Using complex network analysis to assess the ecological security network for a rapid urbanization region in China

De Zhou[1], Zhulu Lin[2], Tingting Yan[1], Jialing Qi[1], and Wenyu Zhong[1]

[1]Zhejiang Gongshang University
[2]North Dakota State University

November 21, 2021

Abstract

A sound ecological security network (ESN) promotes the interconnection of ecological sources, improves the pattern of ecological security, and alleviates the degradation of an ecosystem. Rapid urbanization and land use changes may lead to serious fragmentation and islanding of landscape patches and further to deep disturbance of regional ESNs. However, most studies in the recent years focused on the methodological development of ESN identification, reconstruction, and optimization, but lacked the systematic assessment of the network after its construction. The purpose of this study is to use complex network analysis to systematically assess the constructed ESN for the urban agglomeration around Hangzhou (UAHB), a rapid urbanization region in China. By integrating landscape ecology theory, graph theory, and complex network analysis, we abstracted the ESN into a topological network and developed an index system to assess the abstracted network, which was based on the structural elements of the topological network (nodes, edges, and the overall network). Our results show that the connectivity and stability of the UAHB's ESN have been improved in the last 20 years, although isolated nodes are still existing in the ESN. Our study also shows that the network's robustness under human disturbance has been affected more than that under non-human disturbance. Finally, we proposed five optimization strategies from the perspective of topological structure and ecological function to maintain a sustainable and well-protected ecological system.

Title page

Using complex network analysis to assess the ecological security network for a rapid urbanization region in China

De Zhou

Department of Land Resources Management

Zhejiang Gongshang University

Zhulu Lin

Department of Agricultural and Biosystems Engineering

North Dakota State University

Tingting Yan

Department of Land Resources Management

Zhejiang Gongshang University

Jialing Qi

Department of Land Resources Management

Zhejiang Gongshang University

Wenyu Zhong

Department of Land Resources Management

Zhejiang Gongshang University

Correspondence information: De Zhou

Department of Land Resources Management

Zhejiang Gongshang University

18 Xuezheng St., Xiasha University Town

Hangzhou 310018, China

Phone: (+86) 0571-28008327

Email: zhoude520@163.com

Using complex network analysis to assess the ecological security network for a rapid urbanization region in China

De Zhou[1,] 11[*] Corresponding author.*E-mail addresses*: zhoude520@163.com (D. Zhou).**, Zhulu Lin** [2]**,Tingting Yan**[1]**, Jialing Qi**[1]**, Wenyu Zhong**[1]

[1] *Department of Land Resources Management, China Institute of Land and Urban Governance, Zhejiang Gongshang University, 18 Xuezheng St., Xiasha University Town, Hangzhou 310018, China*

[2] *Department of Agricultural and Biosystems Engineering, North Dakota State University, Fargo, North Dakota 58108, USA*

Using complex network analysis to assess the ecological security network for a rapid urbanization region in China

Abstract: A sound ecological security network (ESN) promotes the interconnection of ecological sources, improves the pattern of ecological security, and alleviates the degradation of an ecosystem. Rapid urbanization and land use changes may lead to serious fragmentation and islanding of landscape patches and further to deep disturbance of regional ESNs. However, most studies in the recent years focused on the methodological development of ESN identification, reconstruction, and optimization, but lacked the systematic assessment of the network after its construction. The purpose of this study is to use complex network analysis to systematically assess the constructed ESN for the urban agglomeration around Hangzhou (UAHB), a rapid urbanization region in China. By integrating landscape ecology theory, graph theory, and complex network analysis, we abstracted the ESN into a topological network and developed an index system to assess the abstracted network, which was based on the structural elements of the topological network (nodes, edges, and the overall network). Our results show that the connectivity and stability of the UAHB's ESN have been improved in the last 20 years, although isolated nodes are still existing in the ESN. Our study also shows that the network's robustness under human disturbance has been affected more than that under non-human disturbance. Finally, we proposed five optimization strategies from the perspective of topological structure and ecological function to maintain a sustainable and well-protected ecological system.

Keywords: ecological security network; complex network; connectivity assessment; robustness assessment; urban agglomeration around Hangzhou Bay

1 INTRODUCTION

Global and regional ecological security patterns are facing grand challenges (Xie & Wu, 2020). The rapid urbanization and industrialization in most countries had led to various ecological problems (Bai et al., 2018; Ma, Bo, Li, Fang, & Cheng, 2019; Xie, He, Choi, Chen, & Cheng, 2020), such as ecological sources encroachment and destruction (Han, Liu, & Wang, 2015), habitat fragmentation (Ng, Xie, & Yu, 2011), biodiversity loss (Kong, Yin, Nakagoshi, & Zong, 2010), ecosystem deterioration (Ernstson, 2013), and ecological function and service value deterioration (Costanza et al., 1997). A well-performing ecological security network (ESN) is necessary to enhance landscape connectivity, protect biodiversity, mitigate ecosystem degradation, improve ecological security patterns, and promote sustainable development (Cui, Wang, Sun, & Lv, 2020; Dai, Liu, & Luo, 2020; Dame & Christian, 2008; Zhao, Ma, Wang, & You, 2019). As one of the most important concepts and methods of landscape ecology (Forman, 1995), the ESN is a spatial organization system that identifies the characteristics of linear ecological corridors (i.e., network edges), connects various ecological sources (i.e., network nodes), and reflects the combinations of spatial elements with structural and functional characteristics in a specific space (i.e., the overall network). The ESN couples network structure, function, and ecological processes.

Since the 1970s, scholars have been studying different aspects of ESNs, such as network construction (Fath, Scharler, Robert, & Hannon, 2017), network planning and assessment (Cook, 2002), nature conservation (Hepcan, Hepcan, Bouwma, Jongman, & Ozkan, 2009), collaborative environmental governance (Bodin et al., 2016), species interactions (Delmas, 2018), and biodiversity conservation (Modica et al., 2021). However, most studies in the literature have focused on the development of the methods for ESN identification, reconstruction, and optimization (Hu et al., 2018; Kong et al., 2010; Shen, Wang, & Fu, 2014; Shi et al., 2020; Xie, Zhou, & Guan, 2014; Yin et al., 2011; Zhang, Yang, & Fath, 2010). A few studies have dealt with spatial and temporal evolution and systematic assessment of the constructed ESNs (Fan & Yang, 2019; Wang et al., 2020; Yu et al., 2018; Zhou, Lin, Ma, Qi, & Yan, 2020). In China, assessing the constructed ESNs is still at the exploratory stage by using landscape pattern index or traditional network structure index of graph theory (Liu et al., 2019; Pascual-Hortal & Saura, 2006), apparently lacking a systematic evaluation index system based on the complex network theory. In addition, a few studies had explored the scale effect (Dong et al., 2021), especially on network stability and connectivity under different disturbance mechanisms (Fu, Mo, Peng, Xie, & Gao, 2019; Pocock, Evans, & Memmott, 2012). It is necessary to develop a set of scientifically defensible index systems for ESN assessment that will help to discover the similarities and differences between different ecosystems and to provide decision-makers with science-based network optimization strategies.

