Research Paper

Exploring the resilience evolution law of Shenzhen's ecological network

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Abstract

In order to explore the resilience evolution law of urban ecological network, in the cross field of urban planning, landscape ecology and complexity science, this paper adopts the principles and methods of landscape ecology and complex network analysis, selects Shenzhen as the research area, constructs multiple ecological networks based on 8 years' land cover data, and identifies ecological network clusters at the optimal scale through the percolation theory. This paper reveals the evolution characteristics of urban ecological network from monocentric network structure to polycentric network structure under the background of rapid urbanization, and the trend of stable ecological network cluster pattern but declining ability to control urban expansion and to separate urban centres, which provides an idea for evaluating the impact of urban master planning and ecological planning policies on urban ecological network's resilience.

Keywords

Resilience, Ecological Network, Evolution, Shenzhen

1. Introduction

Worldwide urban ecological space is facing the risk of encroachment by urban expansion in the process of urbanization, which will lead to a series of ecological and environmental problems that increase the vulnerability of cities. Improving the resilience of ecological space is an important measure for countries and cities to achieve sustainable development. Western world has long explored ecological spatial structure models to limit urban expansion and to protect ecological space, such as Pan-European Ecological Network, London Green Belt and Maryland Green Infrastructure. In China, ecological space control policies of Beijing Green Belt, Shanghai Green Belt and Shenzhen Ecological Redline have achieved certain effects in protecting urban ecological resources and building urban ecological security pattern in early stages, but the phenomenon of erosion of structural green space and breaking the ecological redline still exists. The resilience of urban ecological space fails under the risk of continuous urbanization. Measuring the evolution characteristics of resilience of urban ecological space of the past and mastering the dynamic law of urban ecological security pattern are of great significance for developing strategies for improving resilience of urban ecological space under the background of rigid urban development needs.

Research on the relationship between urban space and ecological space can be divided into three categories. The erosion impact of urban expansion on ecological space, the constraints of ecological space on urban space, and the coupling effect of urban space expansion and ecological space protection (Ouyang et al, 2021). When studying the effect of ecological space on urban construction land, urban expansion has been simulated based on ecological constraint mechanism to delineate urban development boundaries (Sun et al. 2021).

Under the influence of urbanization expansion and clustering of human activities, different research fields have different research emphases on ecological spatial resilience. Geography pays attention to the change characteristics of resilience indicators constructed by economic, social, geographical and ecological factors that affect regional ecological environment, so as to identify the differences in resilience levels in different regions and propose strategies to improve resilience from various aspects (Tao et al, 2022; Zeng et al, 2022; Wang et al, 2021; Xia et al. 2022). Ecosystem ecology focuses on the ability of ecosystems to maintain and restore their own provisioning, regulating, supporting and cultural services in order to sustain regional natural life systems (Liu et al, 2023). Landscape ecology focuses on the ability of ecological landscape patches to maintain and restore original landscape size, composition, quality, form and pattern, so as to construct regional ecological security pattern (Shi et al, 2023; Niu et al, 2019). Conservation biology focuses on the ability of landscape ecological network to maintain and restore connectivity, so as to ensure species migration and protect biodiversity (Andrea et al, 2019; Isaac et al, 2018). The research method of landscape ecological network has been extended to the field of urban planning to represent urban ecological spatial structure. The measurement of resilience indicators such as connectivity and redundancy can provide a basis for realizing habitat restoration, protecting and maintaining regional ecological security pattern (Xu et al, 2022; Song et al, 2021). In general, the measurement of the resilience of ecological space pays more attention to the ability of ecological space to maintain its own landscape pattern, ecological process and ecosystem services after being disturbed, while there is a lack of research on the feedback effect of ecological space on urban construction land, such as the ability to restrict the expansion of urban construction land and isolate urban centres.

Taking Shenzhen as an example, this paper constructs ecological networks to represent the urban ecological spatial structure based on the structural connectivity among landscape ecological patches, identifies ecological network clusters at the optimal scale through the percolation theory, and analyses the changes of ecological networks' ability to control urban expansion and to separate urban centres over the years, so as to explore the resilience evolution law of ecological space in response to urban expansion under the background of rapid urbanization. This paper provides reference for the optimization of urban ecological security pattern and the practice of resilient cities.

2. Literature review

2.1. Mechanism of ecological network construction

Ecological network provides a new direction and method for the identification and analysis of ecological spatial structure. In terms of highly summarizing landscape pattern information, the traditional landscape pattern index can describe the overall characteristics of landscape form, while the ecological network based on graph theory emphasizes the relationship between landscape patches and has more advantages in describing the characteristics of hierarchical structure of ecological space (Liu et al, 2017).

