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Analysis of Spatial Scale Effect on Urban Resilience: A Case Study of Shenyang, China

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Abstract: Based on urban physical space and theory of landscape ecology, a triune assessment framework —'size-density-morphology'—was constructed in order to analyze the spatial pattern and the scale effect of urban resilience in Shenyang of China in 2015, and to explore the main impact factors of landscape under different spatial scale backgrounds. The results show that: 1) Urban resilience is an optimal combination of the resilience of size, density, and morphology. The urban resilience of Shenyang displays scale effect; the overall resilience level increases with the increase in scale, while the spatial difference and spatial similarity tend to decrease resilience. 2) As 2 km, 1 km and 2 km are scale inflection points of average value curves for size resilience, density resilience and morphology resilience, respectively in an urban setting; the optimal scale unit of comprehensive resilience is 1 km. Choosing 1 km–2 km as the basic spatial scale better depicts overall pattern and detailed characteristics of resilience in Shenyang. The spatial amplitudes of 0.5 km and 1 km are sensitive points for spatial autocorrelation of morphology and density resilience, size, and comprehensive resilience to scale effect. 3) The major landscape factors of urban size and morphology resilience transform with scale expansion. Aggregation index (AI) has a significant impact on urban resilience at different scales; its influence increases significantly with the increase in scale. 4) The high-level area of comprehensive resilience in Shenyang is the eastern ecological corridor area, while the low value area is the peripheral extension area of the city. To promote the overall level of resilience in Shenyang, this paper argues that the construction of ecological infrastructure should be strengthened in the peripheral extension area in a balanced manner. In the city center, population and building density should be controlled; the intensity of human activities should be reduced; impetus should be placed on landscape heterogeneity; and the homogeneous expansion of the area of construction should be prevented. In the eastern ecological corridors, the exploitation of ecosystem lands should be strictly controlled, and the integrity of the green landscape patches should be maintained.

Keywords: landscape pattern; size-density-morphology; urban resilience; scale effect; Shenyang City, China

1 Introduction

Ever since their formation, cities have suffered from the various shocks and disturbances arising both from the outside world and within themselves. These distur-bances not only include the acute impact of uncertain factors such as flood, terrorist attack, earthquake, *etc*., but also include the chronic stress arising in the process of the city's development, such as traffic jams, heat waves, air pollution, and so on. Since the 21st century,

disturbance factors faced by urban development have become increasingly severe, and the potential risks have increased significantly. At the same time, rapid urbanization has led to the accelerated expansion of cities, highly concentrated populations, rapid increase in building density and other development situations, all of which reduce the anti-interference ability of a city, cause huge losses and seriously affect the sustainable development of the city. In this context, the development model of a city with resilience has gradually attracted the attention of people from all walks of life. Many beneficial studies have been conducted and policies created: the evaluation framework of resilience proposed by the Rockefeller Foundation in the United States; the plan of 'risk management and resilience improvement' in London in the United Kingdom, *etc* (Zaidi and Pelling, 2015; Leitner et al., 2018). In October 2016, the 'new urban agenda' proposed during the Habitat III–United Nations Conference on Housing and Sustainable Urban Development further clarified the challenges and goals of resilient cities, and identified the vision of future cities as sustainable and resilient, and provide basic health and a good environment for their citizens (Caprotti et al., 2017).

In 1973, C.S. Holling, an ecologist, first introduced the concept of resilience into ecology and defined it as the ability of the system to absorb changes and disturbances, to depict the characteristics of the stable state of the ecosystem (Holling, 1973). This concept is also considered to be the origin of modern resilience theory (Meerow et al., 2016). In the 1990s, the view of scholars gradually changed from natural ecology to human ecology. The concept of resilience at this time was extended and enriched, and its meaning was expanded from engineering resilience and ecological resilience to social-ecological resilience (Alberti et al., 2003; Jiménez et al., 2020; Walter et al., 2020). Gunderson and Holling (2002) illustrated the relationship between the resilience of a system and the adaptive cycle stages in detail, and pointed out that the hierarchical system and adaptive cycles are the bases of social ecological system at different scales. When faced with the contradiction between the increasing potential risks of cities and the demand for sustainable development, the research concept of urban planning scholars began to shift from 'command and control' to 'learning and adaptation'. The concept of resilience has been introduced into urban studies (Bush and Doyon, 2019;

Huck and Monstadt, 2019), but there still have not been any relatively unified and complete discussions on the concept of urban resilience (Ahern, 2011; Rus et al., 2018; Zimba, 2019; Chen et al., 2020). By analyzing the extant literature, we believe that urban resilience refers to restoring force, adaptability, and self-organizing force when the urban system and its social-ecological and technological networks can maintain or rapidly return to the ideal state in the face of the interference. Subsequently, the concept of resilience has also been applied in the research and planning practice of climate change, urban heat island, and disasters such as war, floods, hurricanes, and other aspects (Campanella, 2006; Gleeson, 2008; Carvalho et al., 2017; Almeida et al., 2020; McEvoy et al., 2020). Overall, there are two significant characteristics of this kind of research. On the one hand, academic research is mostly oriented to maintaining urban security and stability, and discusses the ability of a city to respond to or adapt to natural disaster events from the perspective of short-term engineering resilience, which has the characteristics of easy operation and strong pertinence (Chelleri, 2015). On the other hand, most planning practices are based on principles of a resilience framework (Spaans and Waterhout, 2017; Ribeiro and Goncalves, 2019), and exhibit a lack of spatial description and quantitative analysis of the characteristics of resilience heterogeneity. As a result, the implementation effect of the policy is relatively poor (Desouza and Flanery, 2013). From the perspective of the practical processes for assessing resilience in cities, the development of resilience requires urban managers to grasp the complexity and interaction between cities and disturbance elements based on the system approach, and to better understand how the components of an urban system respond to threat factors and their interactions in different spatial and temporal scales (Ahern, 2013; Wardekker et al., 2020). In recent years, some scholars have begun to explore the relationship between landscape pattern and urban resilience from the perspective of landscape ecology, in an attempt to find the internal relationship to promote urban sustainable development (Allen et al., 2016; Ascott and Kenny, 2019). Urban morphology indexes such as location, size, density and connectivity, and landscape pattern indexes such as Shannon's diversity index, contagion index and fragmentation index become components of the evaluation system for urban resilience, which makes urban resilience more easily quantified (Olds et al., 2012;

Liu et al., 2019). The adaptive cycle model provides a basis for distinguishing urban resilience development stages and the characteristics of cognitive resilience evolution (Luo et al., 2018). Although the study of urban resilience has gradually become the central issue of landscape application and urban ecology, as a new hot topic with strong and comprehensive theoretical basis, further research is still needed on how the resilience model of urban physical elements based on landscape patterns can be further discussed and explored (Fischer et al., 2016; Wardekker et al., 2020).