In the recent years, complex network analysis derived from graph theory has been widely used to assess the pattern and process of various networks (Yong, Donner, Marwan, Donges, & Kurths, 2018), such as urban networks (Fang, Yu, Zhang, Fang, & Liu, 2020), social networks (Vahidzadeh, Bertanza, Sbaffoni, & Vaccari, 2021), water networks (Sitzenfrei, 2021), transportation networks (Soh et al., 2016), ecological networks (Pocock, Evans, & Memmott, 2012), energy metabolism (Zhai, Huang, Liu, & Zhang, 2019), economic performance (Gao, Tian, Zhang, Shi, & Shi, 2021), land use decision-making (Xia, Li, Zhou, Zhang, & Xu, 2020), land use effects (Xia & Chen, 2020), and CO_2 transfer (Wang et al., 2021). A complex network is often understood as a distributed system that consists of multiple interconnected components with the network functionality being largely influenced by its structure, which, in turn, depends on the complexity of the network and the level of the interactions among components (Sitzenfrei, 2021). The network's ubiquity, importance, and complexity intrigued the scientific community to study the formation and the growth dynamics of the network, as well as to explore the security of the network, the vulnerability of the network's structure, and its robustness to random disaster and targeted disturbances (Callaway, Newman, Strogatz, & Watts, 2000; He, Liu, & Zhan, 2013; Yazdani & Jeffrey, 2011). Many statistical parameters have been proposed to describe the topology of complex networks (Jing & Wang, 2020), among which, degree, aggregation degree, betweenness centrality, closeness centrality, and network diameter are the most important parameters (Chen, Lu, Shang, Zhang, & Zhou, 2012; Liu, Slotine, & Barabási, 2011; Xia et al., 2018). These parameters cover many aspects of the network, such as static statistical characteristics, relatedness, connectivity, robustness, and resilience. In addition, some scholars have also evaluated the cluster characteristics of the network (Liu, Cao, Liu, Shi, & Liu, 2020).

The purpose of this study is to develop a framework and index system to assess the spatial topological structure of the ecological security network by integrating landscape ecology theory, graph theory, and complex network analysis for a rapid urbanization region in China, the urban agglomeration around Hangzhou Bay (UAHB) (see Supplemental Information (SI) Study area & Figure S1). The specific tasks include: (i) to construct a four-dimension assessment index system in terms of the network's nodes, edges, connectivity, and robustness; (ii) to explore the stability and anti-disturbance ability of the network through scenario simulation; (iii) to propose the feasible measures for the optimization of the UHAB's ecological security network. The framework and the technical roadmap of this study are shown in Figure 1.

The potential innovation of our study include: (i) evaluating the ESNs from the perspective of the network's topological structure by integrating landscape ecology theory, graph theory, and complex network analysis; (ii) comparing the characteristics of the ESNs under two different disturbance scenarios to reveal the dynamic evolution process of the connectivity and stability of the ESNs; and (iii) proposing measures for the optimization of the ESNs.

2 MATERIALS AND METHODS

2.1 Complex network analysis

Network structure analysis is the basis of network function optimization (Wang et al., 2019). As shown in Figure 2(a), a landscape is composed of ecological sources and ecological corridors (Turner, Gardner, & O'Neill, 2001). The constructed ESN of a landscape may be simplified into a topological network of nodes and edges (Figure 2(b)). As more and more topological networks join together, they form a complex network system as shown in Figure 2(c). Therefore, an ESN in this study is a complex spatial network with hierarchy and ecological attributes (Dehmer, Emmert-Streib, & Shi, 2017; Dai, Liu, & Luo, 2020). This study used complex network analysis to explore the spatial topological structure of the ESN. The topological structure of the ESN mainly includes nodes, edges, and the overall network. Nodes represent the basic units of the network and edges indicate the functional relations among the basic units. More details of assessment methods including ecological corridors, ecological nodes, network connectivity, and network robustness can be found in SI Complex network analysis methods and Eq. S1 to S11.

2.2 Disturbance scenarios

In this study, we designed two disturbance scenarios including non-human disturbance (NHD) and human disturbance (HD) based on the robustness assessment. NHD can be regarded as random natural disasters (e.g., forest fire, debris flow), whereas HD can be understood as purposeful human activities (e.g., land use change, urban sprawl).

In terms of NHD, we randomly deleted the nodes in the network by the "online random number generator" tool (https://rand.91maths.com/) to ensure the randomness of disturbance. The corresponding nodes were deleted in random numerical order to calculate the connectivity robustness and vulnerability robustness of the ESN. HD refers to the purposeful deletion of nodes in the ESN. We introduce the "disturbance radius" to control the initial direction of the disturbance. The specific operation in ArcGIS took the boundary of the developed land as the starting point and the value of 500 m as the radius to conduct buffer and spatial overlay analysis and to obtain the corresponding nodes distribution. The nodes within the radius were removed according to the comprehensive importance of the nodes, and then the nodes outside the radius were deleted to calculate the network robustness.

To simplify the problem, the following three assumptions were made when simulating network robustness:

- When the nodes or edges of the network are disturbed, the destructive power of each disturbance and the time needed for the disturbance to result in consequences are not considered; that is, once the disturbance occurs, the nodes or edges will be deleted and cannot be recovered.
- Once the nodes in the network are removed all the edges related to the removed nodes are also deleted; accordingly, that is, information transmission and energy flow through the removed nodes are blocked.
- A node in the disturbed network will become an isolated node when its neighboring nodes are deleted, but it can still perform some functions. Only when the node is destroyed by the direct disturbance, the node will be completely deleted.

2.3 Data sources and statistical analysis

The UAHB's ESN in 1995 and 2015 was constructed by Zhou, Lin, Ma, Qi, & Yan (2020), where the details of original data and analysis can also be found. In 1995, 43 ecological sources, 85 ecological nodes, and 134 key ecological corridors were identified or extracted (Figure 3); in 2015, these numbers were 41, 96, and 161, respectively.

In this study, network analyses were mainly performed in ArcGIS® (version 10.6), Excel® (version 2019), Pajek® (version 2.00), SPSS® (version 25.0), and R® (version 36.3). The indexes including degree, clustering coefficient, core of node, and node centrality indexes were calculated using Pajek software. The robustness assessment was achieved using R® and Pajek®. It should be noted that the isolated nodes in the ESNs were not included in calculating clustering coefficient, core of node, node comprehensive importance, and network robustness because their presence does not affect the functions of the network.

3 RESULTS

3.1 Key ecological corridors assessment

Although the UAHB ESN had about the same number of ecological sources in 1995 and 2015, it had 27 more key ecological corridors in 2015 than in 1995. This means that the connection between ecological nodes was strengthened in 2015. The total length of the key ecological corridors decreased slightly from 2289.25km in 1995 to 2238.50km in 2015 (see also Figure 3).

In the past 20 years (Table 1), the length of the key ecological corridors in Ningbo, Shaoxing, and Huzhou had increased from 1995 to 2015. The length of the *key* ecological corridors in Jiaxing remained zero, meaning that there were only isolated sources and/or the*general* ecological corridors in this area (Zhou, Lin, Ma, Qi, & Yan, 2020). Hangzhou had still the longest key corridors among the five cities and had the best network connectivity. However, the length of the key ecological corridors in Hangzhou had decreased from 1995 to 2015, which was mainly due to urban expansion and the increase of ecological sources area.

3.2 Ecological nodes assessment

3.2.1 Degree and degree distribution

The number of ecological nodes in the network increased from 85 nodes in 1995 to 96 nodes in 2015, which means that the number of habitats for migrating species in the UAHB had increased. The average degree of the network increased from 3.14 in 1995 to 3.36 in 2015, indicates that the network connectivity had slightly improved in the past 20 years.

Figure 4 shows the degree distributions of the UAHB's ESN in 1995 and 2015. In 1995, the maximum value of degree was 8, the minimum value of degree was 0, and the number of nodes with degrees 8, 7, and 6 only was accounted for 1%. In 2015, the maximum degree was 9, the minimum degree was 0, and there was one node with degree 9, accounting for 1%, and there was no node with degrees 8 and 7.