There are two main mechanisms of ecological network construction. Namely structural connectivity and functional connectivity (Susanne et al, 2010) (Table 1). Structural connectivity refers to the connection of landscape patches in spatial structure, focusing on the continuity of landscape patches. Euclidean distance between patches is often used to describe the physical relationship between them. Functional connectivity refers to the connection between landscape patches in terms of function and ecological processes. It focuses on the exchange of matter and energy between landscape patches, and takes into account environmental influences during species diffusion, such as urban roads, terrain, vegetation cover, construction land and other influencing factors. Scholars often simulate the migration path of species based on cost-distance methods, such as minimum cost distance, minimum cumulative resistance model, circuit theory, etc., and use the furthest migration distance of species to represent the dispersal ability of species. The two ecological network construction mechanisms can summarize the degree of landscape patch connection and proximity to a certain extent. This paper emphasizes the physical connection of landscape patches in spatial structure, so the ecological network construction method based on structural connectivity is more suitable for this paper.

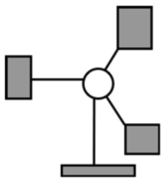
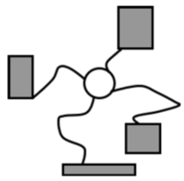
Construction mechanism	Structural connectivity	Functional connectivity
Graphical representation		
Construction method	Proximity Euclidean distance	Cost distance（Minimum cost path, minimum cumulative resistance model, circuit theory）
Connection connotation	Landscape patch connection	Potential ecological corridor, potential species migration path, species diffusion ability, etc
Research focus	The continuity of landscape	The ecological process of landscape

Table 1. Structural connectivity and functional connectivity diagram, construction method, connotation and research focus. Source: Author.

2.2. The connotation and measurement of resilience, ecological resilience and ecological network resilience

Resilience can be divided into three research perspectives. Engineering resilience refers to the ability of the whole system to restore to the equilibrium state or stable state before the disturbance (Holling, 1973). Ecological resilience means that the system can have multiple equilibrium states. The resilience of the system may not urge the system to recover to the original equilibrium state, but also guide the system to adjust itself and jump to the new equilibrium state (Holling, 1996). From the perspective of social ecological resilience, a region is a complex adaptive system without a stable equilibrium state, which adapts to long-term external environment changes by constantly adjusting its own structure and continues to grow (Walker et al, 2004). The overall cognition of resilience has changed from owning a single equilibrium steady state and multiple equilibrium steady state to owning no equilibrium steady state but constantly adapting and adjusting.

In recent years, the rapid development of complex network science provides a new perspective for measuring the resilience of ecological space. Complex network theory can highly abstract the real ecological space into a topological structure, extract the topological relationship of ecological material, energy and information flow among ecological spaces, use indicators to measure the ability of ecological networks to keep running even after node and edge failures, and reveal the structural stability of ecological networks and the dynamic propagation characteristics under attack. At present, indicators such as connectivity, redundancy and network efficiency are commonly used to measure the resilience of urban ecological networks, focusing on the ability of network connectivity and operation when the network is attacked. In the context of rapid urbanization, the resilience of ecological networks should also focus on its ability to control urban expansion or to isolate urban construction clusters. Large contiguous green space and green belt play an important role in limiting urban expansion. The continuous expansion of urban construction land causes the fragmentation of ecological patches, and the barrier ability of ecological space to urban expansion is reduced. In highly urbanized areas, large green corridors are often built between ecological clusters to limit urban expansion and isolate urban construction clusters, but such large green corridors often become just blueprint planning, which is eroded in the real urban construction. This paper constructs ecological network based on structural connectivity, identifies ecological network clusters based on percolation theory, and analyses the change of urban ecological spatial barrier ability by analysing the evolution of ecological network clusters.

3.Methodology

3.1. Study area and data collection

Shenzhen is located in the south of Guangdong Province, south of the Tropic of Cancer. Shenzhen has a subtropical monsoon climate, with an average annual rainfall of 1933.3mm. Shenzhen has a total area of 1996.9 square kilometres, wide from east to west, narrow in the middle. Landform types include hills, terraces and plains. The terrain is high in the east and low in the west, and the highest elevation is more than 900 meters. Hilly areas account for 39.6% of the total area, terraces, plains and plateaux account for about 20% of the total area. There are also some low mountains. Shenzhen has jurisdiction over nine administrative regions including Luohu, Futian, Nanshan, Yantian, Baoan, Longgang, Longhua, Guangming, Pingshan and Dapeng (Figure 1), among which Luohu, Futian, Nanshan and Yantian are the former Shenzhen Special Economic Zone.