'Size-density-morphology' is the basic feature of dynamic urban development, and it is also a macroscopic and explicit index for measuring urban development. In large cities, the size and elements' density of built-up areas are higher. This means that more people and resources may have potential risks in the face of rapid risk disasters. In the absence of appropriate planning and preparatory action to enhance urban adaptive capacity, larger cities will be more vulnerable to the adverse impacts of disastrous events. It is the pattern of urban growth and how urban activities are distributed that determines if increasing city size can also provide environmental benefits (Lee and Lee, 2014; Sharifi, 2019). In contrast, sprawling patterns result in over exploitation of land and resources, encroachment on sensitive resources such as wetlands and grassland, disrupt the natural flow of energy and resources between the built environment and the natural environment. Density is arguably the most explored attribute in urban planning. Urban density is a characteristic of urban-development intensity, such as population density and building density (Silva et al., 2017). The high density of regional not only deepens the damage intensity of regional environment, but also increases the risk exposure of population. In terms of emergency response, it is evidenced that high density can be an impediment to absorption and response capacities and resulting in secondary disasters or greater losses in urban areas. For instance, major destructions in high density areas will result in the obstruction of streets and emergency access routes (Wamsler et al., 2013). While identifying optimum thresholds for density is important, it should be acknowledged that such thresholds may vary from one context to another (Lohrey and Creutzig, 2016). From the perspective of landscape ecology, ecological carrying capacity is the safe threshold for urban density (Xiu et al., 2018). The

significant implications of urban morphology for achieving sustainable and resilient cities are increasingly recognized (Creutzig et al., 2016). Since the outbreak of SARS in 2003, some scholars have discussed the security significance of urban size, density, and morphology (Xiu and Zhu, 2003; Ng et al., 2011), and they concluded urban morphology has important research significance for resisting sudden disasters and protecting human urban settlements. By minimizing appropriate changes to the natural routes of ecological corridors and by integrating blue and green networks, the urban system provides various service benefits such as flood control and rainwater management, buffer capacity provision, urban heat island effect mitigation, air quality improvement, economic vitality, human pressure relief, *etc*. (Jayawardena and Van Roon, 2017; Olazabal et al., 2018). Although many scholars have discussed the relationship between urban resilience and size, density and morphology. Their perspectives mostly start from a single urban dynamic attribute, and fail to fully understand that urban size, density and morphology exist in the process of urban dynamic development. It leads to the lack of dynamic and coupling relationship between urban resilience and size, density and morphology. In this paper, we believed that urban size, density and morphology are different aspects of urban attributes, which are important reflection of urban development process. The advantages of any two parties can alleviate the adverse impact of the third party on urban resilience to a certain extent. Excessive urban size and population density are the most direct causes of increased exposure and risk when sudden disasters occur, and poor urban morphology exacerbates urban safety problems due to size and density.

As a multi-level nested structure system, a city has the characteristics of openness and chaos. The effect of disturbance factors shows differences in spatial scale. The interaction between them makes it evident that the development of urban resilience not only has spatial heterogeneity, but also has scale characteristics (Quinlan et al., 2016). For example, some disasters and problems do not cause serious or even catastrophic damage to small cities, but they may cause major damage in the case of large cities. For this reason, there are differences in urban resilience under different spatial scales. That is, there are spatial scale effects in urban resilience research (Brown et al., 2012). Scale features are not only the representation of geographical phenomena and proc-

esses in time and space, but also their inherent properties. The pattern, process and mechanism of geographical phenomena differ significantly with change in spatial scale. Many studies have shown that the difference in research scale often leads to differences in the presentation and extraction of spatial features and information content. If the space scale is too large, although it can grasp the overall pattern of elements, it is easy to ignore the internal details. While the space scale is too small, although it can show internal heterogeneity, it is difficult to discern the overall characteristics and patterns of things. Thus, the choice of spatial scale is important for the correct understanding of the scientific nature of research objects. Spatial scale effect is widely encountered in geographical studies (Klotz et al., 2016; Witt and Lill, 2018), such as the process of landscape pattern, remote sensing inversion, economic development, *etc*. However, in the research on urban resilience, it has not received the attention that it deserves. Based on existing studies, most of the research on urban resilience has been on the macro scale and comprehensive measurement carried out based on the city as the basic unit (Johnson and Blackburn, 2014; Schlör et al., 2018). This not only ignores the characterization of the heterogeneity within the city, but also affects comprehensive analyses of and deductions from the urban resilience process, as well as the effective identification of the internal mechanisms to a certain extent.

The rapid development of urbanization has not only promoted the accumulation of social wealth in big cities, but has also increased the disturbance factor of uncertainty in urban development to some extent, which has become an important bottleneck restricting the sustainable development of cities. The study of its resilience and the characteristics arising from scale effect is helpful to understand the safety and development issues of big cities in China and to enrich the theories and cases of sustainable urban development. In view of this, this paper uses the theories and methods of landscape ecology as reference to construct the research framework for urban resilience; it also describes the characteristics of scale effect on urban multidimensional resilience, and probes the concerned landscape factors, so as to seek the optimal scale units for the optimization and adjustment of resilience and the landscape pattern elements for the development of resilience under different scale backgrounds. It also aims to further expand the perspective

and content of the study of urban resilience and provide some insights into the development of urban resilience and the construction of a suitable development environment for urban security in big cities.

2 Materials and Methods

2.1 Study area and data source
Shenyang is located in the southern part of the Northeast China Plain and is the provincial capital city of Liaoning Province. In 2015, the average annual population of the urban area was 5.2915 million, the built-up area was 465 km^2, the urban GDP was 58.91 yuan (RMB) million, and the urbanization rate reached 80.55% (Shenyang Survey Team of the National Bureau of Statistics, 2016). It is one of the central cities with the largest population and economic scale in Northeast China. The city has several rivers passing through it, such as the Liaohe River, Hunhe River, Puhe River, and Baisha River, and mountains, such as the Qipan Mountain, Shiren Mountain and Meteorite Hill, as well as the land in between. The urban area mainly includes the main urban area and the construction land groups such as Sujiatun, Zhangshi, Daoyi, Hushitai, and Xinchengzi (Fig. 1a). In recent years, along with its rapid development, Shenyang has also experienced or is experiencing security threats like those in other big cities, such as heavy pollution, accidents, disasters, and so on. To further analyze the spatial differentiation rules and scale effect characteristics of urban resilience, this paper divides the research area into six spatial ranges according to the sampling method of the equally spaced system (Fig. 1b).

The main data of this paper includes 30-m resolution remote sensing image data of Shenyang in 2015 (http://www.gscloud.cn/). The 2015 grid source data comes from the WorldPop website (http://maps.worldpop.uk/#/map/layers/), which is re-sampled at 62.5 m via the ArcGIS 10 platform. Resource and energy use data of 2015 are from the Statistics Yearbook of Shenyang (2016) (http://tongji.cnki.net/kns55/navi/navidefault.aspx). Landscape indexes within each spatial range are obtained by batch calculation using Fragstats v 4.2.

2.2 Research methods
Based on the urban physical space attributes, this paper attempts to incorporate the three dimensions of urban size, density and morphology into the concept of urban
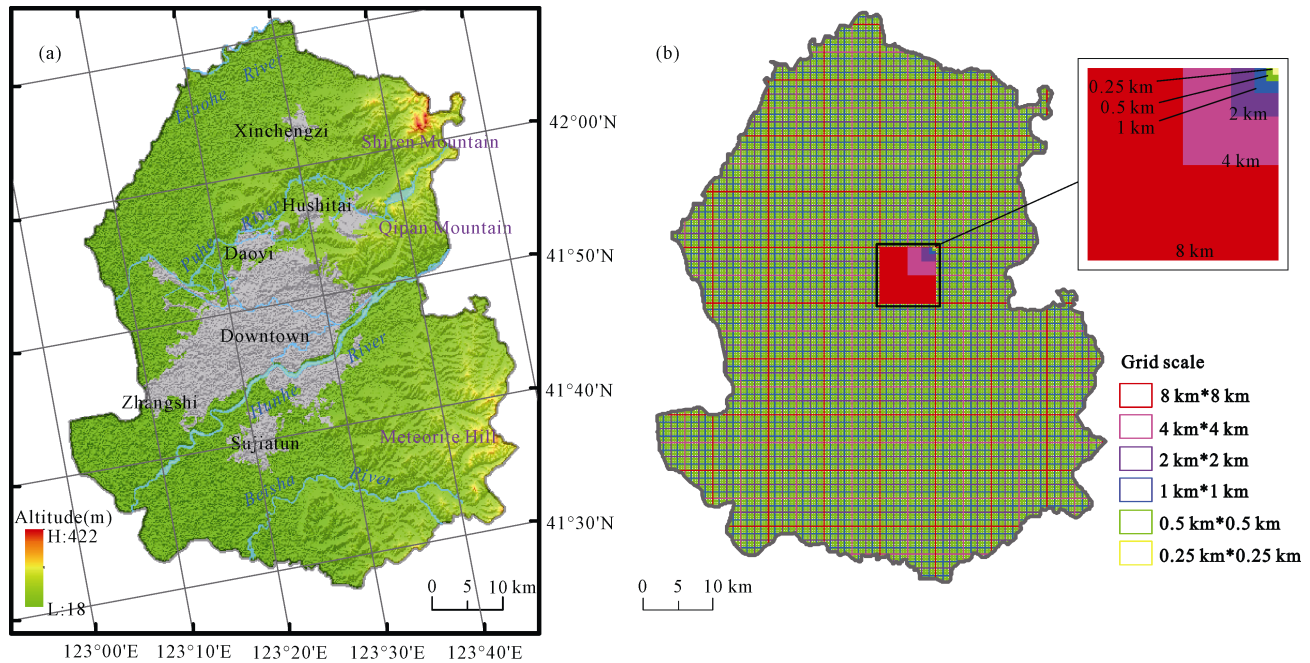
Fig. 1   Study area (a) and division of spatial amplitude (b)