The proportion of the nodes with a degree greater than and equal to 4 was 29.4% in 1995 and 36.0% in 2015, indicating that the number of the nodes with a large degree increased significantly. However, the number of nodes with degree 3 accounted for the largest proportion in both years (48.2% in 1995 and 47.0% in 2015). The number of nodes with lower degrees (0, 1, and 2 degrees) decreased from 22.4% in 1995 to 17.0% in 2015. Overall, the connection between ecological nodes in 2015 was better than that in 1995.

Table 2 shows that the average degree (k') and the maximum degree (k_{max}) of the nodes in Ningbo, Shaoxing, and Hangzhou increased from 1995 to 2015, indicating that the network structure connectivity of these three cities increased. But, in Huzhou, all three indicators (k' , k_{max} , andk_{min}) decreased from 1995 to 2015, signifying decreasing network connectivity in this city in the past 20 years. Because Jiaxing had only isolated ecological sources in the network, the average degree, maximum degree, and minimum degree of the nodes were 0 in both 1995 and 2015.

3.2.2 Clustering coefficient

Table 3 presents the changes in clustering coefficients in 1995 and 2015. There were 30 and 31 nodes (accounting for 37.97% and 34.07% of the total number of nodes) with a clustering coefficient of 0 (no clustering) in 1995 and 2015, respectively. There were two nodes with a clustering coefficient of 1 (obvious clustering) in both 1995 and 2015. The nodes with a clustering coefficient greater than and equal to 0.4 accounted for 6.33% in 1995 and 11.00% in 2015, while the nodes with a clustering coefficient less than 0.4 accounted for 93.67% in 1995 and 89.01% in 2015, indicating that the cluster characteristics for most nodes were not obvious. The results show that the ESN in 2015 had obvious non-uniformity and the network structure was unstable, but compared with 1995, the structural stability of the ESN was slightly improved.

The average clustering coefficient of the ESN was 0.20 in 1995 and 0.22 in 2015. Although the average value in 2015 was slightly higher, the small world characteristic of the network was not obvious.

3.2.3 The core of node

Figure 5 shows that the maximum number of the core of nodes in the UAHB's ESN was 3 in 1995 and 2015, and the nodes with a core of 2 accounted for the highest proportion (80-86%). The percentage of the nodes with a core of 1 did not change from 1995 to 2015. The percentage of the nodes with a core of 2 increased from 80% to 86%, whereas the percentage of the nodes with a core of 3 decreased from 16% to 10%.

In terms of spatial pattern, Figure 5 shows that the nodes with a core of 3 were mainly concentrated in the southwest of the UAHB, while the nodes with a core of 2 were mainly distributed in the middle and southeast of the study area. The number of nodes with a core of 2 increased significantly from 1995 to 2015. The nodes with the decreasing core (from 3 to 2) were mainly distributed at the edge of the network, so we should pay more attention to protecting the nodes at the edges of the network in the future. Overall, the network connectivity had improved from 1995 to 2015.

3.2.4 Node comprehensive importance assessment

As shown in Figure 6, the node comprehensive importance was classified into five levels (higher, high, general, low, and lower). There were 10 nodes with high and higher importance levels in both 1995 and 2015. In 1995, more than half of the nodes were at the low level of importance, and 20 nodes were at the general level of importance. In 2015, the number of nodes with the general importance level increased significantly, while the number of nodes with the low importance level decreased evidently. However, the number of nodes with a lower importance level increased slightly.

Figure 6 also shows that the nodes with the high and higher importance levels were mainly distributed in the southwest of the study area, and a small number of nodes were in the south of the study area. Many corridors were passing through these nodes, and the land use in the areas was mainly forest, and the terrain was mainly mountainous and hilly. Therefore, these nodes played an important ecological function in the UAHB's ESN, they were the key to maintaining the stability of the ESN, and the protection of these nodes should be the focus of the construction of regional ecological security. Moreover, the nodes with the general importance level were mainly distributed in Hangzhou and Shaoxing, while the nodes with the lower importance were mostly dispersed in Ningbo and Huzhou. The protection of the ecological nodes in these cities should be strengthened.

3.3 Network connectivity assessment

Table 4 shows that the index a of the UAHB's ESN was higher in 2015 than in 1995, indicating that the material circulation in the ESN was smoother in 2015 than in 1995. The two indexes β and γwere also higher in 2015 than in 1995, which indicates that the network connection was complex. Although the network connectivity of the ESN had improved, there were still isolated nodes in the network.

Although the *Cost Ratio* declined from 0.94 in 1995 to 0.93 in 2015, the network cost was still relatively high, mainly because the ecological corridors (edges) constructed on the large scale of urban agglomeration stretches across more counties and cities, leading to higher network connection complexity. The results show that it is especially important for the regional ESN to give priority to the construction of ecological corridors with higher importance levels.

3.4 Network robustness assessment

As discussed above, the connectivity robustness (R_1) and the vulnerability robustness (R_2) represent the connectivity and the operation efficiency of the ESN, respectively. As shown in Figure 7(a,b,c,d), the initial values of R_1 of the ESN in 1995 and 2015 were both 1.0 and those of R_2 in 1995 and 2015 were 0.23. This indicates that the ESN in 1995 and 2015 had the same network connectivity and operation efficiency.

By and large, with more nodes being deleted from the network,R_1 and R_2 decreased under the two disturbance scenarios (NHD and HD). The number of deleted nodes and connected components appeared to be the inverted V-shaped relationship in 1995 and 2015 (Figure 7(e,f)).

4 DISCUSSION

4.1 Influencing factors of network stability

Our study shows that the structure and function of the ESN in the UAHB had improved significantly in the past 20 years. But how about the anti-jamming ability of the network? What were the factors that affected the network's connectivity and stability?

The network stability was closely related to the number of deleted nodes. In terms of the number of deleted nodes (Figure 7a,b,c,d),R_1 and R_2 under different disturbance scenarios were correlated with the number of deleted nodes, and both showed a decreasing trend. The overall trend ofR_1 and R_2 in the same year was roughly the same, but there were local differences. In 1995 (Figure 7a,c), when the node failure ratio (NFR, the ratio of the number of the deleted nodes to the total number of the initial nodes in the network) did not exceed 15% (12 nodes), the values ofR_1 and R_2 almost remained unchanged and the number of the connected components did not change, either (Figure 7e). The results show that the network structure was relatively complete, while the network was in a relatively stable state. When the NFR was at 15%-46%, R_1 andR_2 took different values under the two different disturbance scenarios (Figure 7a,c) and the number of the connected components increased, indicating that the degree of network fragmentation increased (Figure 7e). When the NFR was between 46% to 95%, the network complexity declined significantly with bothR_1 and R_2 reducing to less than half of their initial values and the network was extremely sensitive. When the NFR exceeded 95%, the number of the connected components in the two disturbance scenarios dropped to 0. At this time, there were only a few isolated nodes in the network, and the exchange and transmission of information and energy could not be carried out between the nodes, and the network was in a state of paralysis. Compared to 1995, the network structure in 2015 was relatively complete and the network was in a relatively stable state (Figure 7b,d,f). When more than 25% of nodes were deleted, the disturbance of the network structure became obvious, and the network started to break down. With increasing NFR, network stability declined, the number of the connected components increased rapidly, and the network fragmentation increased until the network was finally paralyzed.

In summary, it was found that the number of nodes influenced the integrity and complexity of the network and had an impact on the stability of the network. In 2015, the NFRs in the network characteristics including stable state, sensitive state, and paralytic state were all greater than that in 1995, indicating that the stability of the ecological security network in 2015 was better than that in 1995. Table 5 further describes the relationship between network robustness and the number of deleted nodes.