Since the establishment of Shenzhen Special Economic Zone, it has experienced rapid urbanization process. Shenzhen's GDP has grown from 270 million yuan in 1980 to 276.70 billion yuan in 2020, ranking third in China. The resident population has increased from 332,900 in 1980 to 17,633,800 in 2020, with a population density of 8,828.1 people per km², second only to Macau (19,700 people per km²) in China. Urban construction land increased from 3 km² in 1980 to 1006 km² in 2020, accounting for 56.1% of the city's total area, far exceeding the international warning line of 30%. While Shenzhen has achieved rapid social and economic development, the continuous and rapid expansion of urban construction land has led to a decrease in the total amount of ecological land, and therefore the urban ecological resources are under great pressure, which is in contradiction with the people's ever-growing need for a beautiful ecological environment. At the same time, Shenzhen promulgated a series of ecological spatial planning policies, the main purpose is to protect the ecological environment and isolate the urban cluster, and further limiting the expansion of the city. However, Shenzhen's structural green space has been eroded over the years, failing to play its role of isolating urban clusters. With rigid urban development needs, Shenzhen's sustainable development is still facing severe challenges.

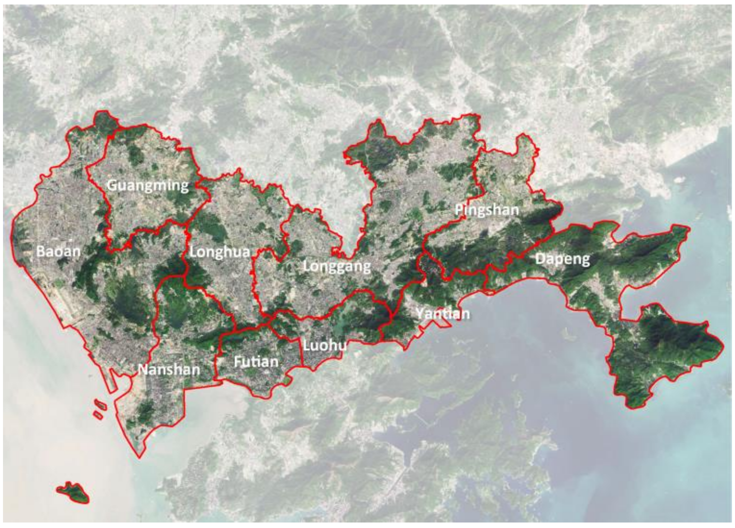


Figure 1. Administrative divisions of Shenzhen. Source: Author.

Data of this study includes the 30m resolution land use cover data of Shenzhen City in 1985, 1990, 1995, 2000, 2005, 2010, 2015 and 2020. The dataset is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences(RESDC) (http://www.resdc.cn). Land cover data are manually corrected according to the visual interpretation of Landsat satellite images.

3.2. Ecological network construction

In the data preprocessing stage, the main task is to build the urban ecological network (Figure 2). In this study, based on land cover data, woodland, shrub, grassland and water were extracted as landscape ecological patches, and landscape ecological patches with an area larger than 0.1km² were screened as nodes of the ecological network, and adjacent landscape linkages were constructed based on Tyson polygon as edges of the ecological network. The weight of edges was the Euclidean distance between landscape ecological patches.

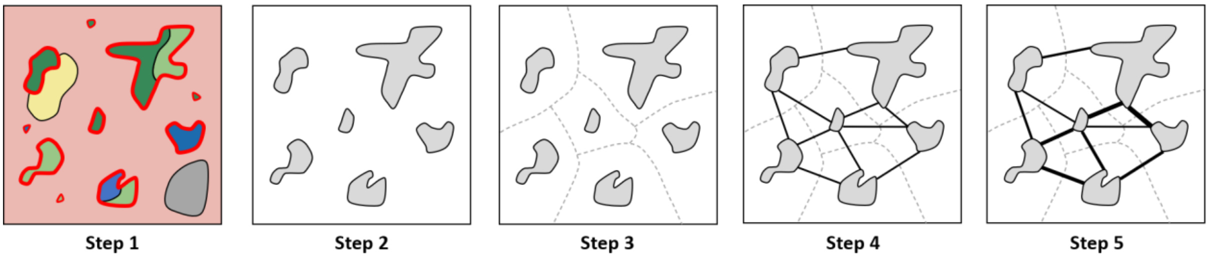


Figure 2. Construction of ecological network based on structural connectivity. Step 1: Woodland, shrub, grassland and water were extracted as landscape ecological patches; Step 2: The landscape ecological patches with an area greater than 0.1km² were screened; Step 3: Generating ecological patch field based on Tyson polygon; Step 4: Construct a network of adjacent landscape connections; Step 5: The Euclidian distance between patches is assigned as an edge weight. Source: Author.

3.3. Identification of ecological clusters at optimal scales

The identification of urban ecological clusters from the perspective of network percolation can be considered as a filtering model for low-probability ecological patch connections. For the ecological network generated based on structural connectivity, the connections whose distance is greater than the selected scale threshold are eliminated, and the unconnected ecological clusters in the remaining network are identified.