resilience. It is considered that urban size, density, and morphology are important factors in the development of resilience and that the three factors supplement each other and also exist uniformly in the urban system. This paper holds that urban size refers to the built-up area size of urban development, urban density refers to the representative elements of urban development intensity (population, building density, *etc*.), and urban morphology includes the urban physical space composition and spatial allocation of various types of land. Moderate urban size, reasonable urban density and excellent urban morphology are effective means for solving the acute impact and chronic stress in the city.

Based on these, this paper tries to build 'size-density-morphology' into a three-dimensional analysis framework, and measures urban size, density, and morphology resilience through the InVEST (*Integrated Valuation of Ecosystem Services and Tradeoffs*) model, the ecological footprint model, the 'source-sink' theory, and the accessibility model from the perspective of the theory of landscape ecology. Comprehensive resilience is judged according to the combination of conditions of three-dimension resilience. This paper attempts to measure the spatial pattern and scale effect of urban resilience at different scales to explore the optimal scale for urban resilience research and optimization. At the same time, based on the response relationship of the

landscape pattern, this paper further analyzes the main landscape factors under different scale backgrounds, so as to provide a meaningful basis for the optimization of urban resilience patterns (Fig. 2).

2.2.1   Urban size resilience

Many scholars have considered habitat analysis in landscape ecology and the boundary of urban growth comprehensively and tried to delimit the 'ecological boundary' of urban growth. We believe that habitat quality generally decreases gradually with the increase in human land use and its intensity and shows a certain distance attenuation in space. However, when the urban size exceeds or encroaches on the ecosystem land, the regional habitat quality weakens, the sustainable development ability of the city is damaged, and the urban resilience level is low. This paper starts from the concept of urban growth boundary and uses Habitat Quality in the InVEST model to analyze the resilience of urban size. The operation of the InVEST model requires that the threat source be defined, along with the relative sensitivity of habitat for each threat source, the distance between habitat and threat source, and the legal protection level of land. The more sensitive the habitat is to the threat factor, the greater the impact of that factor on habitat degradation. Assuming that the land or habitat type at the grid x is j, the total threat index D_{xj} at this point can be expressed as Equation (1):
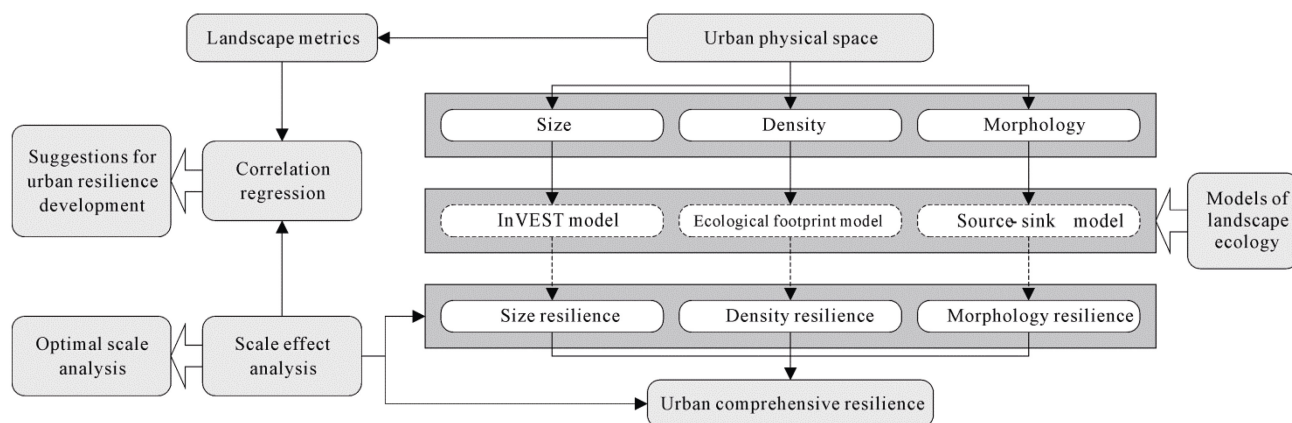
Fig. 2 Research flow chart

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} r_y \left(\frac{\omega_r}{\sum_{r=1}^{R} \omega_r} \right) i_{rxy} \beta_x S_{jr}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{r\max}} \right) \text{(for linear decay)}$$

$$i_{rxy} = \exp\left(\frac{-2.99 d_{xy}}{d_{r\max}} \right) \text{(for exponential decay)} \quad (1)$$

where D_{xj} is the habitat degradation degree of the grid x in the habitat type j; R is the number of threat sources; ω_r is the weight of threat source r; Y_r is the grid number of threat source r; r_y is the stress value of grid y; i_{rxy} is the stress level of the stress value of grid y to the grid x; β_x is the accessibility of the threat source to the grid x; S_{jr} is the sensitivity of habitat types j to threat source r; d_{xy} is the Euclidean distance between the habitat of the location and the threat source; and, $d_{r\max}$ is the maximum interference radius of the threat source r.

On this basis, the calculation of habitat quality is as given in Equation (2):

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right] \quad (2)$$

where Q_{xj} is the habitat quality index of the grid x in the habitat type j, H_j is habitat suitability of habitat type j, D_{xj} is the habitat degradation degree of the grid x in the habitat type j, k is the semi-saturation constant, z is a normalized constant, generally 2.5.

Based on the remote sensing images of Shenyang in 2015, this paper considers that farmland, forest land, grassland, and water bodies are all carriers of urban risk sharing in size resilience and belong to habitat land. Construction land, railways, expressways, national roads, provincial roads, and county roads are risk sources or diffusion channels, which are threat sources. Combined with previous studies (Wu et al., 2014; Yan et al., 2018; Bai et al., 2019), model recommendation and expert interviews, the weight of threat source, the maximum influence distance and attenuation model of threat source on habitat land, and the sensitivity of habitat land to threat source were determined, as shown in Table 1.

Table 1 Data table of habitat threat source and habitat sensitivity in Shenyang City

Threats	Weight	Sensitivity					Max-distance (km)	Decay model
		Farmland	Forest land	Grassland	Water body	Unused land		
Construction land	1.00	0.40	0.75	0.45	0.80	0.50	10.00	Exponential
Railway	0.80	0.30	0.65	0.25	0.65	0.40	3.00	Linear
Highway	1.00	0.30	0.65	0.35	0.65	0.40	5.00	Linear
National road	0.80	0.30	0.75	0.45	0.75	0.50	3.00	Linear
Provincial road	0.60	0.20	0.55	0.20	0.80	0.20	2.00	Linear
County road	0.40	0.10	0.45	0.10	0.45	0.10	1.00	Linear

According to the state of urban habitat, the urban size resilience index under grid scale is constructed as Equation (3):

$$SR_i = \sum Q_i \big/ A_i \qquad (3)$$

where SR_i is the size resilience index of the grid i, Q_i is the sum of habitat quality within the grid i and A_i is the area of the grid i.