The way of nodes deletion was related to the stability of the network . As discussed above, the disturbance scenarios represented different ways of removing nodes from the network, i.e., NHD representing random deletion, whereas HD deleting the nodes with the higher level comprehensive importance first. As shown in Figure 7a,b,c,d, although the values of bothR_1 andR_2 eventually dropped to zero in both disturbance scenarios, the curves of the HD scenario had more fluctuation. For example, R_1 andR_2 of the HD scenario decreased more rapidly than that of the NHD scenario (Figure 7), when more than 15% of the important nodes were deleted. The results indicate that the stability of the ESN was more sensitive to human disturbance than to nonhuman disturbance. Especially, the nodes with a high level of comprehensive importance had a greater influence on R_2, meaning a greater impact on network efficiency.

Table 6 further illustrates the relationship between the network robustness and the way of node deletion. The stability of the ESN depended on the number of interactions of network nodes. The process of nodes deletion based on the level of comprehensive importance of the nodes usually represented the impact of the purposeful disturbance that was mainly caused by human activities. The network of good spatial structure can maintain high stability under any disturbance scenarios.

4.2 Ecological security network optimization

System scientists believe that restructuring is to reframe the system's structure to promote an optimal combination of the system's internal elements and to achieve the system's fundamental transformation (Zhou, Xu, & Lin, 2016). The optimization and reconstruction of the ESNs provide spatial planning methods to integrate ecological processes, spatial scales, and ecosystems. The complexity and uncertainty of the network's structure should be considered in the reconstruction of the ESNs. Combined with the reconstruction of the ESNs and the difference in ecological space protection strategy, we propose five measures to improve the regional ESN of the UAHB based on our research findings.

*The first measure is to protect the important ecological sources.*As the important network nodes, the ecological sources are the important habitats for the living beings in a region. Increasing their quantities and improving their quality is particularly important for the protection of the regional ecological environment and biodiversity. Compared with 1995, the area of ecological sources of the UAHB increased significantly in 2015 (Figure 3), but the increment was mainly concentrated in Hangzhou, while the areas of the sources in Jiaxing and Huzhou were small, and the corridor length between the sources in these two cities and other sources and nodes was considerable long. Therefore, we suggest that the integrity of national or provincial natural reserves, forest parks, large forest land, and wetlands should be strictly protected, and the forest land around them should be considered as part of the network, to increase sources area, to enrich the biological species, to improve the quality of the habitat, and to increase the suitability of the habitat (Liang, Liu, Liu, Qi, & Liu, 2018; Yin et al., 2011).

The second measure is to improve the effectiveness of connectivity between nodes . Nodes are the key to ensuring network connectivity. Their interactivity, importance, and quantity are important factors to maintain the integrity and complexity of the network structure. As displayed in Figure S2, there were two isolated nodes in Jiaxing (see also Figure S1). Although there were potential ecological corridors in Jiaxing, Huzhou, and other areas (see also Figure 3), only a few*key* ecological corridors existed due to large landscape resistance, so the ESN was not fully connected. On the one hand, the protection of the key nodes will not only help to improve landscape connectivity but also promote the virtuous cycle of logistics and energy flow in the network. On the other hand, we should implement spatially distributed control and protection measures based on the distribution characteristics of the important nodes to change the formation mechanism of the network and to realize the reconstruction of the ESN. At least three reconstruction strategies may be adopted based on the node importance: individual protection, general protection, and extensive protection. According to the needs of biological diffusion and the possibility of ecological construction, we suggest planning corridors to connect the two currently isolated sources in Jiaxing to promote their connection with the nearest nodes and to improve the ESN's structure.

The third measure is to restore ecological breaking points . Ecological corridors are an important part of the regional ESN, which can improve the overall quality of the regional ecological environment (Li, Han, & Tong, 2009). However, the more landscape types the ecological corridors cross, the greater the accumulated resistance of the landscape will be, which, in turn, will reduce the effectiveness of the functions of the ecosystem. Roads, especially high-grade road networks, have a certain barrier effect on the transfer of material and energy flows in the ESN, which may cause ecological breakpoints and habitat fragmentation. We conducted the overlay analysis of railway, expressway, national road, provincial road, and important ecological corridors in the network of the UHAB. The intersections of railways, expressways, and corridors were regarded as the main breaking points, while the intersections of national roads, provincial roads, and corridors were regarded as secondary breaking points. Overall, 36 main breaking points and 23 secondary breaking points were extracted (Figure 8). Currently, many scholars have called to include wildlife passageways such as underground passageways, tunnels, and overpasses in the construction codes of the high-grade roads (Chen, Yin, Kong, & Yao, 2015; Yin et al., 2011). According to the current economic and social development level of the UAHB, it is suggested that the high-grade roads network should avoid the areas where wildlife activities are frequent and provide more access to wildlife by restoring ecological breakpoints.

The fourth measure is to strengthen the protection and planning of steppingstones . The steppingstones can provide temporary habitats for migrating species, especially for the species with long migration distances. The quantity, quality, and spatial locations of the steppingstones are important factors that affect the time, frequency, and success rate of species migration and increase the regional biodiversity (Yin et al., 2011). Therefore, it is necessary to strengthen the protection of the existing steppingstones and the planning and construction of future steppingstones. When combined with the intersection of important ecological corridors and the nodes' comprehensive importance in the network, the nodes with high comprehensive importance are selected as steppingstones. As a result, 21 steppingstones are identified and selected in our study (Figure 9).

The fifth measure is to connectthe ESNs with the surrounding areas at different scales . The interconnection of the networks inside and outside the region can contribute to the material exchange and energy transfer, enhancing the ecosystem stability (Yin et al., 2011). At present, the surrounding areas of the UAHB, such as Jiangsu, Anhui, Jiangxi, Fujian, and Shanghai, also have a good ecological environment. Therefore, in the process of improving the internal network of the UAHB, it is suggested to strengthen the connection of the ESNs between the UAHB and the surrounding areas at different scales. This will not only help to improve the stability of the ecosystems but also enable the ESNs to have longer buffer zones and recovery times when they are damaged by external disturbances.

4.3 Limitations

Our case study in the UAHB may provide empirical evidence and support in terms of space optimization, planning, and protection of the ESNs in other regions where are also experiencing rapid urbanization.

However, our study is not without limitations. First, the assessment indexes of ESNs can be further improved. The area and shape of ecological sources have important influences on the structure and function of an ESN, but these influences cannot be reflected merely based on the analysis of network topology. Second, we assume that nodes and edges are not functioning when they are disturbed and ignore the situations when they may partially or fully recover from disturbance.

5 CONCLUSIONS

Integrating complex network analysis and graph theory, we abstracted the ESN into the topological networks of the UAHB in 1995 and 2015, and further assessed these networks' spatial and temporal evolutions through the constructed index system in terms of network nodes, edges, connectivity, stability, and robustness. We also proposed the corresponding strategies to optimize the structure of the ESN in five aspects. The main findings were as follows:

1. From 1995 to 2015, the area and quantity of ecological sources increased, and the connection between sources had enhanced. The sources of nature reserves and reservoirs of the western areas increased and made an important contribution to the expansion of ecological security space. The improvement was influenced by government policies. The results also mean that there were more channels for material and energy exchanges between the nodes in the UAHB. However, the development of the ESNs was unbalanced within the UAHB. For example, the nodes with the high comprehensive importance levels were mainly distributed in the southwestern and southern areas.
2. Assessment of the network connectivity shows that the connectivity in 2015 had significantly improved compared with 1995, but there were isolated nodes in the network with the high network connection complexity. Furthermore, the regional network needed to be given priority to the construction of ecological corridors with higher importance levels.
3. The robustness assessment shows that the changes of connectivity robustness and vulnerability robustness under human disturbance were more dramatic than those under non-human disturbance. The stability of the ESN was more sensitive to human disturbance, and the nodes with the high comprehensive importance were the key to ensuring the efficiency of network connectivity and information transmission and played an important role in maintaining the stability of the ESN. The results also indicate that the number of nodes had a large impact on the stability of the network. The ESN in 2015 was more connected and more efficient than it was in 1995.
4. There is room for improvement for the UAHB's ESN. For example, the areas of the ecological sources in some cities were too small to realize their intended ecological functions. The protection of important ecological sources and the effectiveness of the connection between patches should be strengthened. Ecological breaking points and steppingstones should be given priority to planning and constructing to improve the quality and effectiveness of network connections.
5. The empirical study shows that a sound assessment framework is an effective tool to enhance the links among the assessment of networks' structure and function, temporal and spatial evolution, driving factors, and optimization strategies of the ESN. The results of our study will provide theoretical reference and empirical support for other areas facing similar ecological challenges.