As shown in Figure 3, at distance scale 1, clusters A and B are formed by the interconnections between ecological patches. At distance scale 2, if the closest Euclidean distance between ecological patches is less than distance scale 2, the connection between them will be eliminated. Therefore, Cluster A splits into Cluster C1 and Cluster D1. At a smaller distance scale 3, the links between ecological patches are again eliminated, and the clusters size becomes smaller.

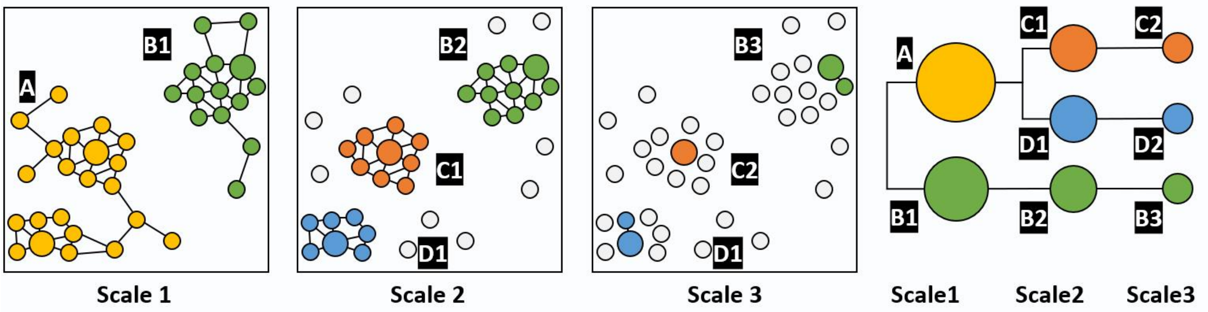


Figure 3. Ecological clusters identification based on percolation theory. Source: Author.

In order to identify the ecological clusters that can reflect the reality, the best distance scale should be selected. In this study, the edge of the ecological network was attacked from large to small according to the size of the distance, and the changes of the area of the largest ecological cluster and the area of the second largest ecological cluster were observed. The distance scale of the second largest ecological cluster reached the largest area and was about to decrease was determined as the best scale (Figure 4), which could be the basis for dividing the real ecological cluster.

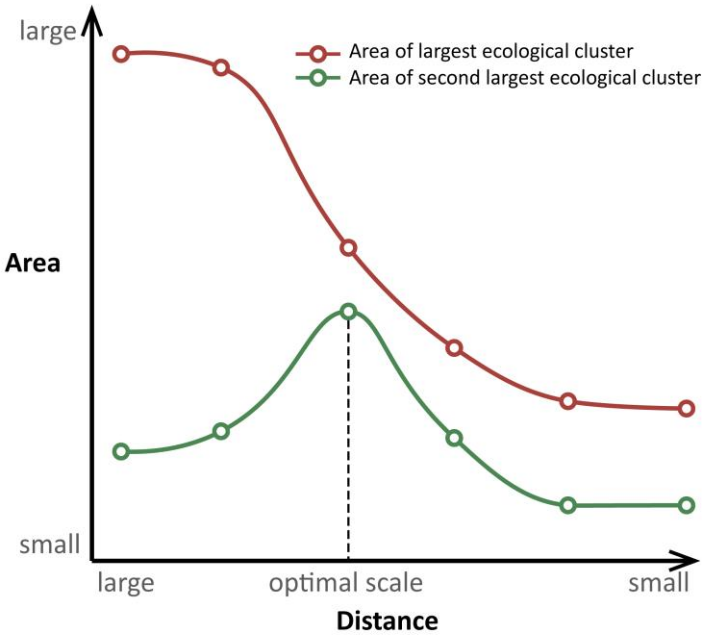


Figure 4. Optimal scale identification. Source: Author.

4. Result

4.1. Evolution of ecological network in Shenzhen

Fragmentation of ecological patches has led to the evolution of ecological network structure from monocentric network to polycentric network (Figure 5). In 1985 and 1990, the construction land of Shenzhen was concentrated in the special economic zone (Nanshan, Luohu and Futian). There was a huge ecological patch in the north, which was closely connected with other ecological patches around, and became the most centralized ecological patch in this period. At this time, the urban ecological space controlled the expansion of urban construction land from the urban periphery. In 1995, the number of ecological patches in Shenzhen changed dramatically. Due to the urban construction outside Shenzhen's special economic zone (Baoan, Longhua and Longgang), the huge ecological patch across Shenzhen was broken into multiple ecological patches dominated by mountains and reservoirs. Shenzhen's ecological network had changed from monocentric network to polycentric network since then. In 2000, ecological patches with high degree of centrality in the northwestern part of Shenzhen ecological network changed obviously, mainly through the conversion of cultivated land near mountains and reservoirs into grassland and forest land, briefly connecting several ecological patches with high degree of centrality in 1995 into one, and then urban expansion further broke the ecological patches into several. After 2005, ecological patches with high degree of centrality in Shenzhen were relatively stable, mainly because the Shenzhen Municipal People's Government promulgated the Regulations on the Management of Shenzhen Basic Ecological Control Lines in 2005. It delineated the basic ecological control lines in order to protect ecological patches of large size.