2.2.2 Urban density resilience

Urban resilience development needs to prioritize the supply of ecosystem services, to ensure the sustainable development of the city, especially in the dynamic evolution process of urban complex systems (Xiu et al., 2018). From the perspective of supply and demand, the ecological footprint model compares the demand of ecological footprint of human activity and the ecological carrying capacity provided by the natural ecosystem to characterize the regional sustainable development status, which provides a relatively accurate measurement method for the urban density resilience condition. Generally, an ecologically deficit city overdraws its ecological carrying capacity, which seriously damages its adaptability and resilience and causes its urban development to lack resilience. The sustainable development ability of ecological surplus city is stronger. Therefore, based on the ecological footprint model and the data of population density and land use, this paper proposes the urban density resilience index at the grid scale from the relation of ecological supply and demand, as Equation (4):

$$DR_i = \frac{EF_i}{EC_i \times (1-12\%)} = \frac{P_i \times \sum r_k \times c_j \big/ w_j}{(1-12\%) \times \sum r_k \times y_k \times a_{ik}} \qquad (4)$$

where DR_i is the density resilience index of grid i; EC_i is the ecological carrying capacity of grid i; EF_i is the ecological footprint of grid i; r_k and y_k represent the balance factor and yield factor, respectively of the k kind of productive land; a_{ik} represents the k kind of productive land area in grid i; P_i is population number of the grid i; c_j is per capita consumption of the j kind of commodities in the area; and w_j is the global average yield of the j kind of consumer goods. According to the report of the WCED (World Commission on Environment and Development), 12% of the ecological carrying capacity is used to protect the area of biodiversity. When $DR_i > 1$, the supply of ecological footprint is less than the ecological demand, and ecological deficit appears,

regional overloading occurs, urban development lacks resilience, and there is insufficient sustainable development potential. When $DR_i < 1$, the regional ecological environment is in surplus, and urban development has higher resilience level.

2.2.3 Urban morphology resilience

From the perspective of 'source-sink' landscape theory, regional heterogeneous landscape can be divided into two types: 'source' landscape and 'sink' landscape. 'Source' landscape refers to the landscape that can promote the development of ecological process, and 'sink' landscape is the landscape that prevents or delays the development of ecological process (Vale and Campanella, 2005). Urban landscape can be divided into gray landscape (such as buildings, roads), blue landscape (water), green landscape (green vegetation), *etc*. In the process of urban disaster or stress, the 'sink' is mainly the gray landscape, while the blue and green landscape is the 'source'. From the perspective of supply and demand, the larger the area of blue and green landscape in the urban system, the better it is. This is conducive for the better mitigation of urban risks and improvement of the capacity of urban ecological services. When the area of required blue landscape and green landscape is ascertained, its spatial configuration becomes particularly important. For example, a balanced green landscape has a better cutting effect on urban heat islands and urban inland inundation. The equilibrium of spatial configuration of 'source' and 'sink' landscape can be measured by the accessibility between 'source' and 'sink' landscapes. Therefore, based on the mean distance index of 'source-sink' landscape proposed by Xiu et al. (2018), this paper constructs the urban morphology resilience index based on grid scale, as Equation (5):

$$MR_i = \sum \frac{L_j}{L_{ijk} \times A_{ij}} = \sum L_j \bigg/ \left(\sum_{j=1}^{n} \min\left(d_{ijk}\right) \bigg/ m \right) \times A_{ij} \qquad (5)$$

where MR_i is the morphology resilience index of grid i; A_{ij} is the proportion of the j kind 'source' landscape in the grid i; L_{ijk} represents the average distance index from j kind 'source' patch to 'sink' patch in the grid i; d_{ijk} represents the distance from each grid of j kind 'source' patch to the grid k of 'sink' patch in the grid i; and, m and n are the grid number of the 'source' patch and the grid number of the 'sink' patch, respectively, in grid i. L_j is a constant representing the average distance index of j kind of 'source' landscape and "sink" landscape. The

smaller the MR_i value, the better the spatial balance of 'source-sink' landscape and the stronger the urban morphology resilience.

In this paper, we believe that construction land is the main source of urban risks, while cultivated land and unused land reduce the service capacity of urban ecosystem through the impact of human activities on regional habitat quality. The above landscape hinders the resilience development of the city to varying degrees and is classified as 'source' landscape. Forest land, grassland, and water bodies are important parts of a regional ecosystem, which can promote the risk mitigation of urban inland inundation, heat island effect and other risks. They are collectively referred to as 'sink' landscape. The average distance between Shenyang City and 'sink' landscape is ascertained and set. According to spatial statistical analysis using ArcGIS software platform, the average distance index between construction land, unused land and cultivated land in Shenyang and 'sink' landscape is 519.9 m, 137.5 m, and 684.6 m, respectively. The distance index of 'sink' landscape is 0.

2.2.4　Urban comprehensive resilience

Urban comprehensive resilience is an organic combination of size, density and morphology resilience, and a good state of urban resilience development should be an optimal combination of the three. Therefore, according to the model significance and score value of resilience in each dimension, this research divides size resilience, density resilience, and morphology resilience into two levels with critical values of 0.5, 1 and 1, and combines them according to Table 2 and assigns the corresponding score of comprehensive resilience, to analyze the pattern of urban comprehensive resilience.

Table 2　Division basis and the setting of score value of urban comprehensive resilience

Comprehensive resilience	Size resilience	Density resilience	Morphology resilience	Scores
High level	High	High	High	4
Medium-high level	High	High	Low	3
	Low	High	High	
	High	Low	High	
	Low	Low	High	
Medium-low level	High	Low	Low	2
	Low	High	Low	
Low level	Low	Low	Low	1

3　Results

3.1　Multi-scale spatial pattern of urban resilience in Shenyang

Based on the spatial scales of 0.25 km, 0.5 km, 1 km, 2 km, 4 km and 8 km, this paper uses the resilience model of each dimension to calculate the urban resilience scores at different scales. At the same time, according to the distribution of resilience score value, the dimensions of size resilience are divided with 0.25, 0.5 and 0.75 as the critical values, and the dimensions of density resilience and morphology resilience are divided with 1.5, 1 and 0.5 as the critical values. The score value of comprehensive resilience is set according to the three-dimensional resilience combination, and a multi-scale spatial pattern diagram of three-dimensional resilience and comprehensive resilience of Shenyang City is formed (Fig. 3), to analyze the spatial variation characteristics of the city's dimensional resilience under the scale background and propose differentiated countermeasures to improve the level of urban resilience.