DECLARATIONS OF INTEREST

None.

ACKNOWLEDGMENTS

This work is supported by the Chinese National Funding of Social Sciences (19BGL283) and the National Natural Science Foundation of China (No. 41301619). The authors want to thank anonymous reviewers for their invaluable comments that led to a much-improved manuscript.

REFERENCES

Bai, Y., Wong, C. P., Jiang, B., Hughes, A. C., Wang, M., & Wang, Q. (2018). Developing China's ecological redline policy using ecosystem services assessments for land use planning. *Nature Communications* , *9* (1), 3034. https://doi.org/10.1038/s41467-018-05306-1.

Bodin, Ö., Robins, G., McAllister, R. R. J., Crona, B., Tengo, M., & Lubell, M. (2016). Theorizing benefits and constraints in collaborative environmental governance: a transdisciplinary social-ecological network approach for empirical investigations. *Ecology and Society* ,*21* (1), 40. http://dx.doi.org/10.5751/ES-08368-210140.

Callaway, D. S., Newman, M., Strogatz, S. H., & Watts, D. J. (2000). Network robustness and fragility: percolation on random graphs.*Physical Review Letters* , *85* (25), 5468. https://doi.org/10.1103/PhysRevLett.85.5468.

Chen, D. B., Lu, L. Y., Shang, M. S., Zhang, Y. C., & Zhou, T. (2012). Identifying influential nodes in complex networks. *Physica A: Statistical Mechanics and its Applications* , *391* (4), 1777-1787. https://doi.org/10.1016/j.physa.2011.09.017.

Chen, J. Y., Yin, H. W., Kong, F. H., & Yao, G. P. (2015). The complex ecological security network development around Taihu Lake, China.*Acta Ecologica Sinica* , *35* (9), 3113-3123. https://doi.org/10.5846/stxb201306101647. (in Chinese).

Cook, E. A. (2002). Landscape structure indices for assessing urban ecological networks. *Landscape and Urban Planning* ,*58* (2–4), 269–280. https://doi.org/10.1016/S0169-2046(01)00226-2.

Costanza, R., D'Arge, R., Groot, R., Farber, S., Grasso, M., Hannon, B., ... Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature* , *387* , 253–260. https://doi.org/10.1016/S0921-8009(98)00020-2.

Cui, L., Wang, J., Sun, L., & Lv, C. (2020). Construction and optimization of green space ecological networks in urban fringe areas: A case study with the urban fringe area of Tongzhou district in Beijing. *Journal of Cleaner Production* , *276* (10), 124266. https://doi.org/10.1016/j. jclepro.2020.124266.

Dai, L., Liu, Y. B., & Luo, X. Y. (2020). Integrating the MCR and DOI models to construct an ecological security network for the urban agglomeration around Poyang Lake, China.*Science of The Total Environment* , *754* , 141868. https://doi.org/10.1016/j.scitotenv.2020.141868.

Dame, J. K., & Christian, R. R. (2008). Evaluation of ecological network analysis: Validation of output.*Ecological Modelling* , *210* (3), 327–338. https://doi.org/10.1016/j.ecolmodel.2007.08.004.

Dehmer, M., Emmert-Streib, F., & Shi, Y. (2017). Quantitative graph theory: a new branch of graph theory and in network science. *Information Sciences* , *418–419* , 575-580. https://doi.org/10.1016/j.ins.2017.08.009.

Delmas, E., Besson, M., Brice, M. H., Burkle, L. A., Dalla Riva, G. V., Fortin, M. J., Gravel, D., Guimaraes, P. R., Hembry, D. H., Newman, E. A., Olesen, J. M., Pires, M. M., Yeakel, J. D., & Poisot, T. (2018). Analysing ecological networks of species interactions. Biological Reviews. *Biological Reviews* ,*94* (1), 16–36. https://doi-org.ezproxy.lib.ndsu.nodak.edu/10.1111/brv.12433.

Dong, J., Peng, J., Xu, Z., Liu, Y., & Li, B. (2021). Integrating regional and interregional approaches to identify ecological security patterns. *Landscape Ecology* , *36* , 2151–2164. https://doi.org/10.1007/s10980-021-01233-7.

Ernstson, H. (2013). The social production of ecosystem services: a framework for studying environmental justice and ecological complexity in urbanized landscapes. *Landscape and Urban Planning* ,*109* (*1*), 7-17. https://doi.org/10.1016/j.landurbplan.2012.10.005.

Fan, Q. Y., & Yang, S. (2019). Evolution and optimization of spatial structure of the Yangtze River Delta Urban Agglomeration from the perspective of coordination. *Journal of Natural Resources* ,*34* (8), 1581–1592. https://doi.org/10.31497/zrzyxb.20190802. (in Chinese).

Fang, C., Yu, X., Zhang, X., Fang, J., & Liu, H. (2020). Big data analysis on the spatial networks of urban agglomeration. *Cities* ,*102* , 102735. https://doi.org/10.1016/j.cities.2020.102735.

Fath, B. D., Scharler, U. M., Robert, E., & Hannon, B. (2017). Ecological network analysis: Network construction. *Ecological Modelling* , *208* (1), 49– 55. https://doi.org/10.1016/j.ecolmodel.2007.04.029.

Forman, R. T. T. (1995). Land mosaics: The ecology of landscapes and regions. Cambridge, NY: Cambridge University Press.

Fu, L. H., Mo, Z. C., Peng, Y. B., Xie, M., & Gao, X. Y. (2019). Stability identification and reconstruction strategy of ecological space network at the county scale: A case study of Chaling County, Hunan Province. *Acta Geographica Sinica* , *74* (7), 1409-1419. https://doi.org/10.11821/dlxb201907010. (in Chinese).

Gao, H., Tian, X., Zhang, Y., Shi, L., & Shi, F. (2021). Evaluating circular economy performance based on ecological network analysis: a framework and application at city level. *Resources Conservation and Recycling* , *168* , 105257. https://doi.org/10.1016/j.resconrec.2020.105257.

Han, B., Liu, H., & Wang, R. (2015). Urban ecological security assessment for cities in the Beijing–Tianjin–Hebei metropolitan region based on fuzzy and entropy methods. *Ecological Modelling* ,*318* (24), 217–225. https://doi.org/10.1016/j.ecolmodel.2014.12.015.

He, Z., Liu, S., & Zhan, M. (2013). Dynamical robustness analysis of weighted complex networks. *Physica A Statistical Mechanics & Its Applications* , *392* (18), 4181-4191. https://doi.org/10.1016/j.physa.2013.05.005.

Hepcan, S., Hepcan, C. C., Bouwma, I. M., Jongman, R. H. G., & Ozkan, M. B. (2009). Ecological networks as a new approach for nature conservation in Turkey: A case study of Izmir Province. *Landscape and Urban Planning* ,*90* (3), 143–154. https://doi.org/10.1016/j. landurbplan.2008.10.023.