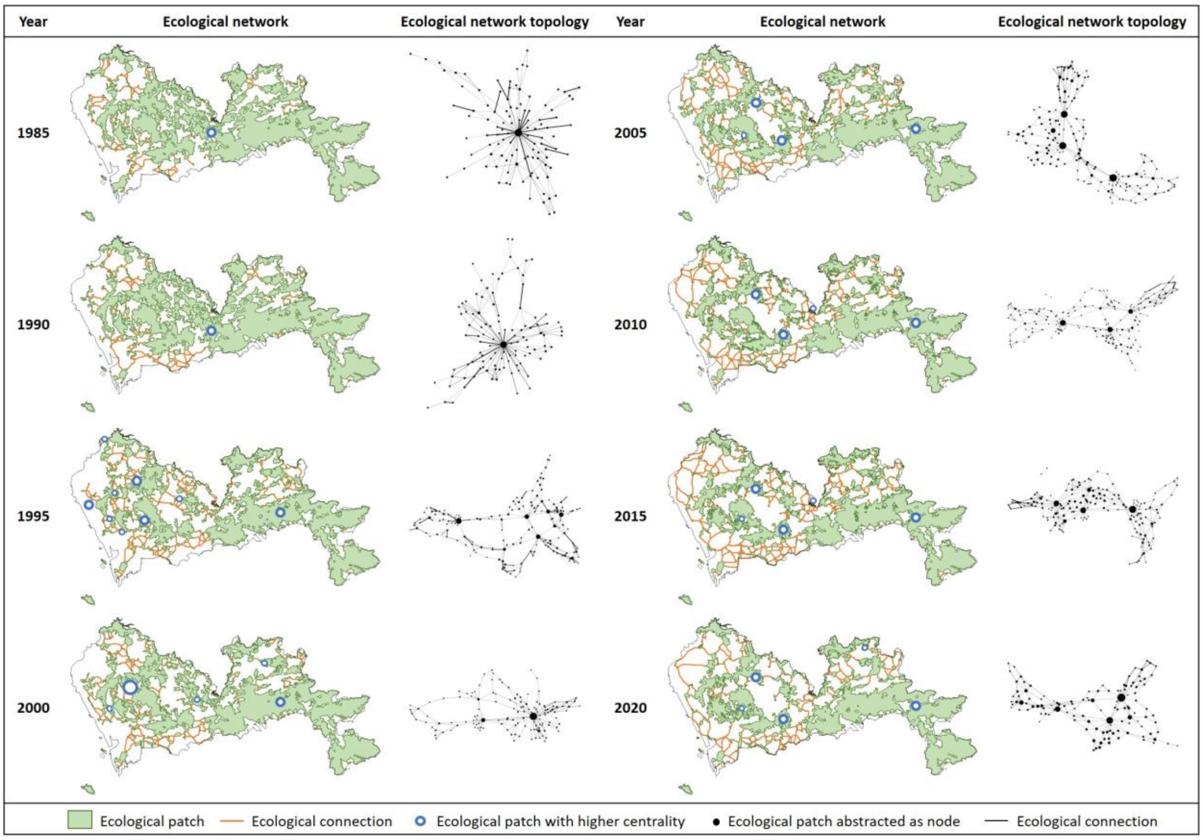


Figure 5. Ecological network and topology structure of Shenzhen City from 1985 to 2020. Source: Author.

4.2. Evolution of optimal distance scale of ecological network clusters in Shenzhen

The edges of ecological networks over the years are attacked from large to small according to the size of Euclidean distance of them. Then the scale when the area of the second largest ecological cluster reaches the largest and is about to decrease is selected as the best scale for dividing ecological clusters. Any edge whose size larger than the best distance scale is deleted, and the remaining interconnected ecological patches are ecological clusters. Ecological patches within the ecological clusters are closely connected, which serve as a large ecological entity to control urban expansion. It can be seen from Figure 6 that the variation of distance scale of ecological network over the years is in common with the size's changes of the first and second largest ecological clusters. When the size of the first largest ecological network cluster decreases sharply, the size of the second largest ecological network cluster increases sharply as well. The scale when both clusters' sizes change dramatically can better divide the real ecological clusters of the year from a more spatial perspective.