The 0.25 km scale better reflects the detailed characteristics of urban resilience. At the scale of 0.25 km, the low-level area of size resilience in Shenyang City is closely related to the spatial distribution pattern of urban construction land and presents a patchy distribution in the regional space, while the high-level area is mainly the large blue and green landscape in the area. In the process of urban expansion, there has been a tendency to allocate construction land, industrial and mining land, and rural residential area, to occupy ecological land in Shenyang. The ecosystem has not only shrunk, but has also become more and more fragmented and its internal integrity is destroyed. The low-value areas of urban density resilience are mainly distributed in the central urban areas and urban cluster areas due to the influence of strong economic activities, low ecological carrying capacity and more urban risks. The high-level resilience zone is basically located at the edge of the urban area, which is mainly green land, arable land, water bodies and other landscapes with relatively sparse population distribution. The regional ecological environment is mainly dominated by surplus development and the ecosystem has a strong ability to resolve regional risks. The low value area of urban morphology resilience has obvious characteristics of fragmentation. The morphology resilience of the central urban area is higher due to
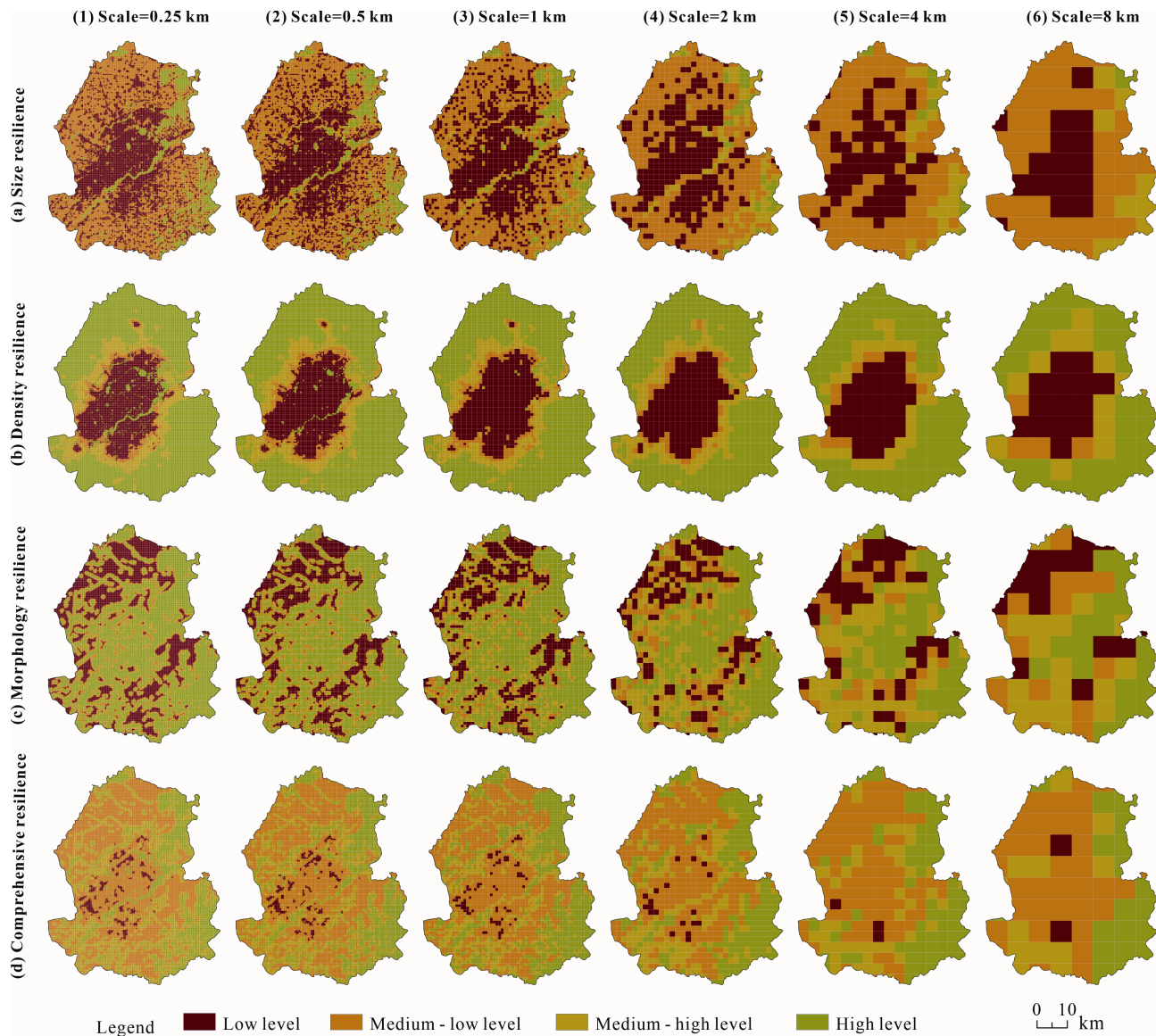
Fig. 3 Multi-scale spatial distribution of three-dimensional resilience and comprehensive resilience in Shenyang

the influence of large parks and water areas. The main landscape type in the peripheral area of the central urban area is cultivated land, which is affected by the segmentation of zonal waters and green belts. The eastern zone is an important ecological barrier land, which has blue landscape and green landscape with relatively complete ecology, and its morphological resilience is at a high level.

With the expansion of scale, the spatial pattern of urban three-dimensional resilience gradually tends to become simpler. At the scale of 1–4 km, the resilience pattern of city size roughly shows a low-level agglomeration area dominated by construction land and a high-level area

composed of large water bodies and green space. The density resilience only depicts the overall pattern of 'center-periphery'. The low level is concentrated in the central urban area, while the high level is distributed in the urban fringe in a ring. However, the edge and inner details of the central urban area gradually become blurred. The morphology resilience in Shenyang City is characterized by high and low distribution. At the scale of 8 km, the two large low-level resilience zones-central urban area and Xinchengzi urban area, the low-level density resilience zones of the central urban area, the high-level morphology resilience zones of Hunhe River-Qipan Mountain area, and the Meteorite Hill area are all displayed

from the macroscopic angle.

From the multi-scale spatial distribution pattern, comprehensive resilience is dominant in medium-low level area in Shenyang, and the development level of urban resilience is low. Each hierarchy resilience has significant heterogeneity featured in space. Medium-low level resilience zones are mainly distributed in the downtown area and the cultivated land area of the periphery, low resilience plaques are mainly located in the spreading area of the city, and the resilience of the eastern ecological corridor is at a high level. Scale growth is negatively correlated with the heterogeneous change of comprehensive resilience pattern, and space 'transition' phenomenon appears in low level resilience areas. At the 0.25–2 km scales, the distribution pattern of low-level resilience space has obvious similarities. The low-level resilience space is mainly distributed in Zhangshi, Dapan, Hushitai, Daoyi, Sujiatun, and other regions, but the low-level resilience zones in the main urban area gradually disappear. The 4-km scale depicts the low-level resilience pattern in the two extended areas of Sujiatun and Zhangshi. The 8-km scale reflects the overall development direction and resilience development of the city and highlights the two low level resilience zones—the northern development zone dominated by Daoyi-Hushitai group and the southern development zone dominated by Sujiatun.

Based on the three-dimensional resilience and resilience pattern, we believe that the expansion of construction land and the continuous growth of density factor in the main urban area are the leading factors for the resilience level of the central urban area, and a reasonable layout of green and blue landscape patches is conducive to alleviating the urban risks. Therefore, it is important to delimit the urban growth boundary, provide for the reasonable evacuation of the population, and situate energy-intensive industries in the main urban area, reduce the building density, and improve the green infrastructure, to promote the resilience level in the main urban area.

The intensity of human activities in the cultivated land landscape inside the city is not high; these cultivated land landscape elements have low space coupled with the 'sink' landscape. In case of a disaster or the city spreads and expands, although it provides buffer zones for urban risks and land resources for urban construction, it is also the primary landscape for disaster diver-

sion or urban expansion. When the potential risks in the region are large and the resilience level is insufficient, the main task to prevent the decline of the resilience level in the area is by controlling the non-agricultural use of the cultivated land landscape. The low-level resilient patches are mainly located in the urban sprawl and expansion areas, which, under the influence of the strategies of 'two-bank-waterfront' and 'new urban', have become the most dynamic areas after the main urban areas. In the process of urban development, attention should be paid to the construction of ecological infrastructure, balanced urban development, smart growth, and multi-scale network construction. The green and blue landscape of the eastern ecological corridor is relatively complete. Size, density, and morphology resilience are all in the high-level zone, and the comprehensive resilience level is accordingly also high. It is an important zone to mitigate and regulate urban risks, and obtain ecological services. However, there is a lack of effective buffer space between urban construction land and ecological land, so it is necessary to avoid the encroachment of construction land on ecological land and the fragmentation of green landscape in future urban development.