Hu, B. X., Wang, D. C., Wang, Z. H., Wang, F. C., Liu, J. Y., Sun, Z. C., & Chen, J. H. (2018). Development and optimization of the ecological network in the Beijing-Tianjin-Hebei metropolitan region. *Acta Ecologica Sinica* , *38* (12), 4383–4392. https://doi.org/10.5846/ stxb201801310259. (in Chinese).

Jing, Z. R., & Wang, J. M. (2020). Sustainable development evaluation of the society–economy–environment in a resource-based city of China: A complex network approach. *Journal of Cleaner Production* ,*263* , 121510. https://doi.org/10.1016/j.jclepro.2020.121510.

Kong, F. H., Yin, H. W., Nakagoshi, N., & Zong, Y. (2010). Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. *Landscape and Urban Planning* , *95* (1–2), 16–27. https://doi.org/10.1016/j.landurbplan.2009.

Li, B., Han, Z. L., & Tong, L. J. (2009). Regional ecological planning and ecological security network construction: A case study of 'Ji Traingle' Region. *Chinese Journal of Applied Ecological* ,*20* (5), 1160-1165. (in Chinese).

Liang, F. C., Liu, H. R., Liu, S. Y., Qi, X. X., & Liu, L. M. (2018). Spatial restructuring countermeasures of landscape ecological security network in southern Fujian: A case study of Jimei District in Xiamen. *Economic Geography* , *38* (9), 231–239. https://doi.org/10.15957/j.cnki.jjdl. (in Chinese)

Liu, L., Cao, Z., Liu, X., Shi, L., & Liu, G. (2020). Oil security revisited: an assessment based on complex network analysis. *Energy* , *194* , 116793. https://doi.org/10.1016/j.energy.2019.116793.

Liu, R. C., Shen, C. Z., Jia, Z. Y., Wang, J. X., Lu, C. F., & Zhou, S. L. (2019) Construction and optimization of ecological security network under the stress of road landscape in coastal beach area: A case study of Dafeng District,Yancheng City. *Chinese Journal of Ecology* ,*38* (3), 828-837. https://doi.org/10.13292/j.1000-4890.201903.017. (in Chinese).

Liu, Y. Y., Slotine, J. J., & Barabasi, A. L. (2011). Controllability of complex networks. *Nature* , *473* (7346), 167. https://doi.org/10.1038/nature10011.

Ma, L. B., Bo, J., Li, X. Y., Fang, F., & Cheng, W. J. (2019). Identifying key landscape pattern indices influencing the ecological security of inland river basin: The middle and lower reaches of Shule River basin as an example. *Science of the Total Environment* ,*674* , 424–438. https://doi. org/10.1016/j.scitotenv.2019.04.107.

Modica, G., Pratico, S., Laudari, L., Ledda, A., Fazio, S. D., & Montis, A. D. (2021). Implementation of multispecies ecological networks at the regional scale: analysis and multi-temporal assessment. *Journal of Environmental Management* ,*289* (4), 112494. https://doi.org/10.1016/j.jenvman.2021.112494.

Ng, C. N., Xie, Y. J., & Yu, X. J. (2011). Measuring the spatio-temporal variation of habitat isolation due to rapid urbanization: A case study of the Shenzhen River cross-boundary catchment, China. *Landscape and Urban Planning* , *103* (1), 44–54. https://doi.org/10.1016/j.landurbplan.

Pascual-Hortal, L., & Saura, S. (2006). Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. *Landscape Ecology* , *21* (7), 959–967. https://doi.org/10.1007/s10980-006-0013-z.

Pocock, M., Evans, D. M., & Memmott, J. (2012). The robustness and restoration of a network of ecological networks. *Science* ,*335* (6071), 973–977. http://www.sciencemag.org/cgi/doi/10.1126/science.1214915.

Shen, Z. H., Wang, Y. L., & Fu, B. J. (2014). Corridors and networks in landscape: Structure, functions and ecological effects. *Chinese Geographical Science* , *1* (1), 1–4. https://doi.org/10.1007/s11769-014-0668-3.

Shi, F. N., Liu, S. L., Sun, Y. X., Zhao, S., Liu, Y. X., & Li, M. Q. (2020). Ecological network construction of the heterogeneous agropastoral areas in the upper Yellow River basin. *Agriculture, Ecosystems & Environment* , *302* (15), 107069. https://doi.org/10.1016/j.agee.2020.107069.

Sitzenfrei, R. (2021). Using complex network analysis for water quality assessment in large water distribution systems. *Water Research* ,*201* , 117359. https://doi.org/10.1016/j.watres.2021.117359.

Soh, H., Lim, S., Zhang, T. Y., Fu, X. J., Lee, G. K. K., Hung, T. G. G., Di, P., Prakasam, S., & Wong, L. (2010). Weighted complex network analysis of travel routes on the singapore public transportation system. *Physica A: Statistical Mechanics and its Applications* , *389* (24), 5852–5863. https://doi.org/10.1016/j.physa.2010.08.015.

Turner, M. G., Gardner, R. H., & O'Neill, R. V. (2001). Landscape ecology: Theory and practice. New York, NY: Springer-Verlag.

Vahidzadeh, R., Bertanza, G., Sbaffoni, S., & Vaccari, M. (2021). Regional industrial symbiosis: a review based on social network analysis. *Journal of Cleaner Production* , *280* , 124054. https://doi.org/10.1016/j.jclepro.2020.124054.

Wang, G., Yu, Q., Yang, D., Zhang, Q. B., Yue, D. P., & Liu, J. H. (2019). Hierarchical ecological security network structure based on complex network analysis. *Transactions of the Chinese Society for Agricultural Machinery* , *50* (7), 258-266,312. https://doi.org/10.6041/j.issn.1000-1298.2019.07.028. (in Chinese).

Wang, J. M., Lei, J. C., Wang, S., Wu, J., Liang, Y., Chen, Y. L., Xiong, X., & Wang, J. W. (2020). Construction and assessment of terrestrial ecological security networks in headwaters region of the Dongjiang

River. *Chinese Journal of Ecology* , *39* (9), 3092-3098. https://doi.org/10.13292/j.1000-4890.202009.037. (in Chinese).

Wang, Y. Y., Lei, Y. L., Fan, F. Y., Li, L., Liu, L. G., & Wang, H. T. (2021). Inter-provincial sectoral embodied CO_2net-transfer analysis in China based on hypothetical extraction method and complex network analysis. *Science of The Total Environment* ,*786* , 147211. https://doi.org/10.1016/j.scitotenv.2021.147211.

Xia, C. Y., & Chen, B. (2020). Urban land-carbon nexus based on ecological network analysis. *Applied Energy* , *276* , 115465. https://doi.org/10.1016/j.apenergy.2020.115465.

Xia, H., Li, C. Z., Zhou, D., Zhang, Y. Y., & Xu, J. L. (2020). Peasant households' land use decision-making analysis using social network analysis: a case of Tantou village, China. *Journal of Rural Studies* , *80* , 452–468. https://doi.org/10.1016/j.jrurstud.2020.10.023.

Xia, L. L., Liu, Y., Wang, X. J., Tian, X., Wu, Q., Zhang, Y., Liu, G. Y., & Hao, Y. (2018). Spatial analysis of the ecological relationships of urban carbon metabolism based on an 18 nodes network model.*Journal of Cleaner Production* , *170* , 61-69. https://doi.org/10.1016/j.jclepro.2017.09.077.

Xie, H., & Wu, Q. (2020). Farmers' willingness to leave land fallow from the perspective of heterogeneity: a case:study in ecologically vulnerable areas of Guizhou, China. *Land Degradation & Development* , *31* (14), 1749-1760. https://doi.org/10.1002/ldr.3564.

