the future to continuously improve the accuracy. At the same time, this study systematically evaluated the spatial and temporal variations of GI network topology sources and corridors using complex network theory. However, it is worth noting that undirected and unweighted analysis methods and indicators are used in complex network analysis. However, the development of urbanization will make the importance of GI network elements different. This GI network is directionless and weighted, which leads to the need for appropriate adjustment based on the research results in practice. The research on this directionless and weighted network is the future research direction of complex networks. In addition, the Qianzhong urban agglomeration in the study area is a key area in the western development strategy of China, and also a key area in the implementation of returning farmland to forests for ecological protection, and different policies will change its GI network, so it is necessary to explore the impact of different policies on the change of the GI network of karst mountain urban agglomerations in the future, to provide a reference for the policy formulation and assessment.

Conclusion

In this study, we analyzed the spatial and temporal variations of GI network elements in karst mountain urban agglomeration and the driving influence mechanism. Firstly, the "pattern-function" ecological resilience assessment model was constructed to quantify the ecological resilience of landscapes to identify the sources of the GI network. Secondly, considering the special geomorphic environment, the resistance surface was modified by adding the rock exposure rate factor, coupling the MCR and gravity model to extract the GI network in the study area in different periods. Then, the complex network theory was innovatively introduced to assess the spatial and temporal variations of the GI network elements. Finally, applying geographical detector to explore the dominant factors and interactions that influence the spatial distribution of the GI network. The research results give an example for the analysis of the GI network in karst mountain cities and provide an important reference for urban ecological managers.

The study reveals that from 2020 to 2020, the overall distribution pattern of ecological resilience in the study area was “high in the west and low in the east”, and the spatial differentiation was significant. The overall development of GI network elements shows a trend of declining first and then rising. Compared with low-urbanized areas, the ecological sources or corridors in high-urbanized areas play an important role in the transmission of ecological flows and the overall structural stability of GI network. The nodes or corridors with high importance generally shifted to the southeast of the study area from 2000 to 2010, and the spatial distribution was more balanced from 2010 to 2020. During the study area, the explanatory power of natural factors to the spatial distribution of the GI network gradually weakened, and the explanatory power of human factors gradually increased. The spatial distribution of the GI network is affected by many factors, and all factors are interactively enhanced. The spatial distribution of the GI network is the result of the superposition of many factors. During the study period, it gradually changed from the interaction-enhancing influence of natural factors to the interaction-enhancing influence of human factors. High rocky desertification and vegetation coverage are the main problems that plague the construction of the GI network in karst mountain cities. The positive effect of human factors on the GI network is emerging, and the implementation of ecological policies plays an important role in the overall spatial layout of GI.

Abbreviations

GI	Green infrastructure
MCR	Minimum cumulative resistance
ECDM	Effective cost distance model
GAP	Geographic approach to protect biological diversity
NDVI	Normalized difference vegetation index
MNDWI	Modified normalized difference water index
DEM	Digital elevation model
GDP	Gross domestic product
NPP	Net primary productivity
HWSD	Harmonized world soil database
ERS	Ecological resilience
AHP	Analytic hierarchy process
EWM	Entropy weight method

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Author contributions
SS: conceptualization, software, validation, writing-original draft, and writing—review and editing. SHW: methodology and investigation. SSH: validation and software. DWX: conceptualization, resources, project administration, and funding acquisition. YG: methodology and investigation. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets used and analysed in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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