3.2 Spatial scale effect of urban resilience in Shenyang

In order to study space effect characteristics of urban resilience with amplitude change, six spatial amplitude standards 0.25 km, 0.5 km, 1 km, 2 km, 4 km and 8 km are selected to analyze the average value of resilience and spatial correlation characteristics of urban areas.

The average value of urban three-dimensional resilience and comprehensive resilience has obvious characteristics of spatial scale effect (Fig. 4). From the point of three-dimensional resilience, the average value of urban size resilience rises from 0.3125 to 0.3434 with scale enlargement, and the level of urban size resilience is improved to some degree. Although the size resilience of Shenyang is on the rise, it still has significant stage characteristics. The difference in the speed of size resilience improvement is obvious. At the 2-km scale, size resilience grows relatively fast, and scale has the most significant impact on urban size resilience. At the scale of 2–8 km, the growth rate of the average value of size resilience is relatively slow, and the scale effect is gradually weakened. Within the scales studied in this

paper, 2 km becomes the scale inflection point for size resilience. The average value curve of urban density resilience presents a typical power-law distribution feature ($R^2 = 0.9649$), and the regional density resilience level is rapidly improved. The scaling attenuation coefficient of density resilience, calculated based on the fitting curve, is 0.2220. The overall regional resilience changes greatly within the range of 1 km, while the change of density resilience in Shenyang tends to be flat after the 1-km scale. Therefore, the scale inflection point of density resilience in Shenyang is 1 km, and the spatial optimal allocation of population and industry on the scale of 1 km in the area with low density resilience is conducive to promoting the level of resilience. Compared with size and density resilience, the average value curve of urban morphology resilience fluctuates, indicating that the spatial segmentation of 'source' and 'sink' landscapes by research scale leads to a prominent scale dependence of morphology resilience. In the scale intervals of 0.25–1 km and 2–8 km, the morphology resilience level of Shenyang shows an upward trend,

while the morphology resilience level shows a downward trend in the scale interval of 1–2 km. The scale inflection point is 2 km. Under the situation that the 'source' and 'sink' landscape scale and space configuration are relatively stable, conducting ecological infrastructure construction and adjusting land use structure with 1 to 2 km as a basic scale can help to resolve the risk of 'sink' landscape. From the perspective of the average value curve of comprehensive resilience, the comprehensive resilience of the city is rapidly improved within the range of 1 km. The comprehensive resilience level is relatively slow within the range of 1–4 km. However, it declines after 4 km, and the characteristics of scale effect are obvious. The optimal scale unit of comprehensive resilience should be 1 km. In general, in the urban resilience analysis of Shenyang City, taking 1–2 km as the basic scale unit can not only better depict the heterogeneous characteristics of urban resilience and identify the low-level urban resilience unit, but also provide a relatively appropriate scale for optimizing the overall resilience pattern.
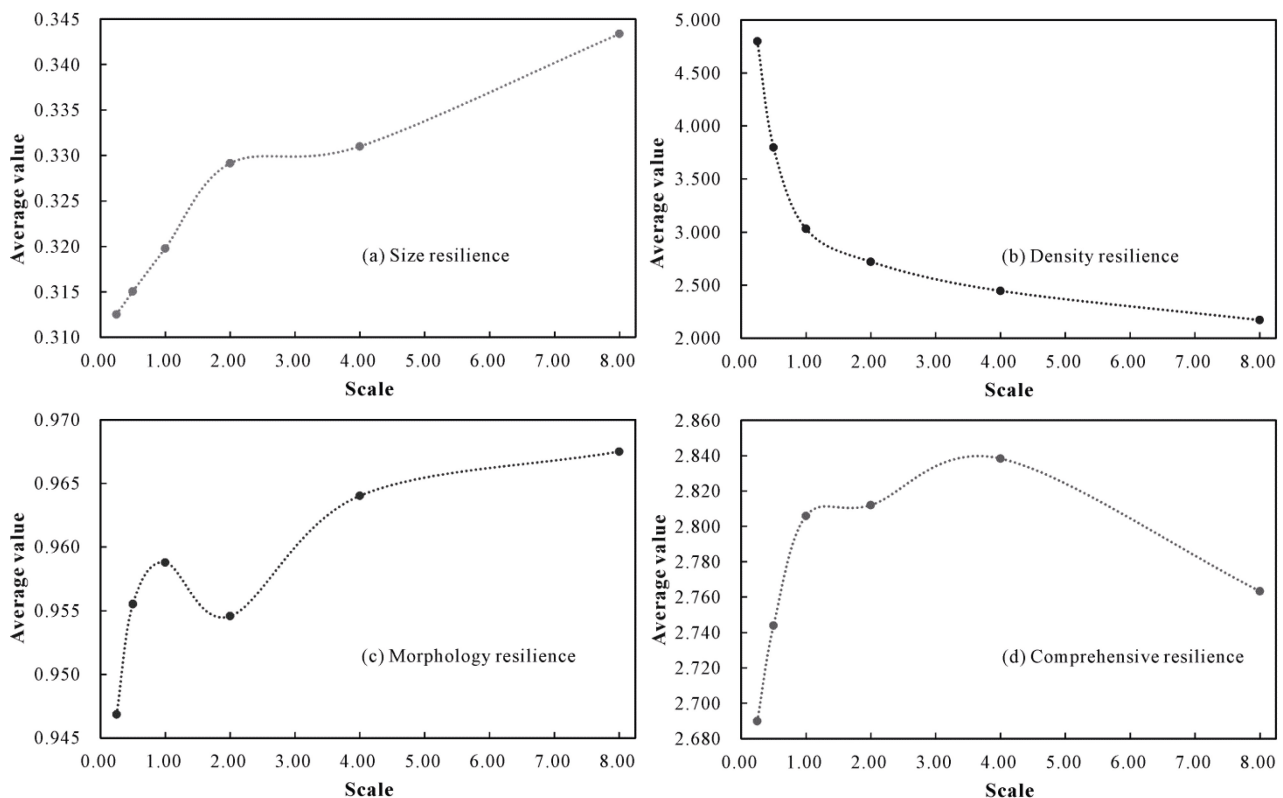

Fig. 4 Responses of the average value of urban three-dimensional resilience and comprehensive resilience to spatial scale in Shenyang City

At all spatial scales, Moran's *I* index is greater than 0 (Fig. 5), indicating that there is a certain positive correlation between each dimensional resilience and comprehensive resilience of Shenyang in space. With the increase in scale, the Moran's *I* index curve of resilience in all dimensions presents an overall downward trend, and the spatial similarity of resilience gradually weakens. Size, density, morphology, and comprehensive resilience all show sharp decline and gentle decline in different scale intervals, and the dependence of urban resilience in spatial scale has obvious scale characteristics. From resilience dimension point of view, the curve change of morphology resilience and density resilience in the 0.5 km scale is relatively flat. The scale space similarity of both in the 0.25 km and 0.5 km is smaller, the differences within neighboring scopes are large, and the scale effect is weak. But in the 0.5–8 km scale interval, it changes sharply. The change of resilience pattern within neighboring scope shows some similarities, and the characteristics of spatial heterogeneity decrease. The spatial amplitude of 0.5 km is an obvious sensitive point of the spatial auto-correlation of morphology and density resilience to scale effect. The Moran's *I* index curve of size resilience and comprehensive resilience

shows an obvious downward trend within the 1 km scale, and the spatial similarity of resilience increases. When the spatial scale exceeds 1 km, the curve changes between them are relatively gentle, the spatial dependence of resilience distribution gradually decreases, and the scale effect gradually disappears, which is highlighted in the dimension of size resilience. Thus, the sensitive point where the spatial correlation pattern of size and comprehensive resilience responds to scale, should be 1 km.