Xie, H. L., He, Y. F., Choi, Y., Chen, Q. R., & Cheng, H. (2020). Warning of negative effects of land-use changes on ecological security based on GIS. *Science of the Total Environment* , *20* (704), 135427. https://doi. org/10.1016/j.scitotenv.2019.135427.

Xie, H. W., Zhou, N. X., & Guan, J. (2014). The construction and optimization of ecological networks based on natural heritage sites in Jiangsu Province. *Acta Ecologica Sinica* , *34* (22), 6692–6700. https://doi.org/ 10.5846/stxb201401080058. (in Chinese).

Yazdani, A., & Jeffrey, P. (2011). Complex network analysis of water distribution systems. *Chaos* , *21* (1), 440-1333. https://doi.org/10.1063/1.3540339.

Yin, H. W., Kong, F. H., Qi, Y., Wang, H. Y., Zhou, Y. N., & Qin, Z. M. (2011). Developing and optimizing ecological networks in urban agglomeration of Hunan province, China. *Acta Ecologica Sinica* ,*31* (10), 2863–2874. (in Chinese).

Yong, Z., Donner, R. V., Marwan, N., Donges, J. F., & Kurths, J. (2018). Complex network approaches to nonlinear time series analysis.*Physics Reports* , 787. https://doi.org/10.1016/j.physrep.2018.10.005.

Yu, Q., Yang, L., Yue, D. P., Wang, Y. H., Su, K., & Zhang, Q. B. (2018). Investigation on complex spatial ecological security network structure based on complex network analysis method. *Transactions of the Chinese Society for Agricultural Machinery* , *49* (3), 214–224. https://doi.org/10.6041/j.issn.1000-1298.2018.03.026. (in Chinese).

Zhai, M., Huang, G., Liu, L., & Zhang, X. (2019). Ecological network analysis of an energy metabolism system based on input-output tables: model development and case study for Guangdong. *Journal of Cleaner Production* , *227* , 434–446. https://doi.org/10.1016/j.jclepro.2019.04.039.

Zhang, Y., Yang, Z. F., & Fath, B. D. (2010). Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing. *Science of the Total Environment* ,*408* (20), 4702– 4711. https://doi.org/10.1016/j.scitotenv.2010.06.019.

Zhao, S. M., Ma, Y. F., Wang, J. L., & You, X. Y. (2019). Landscape pattern analysis and ecological network planning of Tianjin city. *Urban Forestry & Urban Greening* , *46* , 126479. https://doi.org/10.1016/j.ufug.2019.126479.

Zhou, D., Lin, Z. L., Ma, S. M., Qi, J. L., & Yan, T. T. (2020). Assessing ecological security network for a rapid urbanization region in Eastern China. *Land Degradation & Development* , *32* (8), 2642–2660.

https://doi.org/10.1002/ldr.3932.

Zhou, D., Xu, J., & Lin, Z. (2016). Conflict or coordination? assessing land use multi-functionalization using production-living-ecology analysis. *Science of the Total Environment* , *577* , 136–147. https://doi.org/10.1016/j.scitotenv.2016.10.143.

TABLE 1 The *key*ecological corridors length of cities in 1995 and 2015

Cities of UAHB	**Length of *key* corridors (km)**	**Length of *key* corridors (km)**	**Change (km)**	**Percentage**
	1995	**1995-2015**	**2015**	**1995-2015**
Ningbo	354.23	107.23	461.46	30.27
Shaoxing	497.55	144.01	641.56	28.94
Hangzhou	1144.02	-379.3	764.72	-33.16
Huzhou	293.45	77.31	370.76	26.35
Jiaxing	0	0	0	0
Total	2289.25	-50.75	2238.50	-2.22

TABLE 2 The degree of nodes in cities in 1995 and 2015

Cities	**1995**	**1995**	**1995**	**2015**	**2015**	**2015**
	k'	$k_{\mathbf{max}}$	$k_{\mathbf{min}}$	k'	$k_{\mathbf{max}}$	$k_{\mathbf{min}}$
Ningbo	3	5	1	3.2	6	1
Shaoxing	3	5	2	3.5	6	2
Hangzhou	3.3	7	0	3.8	9	1
Huzhou	3.6	8	2	2.9	6	1
Jiaxing	0	0	0	0	0	0

Note: *k'* is the average of degrees; k_{max} is the maximum value; k_{min} is the minimum value.

TABLE 3 Clustering coefficients in 1995 and 2015

Clustering coefficient	**1995**	**1995**	**2015**	**2015**
	The number of nodes (#)	**Percentage (%)**	**The number of nodes (#)**	**Percentage (%)**
1	2	2.53	2	2.20
0.7	2	2.53	3	3.30
0.5	1	1.27	3	3.30
0.4	0	0.00	2	2.20
0.3	27	34.18	32	35.16
0.2	14	17.72	14	15.38
0.1	3	3.80	4	4.40
0	30	37.97	31	34.07

TABLE 4 Network connectivity in 1995 and 2015

Indexes	**1995**	**2015**
α	0.30	0.35
β	1.58	1.68
γ	0.54	0.57
Cost Ratio	0.94	0.93

TABLE 5 Relationship between network robustness and the number of the deleted nodes

NFR in 1995	**NFR in 2015**	**Changes of R_1 and R_2**	**Connected components**	**Network state**
<15%	<25%	Unchanged basically	Unchanged	The network structure was complete and stable.
—	25%-33%	The downward trend was broadly consistent.	Increased slowly	Network fragmentation was increasing
15%-46%	33%-52%	Significant difference	Increasing	Network fragmentation was increasing.
46%-95%	52%-98%	R_1 and R_2 were reduced to less than half of their initial values.	Decreasing	The complexity of the network was significantly reduced and extremely sensitive.
>95%	>98%	0	0	There were only isolated nodes in the network, and the network was in a state of paralysis.

TABLE 6 The relationship between network robustness and the way of nodes deletion

Scenarios	**1995**	**1995**	**2015**	**2015**
	NFR	**Changes**	**NFR**	**Changes of R_1 and R_2**
HD	>15%	R_1 and R_2 were reduced to less than half of their initial values.	>33%	R_1 and R_2 were reduced to
NHD	>46%	R_1 and R_2 were reduced to less than half of their initial values.	>43%	R_2 was reduced to less tha
			>52%	R_1 was reduced to less tha

FIGURE CAPTIONS

FIGURE 1 The whole framework and technical flowchart

FIGURE 2 The theoretical model from ecological security network to complex network

FIGURE 3 Ecological security networks of 1995 and 2015 (Zhou, Lin, Ma, Qi, & Yan, 2020)

FIGURE 4 The degree distributions in 1995 and 2015

FIGURE 5 The core of nodes in 1995 and 2015

FIGURE 6 Node comprehensive importance level in 1995 and 2015

FIGURE 7 The robustness analyses for 1995 and 2015. Note: The percentage corresponding to the dotted line refers to the node failure rate