Distance scale can measure the closeness of urban ecological network clusters. The smaller the distance scale means that the ecological patch only needs a shorter distance to connect with the surrounding ecological patches and form ecological clusters. Similarly, the larger the distance scale, the greater the distance between ecological patches is required to achieve the connection among one another, and the smaller the tightness within the cluster. According to Figure 7, the optimal distance scale of ecological network in Shenzhen has shown a fluctuating growth since 1985. The optimal distance scale of the ecological network in 1985 and 1990 was 241m, and the ecological network was relatively stable and the ecological patches were relatively close in these five years. In 1995, the optimal distance scale of ecological network increased sharply, and the drastic development of urban construction land greatly increased the distance scale required for the formation of clusters among ecological patches. In 2000, the optimal distance scale of ecological network showed a decline, because the restoration of farmland and green space reduced the distance required for the formation of ecological clusters. After intense development, the optimal distance scale in 2000 was 247m, which was almost the same as 241m in 1985 and 1990. This indicates that after the erosion of ecological network patches from 1985 to 2000, the patches in ecological network clusters were still able to maintain tightness among them, resist urban erosion, and effectively isolate urban construction clusters. Since 2000, with continuous urban expansion, optimal distance scale of ecological network has been increasing, and the tightness of the inner patches of ecological clusters has decreased. Therefore, the ability to resist urban expansion has become weaker. From 2005 to 2010, the development of urban construction was rapid, and optimal scale of ecological network changed dramatically. In general, the evolution of the optimal distance scale of the ecological network in Shenzhen showed certain resilience characteristics from 1985 to 2000, while continuous development and construction of the city after 2000 exceeded the resilience threshold of the ecological network, resulting in weaker ability of the ecological network to resist the erosion of urban construction land.

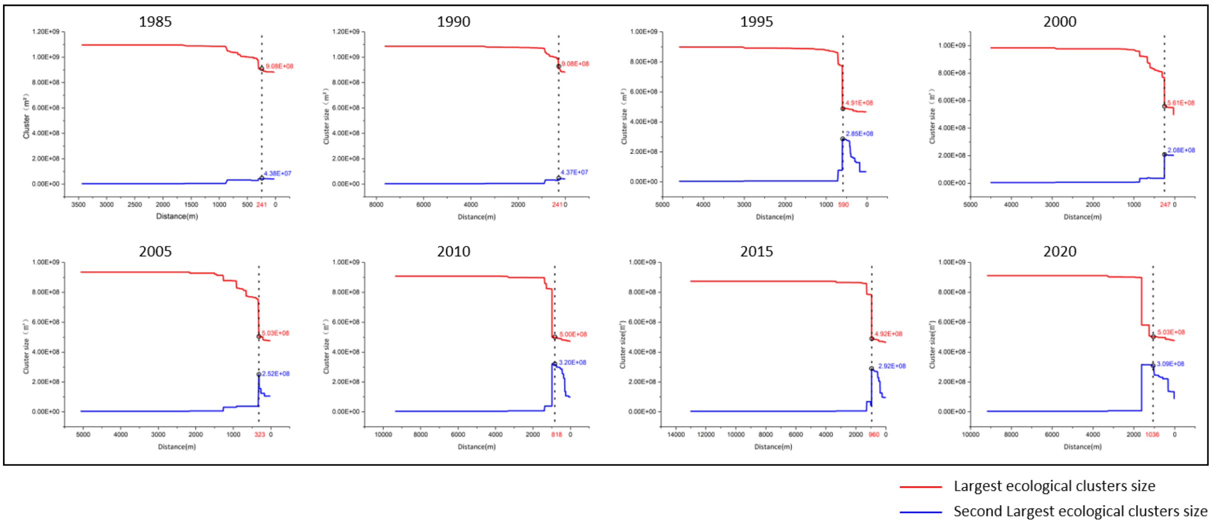


Figure 6. The area of the largest ecological cluster and the second largest ecological cluster changed with the distance scale. Source: Author.

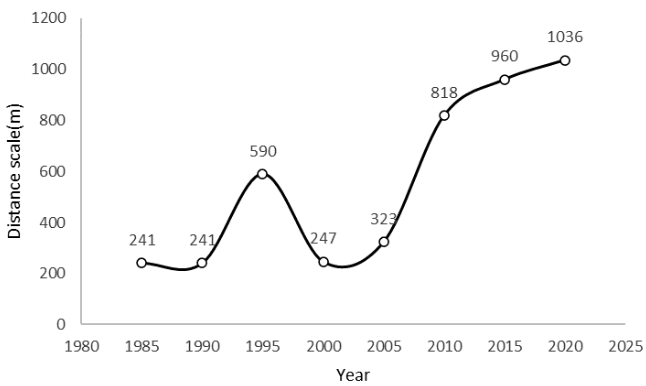


Figure 7. Optimal distance scale change of Shenzhen’s ecological networks from 1985 to 2020. Source: Author.