3.3 The impact of landscape pattern on urban resilience under scale background

The triple attribute of 'size-morphology-density' is not only the reflection of urban development in regional space at each stage, but also one of the methods of optimization for cities so that they can minimize risks under uncertain disturbance factors (Rescia et al., 2010). It is currently an important issue in ecology, geography and urban planning, as it recognizes urban resilience and aims to resolve urban disaster-causing factors from the perspective of landscape ecology. By changing the size, shape, configuration structure, interaction, and other internal patterns of landscape patches, urban development
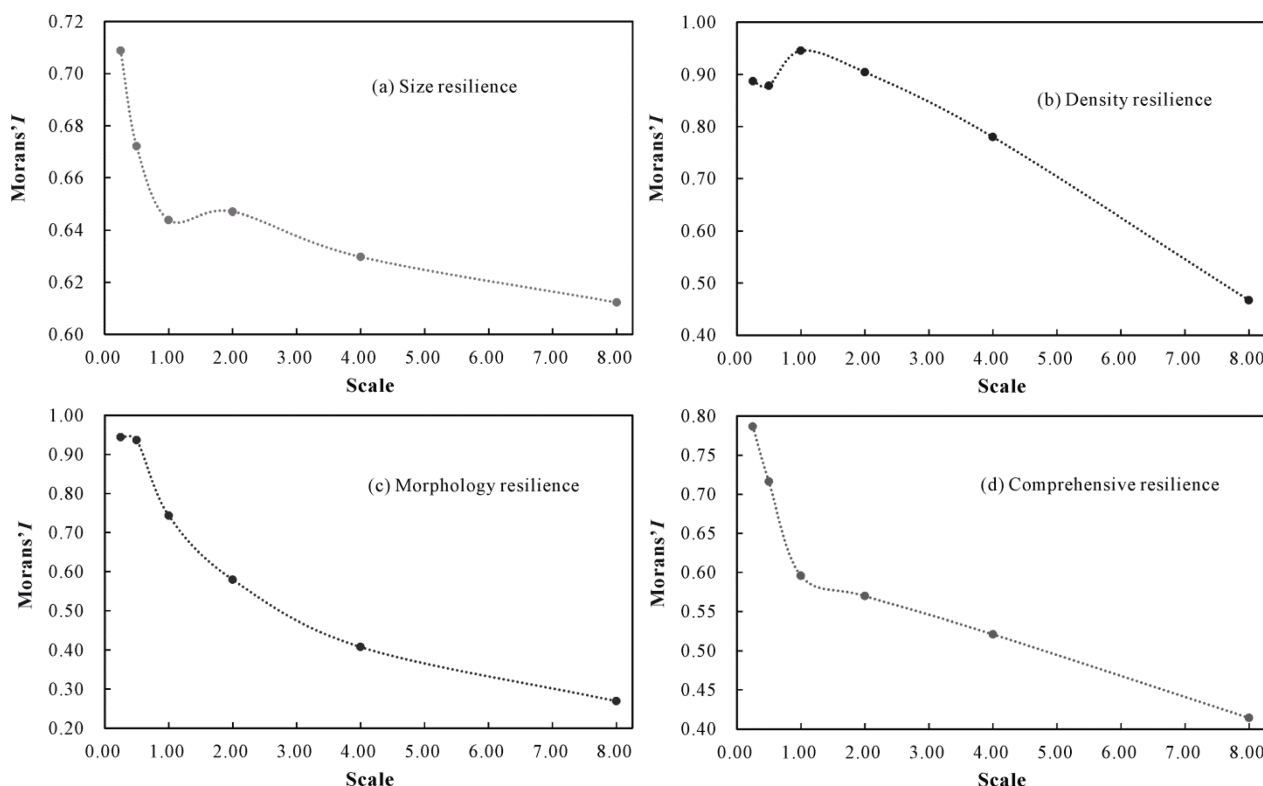

Fig. 5   Response of Moran's *I* index of urban three-dimensional resilience and comprehensive resilience to spatial scale

produces different ecological effects, thus affecting the sustainable development of the city. The nature and size of facets in the landscape pattern can be quantified through the landscape index, revealing the spatial characteristics of urban development and its associated processes (Li et al., 2017), and can be used to represent the influencing factors of the development of urban resilience (Dhar and Khirfan, 2017). For example, indices such as patch density, fragmentation, complexity of morphology and connectivity can be used to depict the heterogeneity of the urban landscape; this heterogeneity interacts on the development level with urban size, density and morphology resilience. At the same time, the situation of landscape patterns in different scale units is obviously different, and the ability to resolve risks within a certain scale is also different. Therefore, based on the spatial characteristics of landscape heterogeneity and multiple scales, this paper takes the research on urban landscape pattern of relevant scholars for reference, and selects Patch density (PD), Edge density (ED), Contagion index (CONTAG), Connectance index (CONNECT), Shannon's diversity index (SHDI) and

Aggregation index (AI) to analyze the landscape factor of urban resilience in Shenyang City, in order to clarify the main influencing factors of urban resilience under different dimensions. Correlation and linear regression analysis are performed based on data processing such as outlier elimination, logarithmic transformation and standardization, and the results are shown in Table 3.

Under the background of scale increase, the explanatory power of landscape pattern index with respect to the regression model of resilience of each dimension gradually increases. In terms of size, density, morphology resilience, and comprehensive resilience, the goodness of fit of linear regression increases with the increase in scale. R^2 increases from 0.1 to 0.4 or 0.5. The reason is that the landscape patches in a small space scale are relatively simple, and the difference of landscape index in a scale is small, which leads to the poor fitting effect. However, the difference of landscape index gradually widens, which is led by spatial scale unit at large scales, and the regression effect between the unit and resilience shows an overall improvement.

Table 3 Regression analysis on indexes between urban resilience and landscape pattern

Resilience	Scale	0.25 km	0.5 km	1 km	2 km	4 km	8 km	Resilience	Scale	0.25 km	0.5 km	1 km	2 km	4 km	8 km
Size resilience	PD	−0.70**	−1.14**					Density resilience	PD			0.772**			
	ED								ED	0.98**	2.76**	4.53**	8.61**		
	CONTAG	0.13**	0.45**	0.77**	0.87**				CONTAG	−2.37**	−2.99**	−4.59**	6.56**		
	CONNECT	0.18**	−0.10**	−0.11**	−0.36**	−0.45**			CONNECT	0.36**	0.47**	0.93**	2.1**	6.24**	
	SHDI	0.59**	0.76**	1.24**	1.51**	0.93**	1.33**		SHDI	−3.8**	−6.04**	−8.98**	−12.97**	−10.32**	−10.37*
	Ln(AI)	0.26**	−0.10**	−0.89**	6.30**	11.21**	104.34*		AI	4.79**	33.47**	87.01**	137.26**	339.35**	895.73*
	Constant	−2.29	−2.3	−2.34	−2.49	−1.95	−1.77		Constant	−1.55	−29.44	−80.75	−127.56	−332.87	−893.13
	R^2	0.106	0.161	0.224	0.317	0.454	0.470		R^2	0.143	0.189	0.270	0.358	0.406	0.422
Morphology resilience	PD	−0.01**	−0.04**	0.09**	−0.58**	−0.97*	1.70*	Comprehensive resilience	PD		0.02**	−0.11**			
	ED	−0.44**	−0.65**	−1.08**	−2.94**	−3.82**	−1.34*		ED	0.08**	0.15**	0.24**	0.76**		
	CONTAG	−0.47**	−0.40**	−0.18**					CONTAG	0.39**	0.46**	0.35**			
	CONNECT	−0.15**	−0.20**	−0.18**					CONNECT	0.11**	0.13**		−0.33**		
	SHDI	−0.13**							SHDI	0.66**	0.77**	1.20**	1.53**	1.51**	2.35**
	AI	1.33**	4.9**	10.27**	−11.06*				AI	−0.88**	−4.22**	−12.42**	−9.16*	−33.92*	224.20**
	Constant	−0.15	−3.5	−8.59	12.72	22.5	25.46		Constant	3.21	6.42	14.42	11.06	35.54	224.81
	R^2	0.109	0.159	0.193	0.224	0.329	0.435		R^2	0.196	0.278	0.336	0.379	0.468	0.511

Notes: **, * are significant at 5%, and 10% respectively

Landscape pattern index has threshold effect on urban size and morphology resilience. Through an analysis of the regression model between the urban size and morphology resilience and the landscape index, we get the following insights: Taking 1 km spatial scale as the critical value, dominant landscape factors of urban size and morphology resilience are changed. At the 1 km spatial scale, SHDI and AI are landscape factors which have a greater influence on the urban resilience. Outside the 1 km spatial scale, the influencing factors are PD, ED, and AI. Therefore, this paper argues that different aspects of landscape patterns should be paid attention to according to different planning scales in the process of urban resilience planning: landscape heterogeneity, stability and reasonable allocation should be paid attention to in a small scale, while at a larger scale, the decline in landscape heterogeneity should be prevented and the agglomeration or mass effect of landscape pattern should be alleviated.