FIGURE 8 The ecological breaking points

FIGURE 9 The important steppingstones in the UAHB

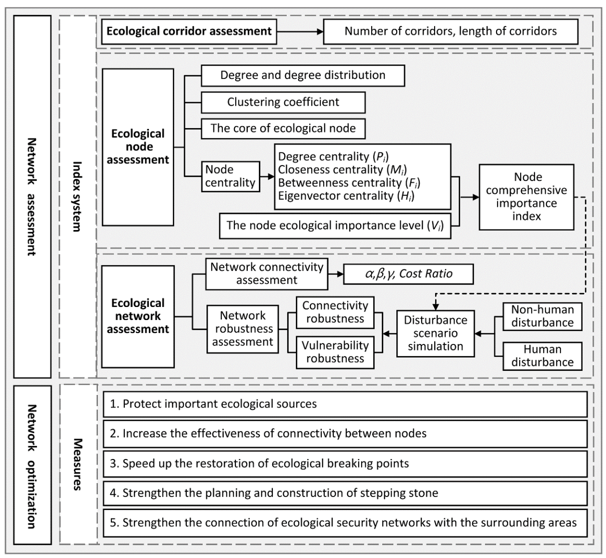


FIGURE 1 The whole framework and technical flowchart

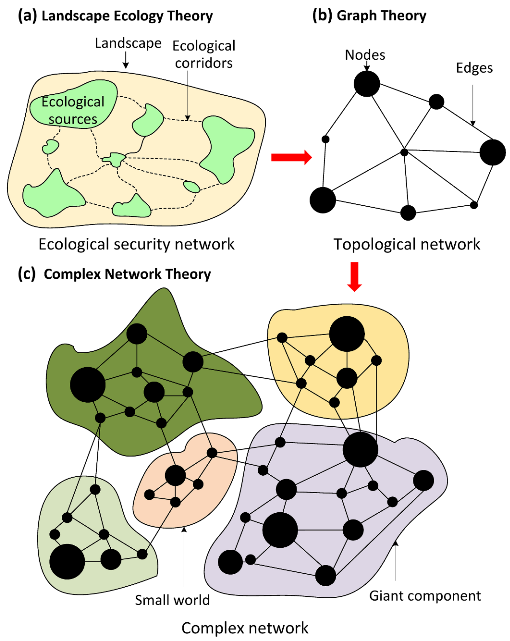


FIGURE 2 The theoretical model from ecological security network to complex network

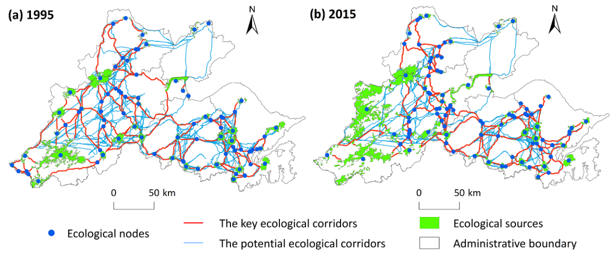


FIGURE 3 Ecological security networks of 1995 and 2015 (Zhou, Lin, Ma, Qi, & Yan, 2020)

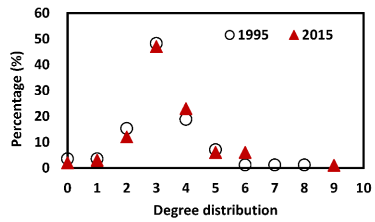
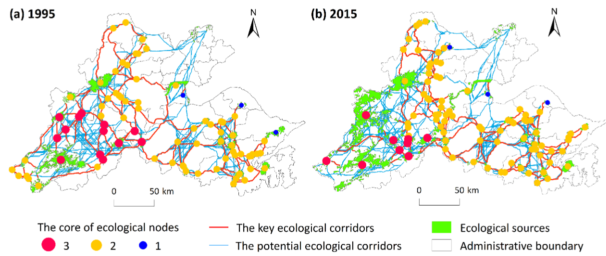
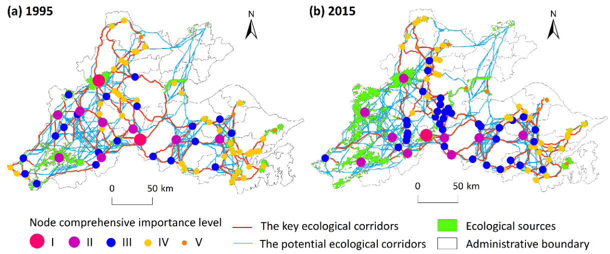


FIGURE 4 The degree distributions in 1995 and 2015



The core of ecological nodes (#)	1995		2015	
	Amount (#)	Percentage (%)	Amount (#)	Percentage (%)
3	13	16	9	10
2	66	80	81	86
1	3	4	4	4

FIGURE 5 The core of nodes in 1995 and 2015



Node comprehensive importance level		The number of nodes (#)	
		1995	2015
I	Higher	2	1
II	High	8	9
III	General	20	37
IV	Low	49	39
V	Lower	3	8

FIGURE 6 Node comprehensive importance level in 1995 and 2015

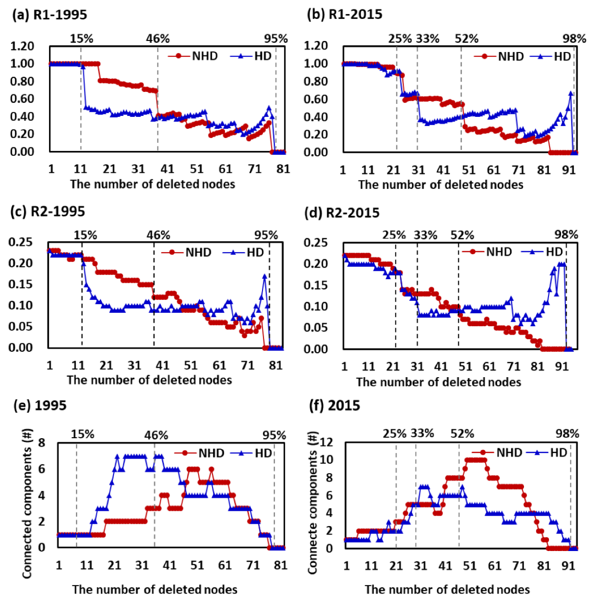


FIGURE 7 The robustness analyses for 1995 and 2015. Note: The percentage corresponding to the dotted line refers to the node failure rate

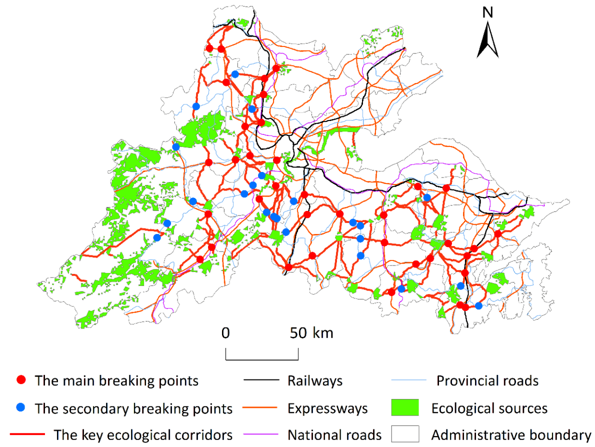


FIGURE 8 The ecological breaking points

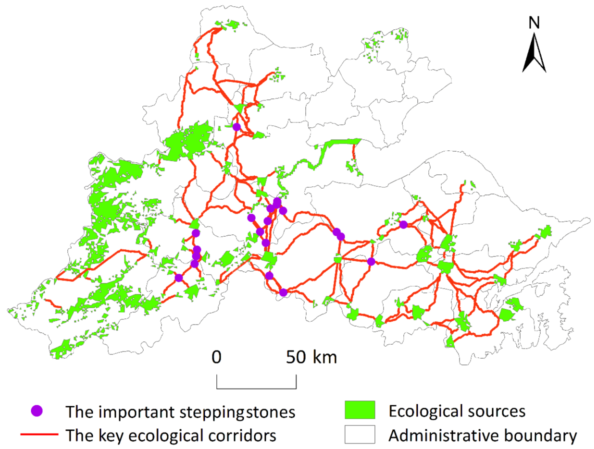


FIGURE 9 The important steppingstones in the UAHB