4.3. Evolution of ecological network clusters pattern in Shenzhen

Ecological network cluster is a cluster of interconnected ecological patches at the optimal distance scale. Ecological cluster may be a collection of multiple ecological patches or a single patch. From Figure 8, we can see the evolution of ecological network clusters pattern in Shenzhen. The overall pattern of network clusters is relatively stable and two different kind of distribution patterns are presented. In 1985 and 1990, the ecological network clusters in Shenzhen showed the distribution characteristics of huge-size ecological clusters across the east and west and small-size ecological clusters around. The barrier ability of ecological networks to restrict urban construction land reached the strongest in this period. From 1995 to 2020, the distribution pattern of ecological network clusters is characterized by eastern, western and northeastern ecological clusters. The eastern ecological clusters are the most stable, and the ability of

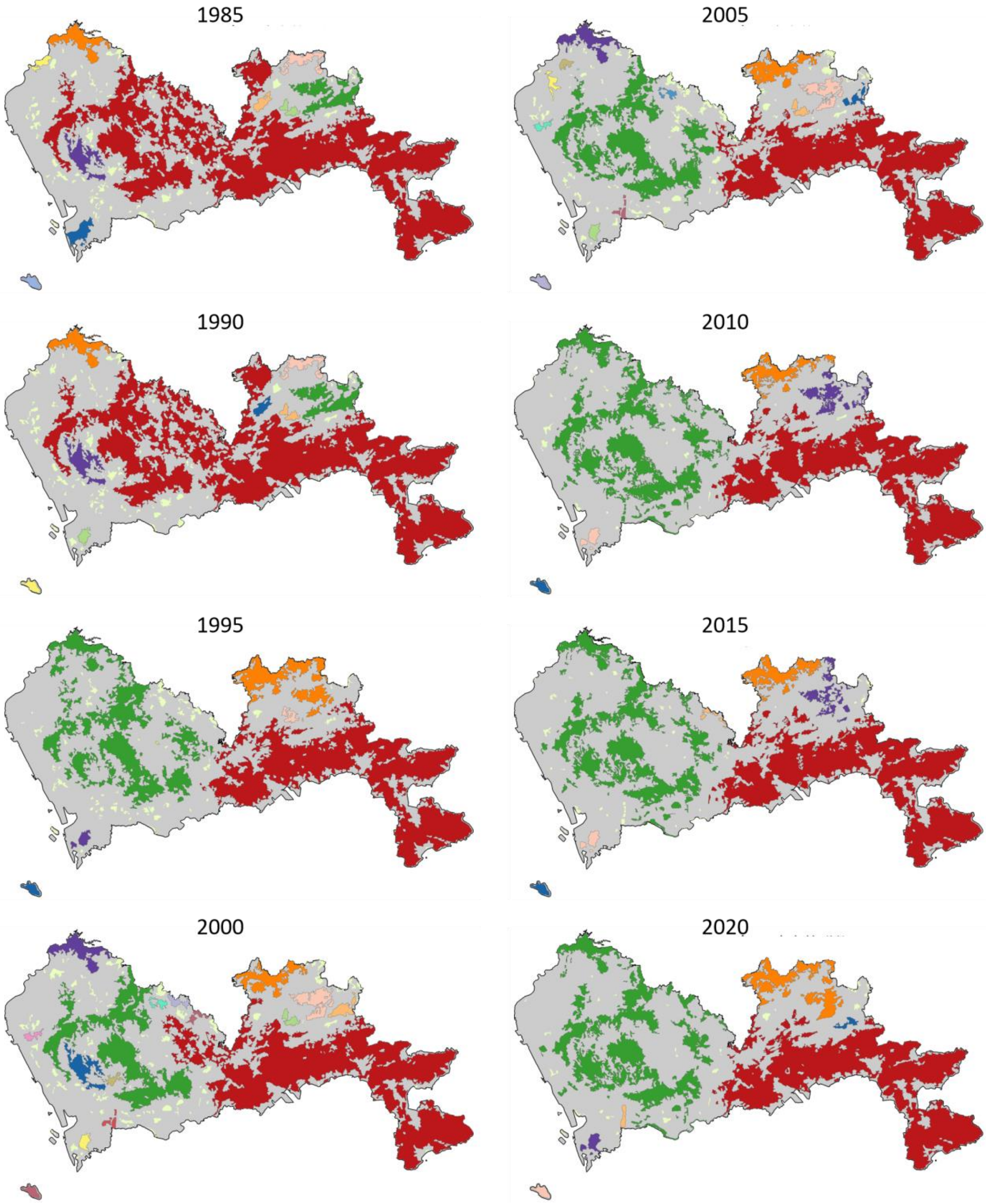


Figure 8. Evolution of ecological network clusters pattern in Shenzhen. If the colors of the ecological patches are the same, they are in the same ecological cluster. Diffent colors represent different ecological clusters. Source: Author.

ecological patches to restrict urban development and construction is the strongest. Changes of ecological patch community exist among the western ecological clusters and the northeastern ecological clusters during the evolution. That is, they break away from the the original ecological cluster and join another ecological cluster, indicating that the original ecological cluster has been eroded by urban construction. Compared with the eastern ecological clusters, the western ecological clusters are more fragmented, but the ecological patches are closely connected and still form an ecological cluster, which resists the erosion of urban construction land and isolates the construction clusters, reflecting the resilience of the ecological clusters.