AI of landscape has significant impact on each dimension of resilience and comprehensive resilience, and its influence grows as scale increases. According to the theory of landscape ecology, AI of a landscape is mainly used to represent the degree of aggregation of landscape patches. Whether it is size resilience, density resilience, morphology resilience, or comprehensive resilience, the regression coefficient of landscape AI is large, which is one of the main influencing factors of urban resilience. Especially at large research scales, AI becomes the dominant landscape factor affecting urban resilience. AI is negatively correlated with the size resilience value and the comprehensive resilience value, and positively correlated with the density resilience value and the morphology resilience value. In the process of urban resilience development, excessive agglomeration of landscape patches should be avoided as far as possible, especially as a lot of homogenization of patches has already been caused by the spread and expansion of construction land. At the same time, a reasonable layout of green landscape patches should be adopted to improve their ability to resolve urban risks.

Landscape diversity is one of the important factors that affect the comprehensive resilience of a city. The heterogeneity of urban landscape is the basic component of urban resilience (Cimellaro et al., 2016). In the regression model of urban comprehensive resilience, there is a typical positive correlation between landscape diversity index and comprehensive resilience. With increase in scale, its regression coefficient gradually increases from 0.66 to 2.35, becoming another important factor affecting comprehensive resilience. Therefore, we should pay attention to the heterogeneity of landscape pattern in urban comprehensive development and form a multifunctional pattern of urban development by interweaving different landscape types.

4　Conclusions and Suggestions

How to measure urban resilience is one of the important and difficult issues in current urban development research. Many studies have comprehensively measured the spatial and temporal characteristics of urban resilience by constructing multi-dimensional or multi-stage evaluation systems, but none of them have taken into full consideration the characteristics of external openness and internal heterogeneity of cities. This paper addresses this limitation. Based on the theory of landscape ecology and spatial analysis method, this paper constructs the three-dimensional analysis framework of research on urban resilience—'size, density, and morphology', through which the scale-dependence of heterogeneity can be evaluated by changing the spatial extent and exploring the response relationship between urban resilience pattern and landscape index in different grid scales. There are four main findings: 1) 'size-density-morphology' is the basic spatial attribute of urban development, as well as one of the important dimensions and quantitative criteria of urban resilience. This paper argues that urban resilience development is not determined by the development of a single dimension, but is influenced by the three-dimensional combination of size, density, and morphology. A good city resilience state should be a perfect combination of size resilience, density resilience, and morphology resilience. 2) The level of urban comprehensive resilience of Shenyang City is low, and the distribution of each resilience area has the typical characteristics of spatial heterogeneity. With the increase in scale, no matter the size, density, or morphology resilience, the high level and the low-level resilience area all shrink significantly, and the development of resilience tends to be balanced. The complexity of urban resilience pattern tends to become simple and the spatial details reflected by it are gradually lost. 3) The resilience average value of urban three-

dimensional resilience and urban comprehensive resilience has significant characteristics of spatial scale effect. From a comprehensive perspective, 1–2 km is not only the optimal spatial scale interval for the urban resilience analysis of Shenyang, but is also the optimal scale unit for the optimization and adjustment of the urban resilience pattern of this city. This scale interval is not only helpful to describe the spatial heterogeneity and overall pattern of urban resilience in Shenyang, but also provides a basis for identifying low level resilience units and optimizing the overall resilience pattern. 4) The explanatory power of the model of the relationship between landscape pattern and urban resilience goes up with the increase in scale. The main landscape factors of urban size and morphology resilience change with the shift in scale and its influence has scale characteristics. AI has significant influence on all dimensions and comprehensive resilience, and its influence and scale are positively correlated. The diversity of the landscape becomes another stable factor of comprehensive resilience.

We believe that an appropriate spatial extent should be selected for the analysis and optimization of resilience at different scales. In order to improve the overall resilience level of Shenyang City, we believe that it is necessary to take 1 km as the basic unit to optimize the environment for the development of resilience from the following aspects: 1) Rational layout of ecological infrastructure, promotion of balanced urban development, and improvement of coupling between source and sink landscapes. Shenyang City needs to strengthen the construction of green and blue ecological landscape in the central urban area, new areas for urban expansion and other areas, such as the construction of urban forest squares, pocket parks, *etc*. At the same time, a multi- center city development model has to be constructed to avoid the landscape pressure and urban sprawl caused by only developing the central city, and to share the development opportunities while sharing the risks, so as to realize the goal of regional convergence and also to improve the spatial coupling between source and sink landscapes. Finally, the overall resilience of the city will be improved. 2) Prevent the sprawl of construction land and the homogeneous development of patches, rationally distribute the population and the density of building elements and advocate a green way of production and life. Shenyang should prevent the continuous expansion of construction land, set the boundary for urban growth, promote the ra-

tional distribution of population, economy, building, and other factors on the basis of multi-level urban scale building, and advocate an urban green lifestyle and intensive production modes, so as to reduce the ecological footprint of the city and realize the sustainable development of the city. 3) Strictly control the exploitation of ecological areas and maintain the integrity of green landscape patches. The eastern zone of Shenyang City is an important ecological protection zone of the city. The blue and green landscapes are rich and complete, which provide ecosystem services for the city and are important zones for risk mitigation of the city. In the process of urban development, Shenyang should strictly control the exploitation of the eastern ecological area, try its best to avoid the encroachment and cutting off of the ecological green space by converting patches of its land for urban development, protect the integrity of the ecological strategic land, give play to the ecological barrier of the eastern ecological land, and block the influence of adverse factors and disasters.

Based on the theory of landscape ecology, this paper constructs a three-dimensional analysis framework of urban resilience and its measurement model, which to some extent enriches the theory and perspective of urban resilience research and is also applicable to other research areas in urban resilience. Taking Shenyang as an example, this paper discusses the urban resilience pattern and its effect under different scales and analyzes the main landscape elements affecting the resilience, which is not only beneficial to the cognition of the development of urban resilience and enables the choice of optimal scale from multiple perspectives, but is also more conducive for urban managers to optimize and adjust the development of urban resilience from the perspective of easy operation and differentiation strategies such as the scale of landscape elements and spatial configuration. It is worth noting that the urban system and its resilience components are complex and diverse. In addition to the contradiction between openness and the interdependence of internal elements, there are many other elements that affect the resilience of the urban system. The size, density, and morphology discussed in this paper all start from the material structure and environmental system of the city, which do not form the whole of the city's resilience. Besides engineering facilities, economic response capacity and social organization level are also important parts of the city's resilience. At the same time, the urban system

has the characteristics of dynamic evolution. This paper provides a certain basis for scale selection, embarking from the spatial scale effect of resilience. Based on the appropriate scale, the discussion on dynamic pattern of urban resilience is not only the key basis for understanding the rules governing urban resilience development and exploration of the mechanism of urban resilience processes, but also sets the direction for further research in the future.

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