5. Discussion

The polycentric urban structure of Shenzhen is constantly evolving under the comprehensive effect of many factors such as natural environment, policy planning and economic development. From the perspective of natural factors, Shenzhen's land surface is complex, with low hills, gentle terraces and terrace hills. Wutong Mountain, Qiniang Mountain, Yangtai Mountain and Danan Mountain are extended within the territory, and there are many rivers, lakes and reservoirs. The unique topography forms a natural barrier to urban construction land, which determines the dispersed development of Shenzhen along the east-west belt space. From the perspective of urban planning factors, urban grouping development is to avoid the monocentric development that leads to urban traffic congestion, environmental pollution, housing congestion and overpopulation, but the effect of urban grouping development does not isolate urban groups as expected.

5.1. Impact of urban spatial planning on resilience of ecological network

The rapid development of Shenzhen determines the continuous adjustment and change of its spatial structure in previous planning to ensure the demand for industrial development and urban construction land of urban clusters. The urban development has shifted from the extension expansion mode to the intensive development, and the urban spatial structure has shifted from the emphasis on polycentric development in the past to the balanced development of the network. This paper tries to strengthen the stability of urban system by connecting ecological clusters with network structure.

However, at the implementation level of urban spatial planning, there is a problem that planning lags behind urban construction and development. For example, from 1990 to 1995, preemptive development and construction outside Shenzhen special economic zone led to excessive erosion of ecological patches in the outer areas of the city. The city quickly entered the polycentric era, and the barrier capacity of ecological land changed drastically. After the overall urban planning, even if the ecological network cluster structure is planned, the unstoppable urbanization process makes the boundaries between the ecological clusters disappear and become contiguous urban construction land.

5.2. Impact of ecological planning policies on resilience of ecological network

According to the relevant planning of Shenzhen’s ecological network, Shenzhen’s ecological network has changed from being the opposite of the urban construction land in the past, emphasizing the role of urban groups isolation and ecological protection based on biological connectivity, to the integration of ecological network and urban construction, emphasizing its accessibility based on the connectivity of social ecological recreational resources. In 2005, Shenzhen promulgated the Regulations on the Management of Basic Ecological Control Lines in Shenzhen to curb the severe situation of urban ecological destruction by delineating the boundaries of urban construction. However, in the early stage, Shenzhen's ecological network did not play its function of curbing urban development or isolating urban clusters as scheduled. Problem of occupying ecological red lines still exist. The total amount of construction land in Shenzhen will continue to increase in the future, and therefore, the scope of ecological red lines will also be reduced. All kinds of ecological planning, such as greenway planning, green space system planning and park city construction planning, can effectively improve the quality of urban green space, but the restoration of urban green space and its ability to control urban expansion are still insufficient.

6. Conclusion

This paper explains the characteristics of ecological network resilience by clarifying the specific definition and measurement methods of urban ecological network and ecological network resilience. First of all, in the field of urban planning, urban ecological network can be understood as a network based on structural connectivity, emphasizing the Euclidean distance relationship among ecological patches. Secondly, under the unstoppable risk of urban expansion, the resilience of urban ecological network should focus on the barrier ability against urban construction land. In this paper, clusters of urban ecological network are identified by the percolation theory, and the resilient barrier ability of urban ecological network is analysed by the optimal distance scale and clusters distribution pattern.

This paper takes Shenzhen as the research area to conduct an empirical study on the resilience of ecological networks. It is found that from 1985 to 2020: (1) Shenzhen's urban ecological network changes from a monocentric network to a polycentric network, and the barrier ability of ecological network against urban construction land changes from the outer green belt restricting the expansion of monocentric construction land to greenbelt network restricting the expansion of polycentric construction land. (2) The optimal distance scale of ecological network clusters in Shenzhen showed a trend of increasing volatility, the overall tightness of ecological network clusters decreased, and the barrier ability of urban construction land decreased. (3) At the optimal distance scale, the overall pattern of ecological network clusters in Shenzhen is relatively stable.

In general, in the context of rapid urban expansion, Shenzhen's ecological network still maintains a certain barrier ability against urban construction land, but this barrier ability is constantly declining. Urban planning and ecological planning have not played an effective role in improving in its ability. The future urban ecological planning should accurately identify the key areas of the city, restore and repair the green space, so as to enhance the barrier ability of the urban ecological network against the urban construction land.

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