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The coupling relationship between urbanization and ecological resilience in the Pearl River Delta

WANG Shaojian, CUI Zitian, LIN Jingjie, XIE Jinyan, SU Kun

Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China

Abstract: Urban resilience is an emerging research topic of urban studies, and its essence is described by the ability of cities to resist, recover, and adapt to uncertain disturbances. This paper constructs a "Size-Density-Morphology" urban ecological resilience evaluation system, uses a coupling coordination degree model to measure the degree of coupling coordination between urbanization and ecological resilience in the Pearl River Delta from 2000 to 2015, and conducts an in-depth discussion on its spatiotemporal characteristics. The results show the following. (1) From 2000 to 2015, the urbanization level of cities in the study area generally increased while the level of ecological resilience declined. The coupling coordination degree between the two systems decreased from basic coordination to basic imbalance. (2) In terms of spatial distribution, the coupling coordination degree between urbanization and ecological resilience of cities presented a circular pattern that centered on the cities at the estuary of the Pearl River and increased toward the periphery. (3) Ecological resilience sub-systems played variable roles in the coupling coordination between urbanization and ecological resilience. Specifically, size resilience mainly played a reverse blocking role; the influence of morphology resilience was generally positive and continued to increase over time; the effect of density resilience was positive and continued to decline and further became negative after falling below zero. The main pathways for achieving coordinated and sustainable development of future urbanization and ecological resilience in the Pearl River Delta include: leading the coordinated development of regions with new urbanization, improving ecological resilience by strictly observing the three areas and three lines, adapting to ecological carrying capacity, and rationally arranging urban green spaces.

Keywords: urbanization; ecological resilience; size resilience; density resilience; morphology resilience; coupling coordination model; Pearl River Delta

1 Introduction

Since reform and opening up in 1978, China's urbanization development has made remarkable achievements. The urbanization rate of the permanent population rose from 17.9% in

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Author: Wang Shaojian (1986−), Associate Professor, specialized in urban geography and regional development.
E-mail: 1987wangshaojian@163.com
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1978 to 59.6% in 2018 (XNA, 2019). Urbanization is materially derived from the ecological environment, and human demand for ecological services makes urbanization sustainable. However, the urban ecosystem is also suffering from unavoidable disturbances and shocks. On the one hand, these disturbances and shocks can come from various natural disasters. On the other hand, they can also come from ecological disorders caused by the extensive development of human beings (Lu *et al*., 2017). In the face of increasing human pressure and encroachment from urbanization, urban ecosystems need to improve their resilience—that is, shock resistance, self-adaptation, and resilience to aftershocks, to eliminate and absorb these disturbances. Therefore, it is important to study the interaction laws between urbanization and urban ecological resilience in this context. In addition, recognizing the underlying causes of lagging ecological resilience of some cities can provide a basis for government policy for their coordinated development.

"Resilience" means the ability to return to the original state (Shao and Xu, 2015). Holling (1973) first applied the concept of resilience to the subdiscipline of system ecology to define the characteristics of stable states of the ecosystem. As the related research gradually extended from natural ecology to human ecology, the concept of resilience has also been extended to the urban field, providing a research foundation for the formation and development of urban resilience (Park and Mckenzie, 1987). The current research on urban resilience centers on three aspects: (1) the conceptual analysis of urban resilience, (2) the measurement of the level of urban resilience, and (3) the theoretical framework for resilient urban planning. In general, the academic community has reached a consensus on the definition of urban resilience, which includes the ability of the urban system to coordinate and organize itself and withstand and recover from uncertain external risks. It can be conceptualized as integrating urban material and non-material elements (Walker *et al*., 2004; Ahern, 2011; Li and Zhai, 2017). Based upon these concepts, existing literature has adopted different perspectives and methods to quantitatively evaluate the level of urban resilience (Najjar and Gaudiot, 1990; Omer *et al*., 2009; Li and Zhai, 2017; Du *et al*., 2019; Zhang and Feng, 2019), and provide basic ideas for the planning and construction of resilient cities (Liu, 2014; Shao and Xu, 2015; Shi, 2016). In terms of research content, scholars have shifted their focus from the built environment to a dynamic social mechanism. The theoretical framework of urban resilience is gradually being developed, which will evolve into a new way to analyze and solve urban problems. However, as an emerging topic, the research on urban resilience is still controversial.

Due to the lack of available data, the secondary indicators of the existing resilience evaluation system often struggle to reflect the true essence of resilience. Taking urban ecological resilience as an example, existing research can well reflect the current "levels" of urban eco-environmental construction and pollutant controls. Still, it cannot fully represent the "ability" of urban resistance to adapt to external disasters and support human consumption. Additionally, discussing the coupling relationship between urbanization and the ecological environment represents an essential link in studying the man-land relationship. Various academic circles have done a great deal of theoretical and empirical analysis in this field. Based on the paradigm of system theory, researchers measure the effects of interactive stress upon the urbanization of ecological environments. To do this, they utilize a variety of methods such as employing a coupling coordination degree model and a gray correlation degree model with the intent of obtaining significant spatiotemporal differentiation characteristics (Huang and Fang, 2003; Liu *et al*., 2005; Cui, 2015; Wang *et al*., 2015; Zhang *et al*., 2016). Moreover, a growing amount of research is directed toward the dynamic evolution of the coupling relationship between urbanization and the ecological environment and try to use system dynamics (SD), artificial intelligence, comprehensive integration, and other technical methods to simulate the dynamic coupling relationship (Cui *et al*., 2019).

Current academic circles have improved upon their research into the coupling relationship between urbanization and the ecological environment. However, from the perspective of resilience, the interaction between urbanization and ecological resilience is less discussed. The following two themes characterize the inherent challenges to this type of research. First, the interactive mechanism between urbanization and the ecological environment is inherently complex, and a single-paradigm study fails to satisfy the needs of guiding planning practice. Second, it is of great significance to first identify the existing problems in the spatial interaction between urban and ecological environments and then provide additional operational guidance at the spatial planning level. Therefore, this paper introduced the concept of resilience into its research framework of urban ecosystems and drew upon the physical coupling model to analyze the spatiotemporal differentiation of the coordinated relationship between urbanization and ecological resilience in the Pearl River Delta. Consistent with the methods of Xiu *et al*. (2018), the evaluation system of ecological resilience was reconstructed based on the characteristics of urban space in scale, density, and form to fit the essential connotation of resilience. Finally, through a comparative analysis of the coupling and coordination between urbanization and three major resilience sub-systems, this article identifies the specific reasons for promoting or blocking the coordinated development of urbanization and ecological resilience. The results provide a pathway and basis for promoting the coordinated and sustainable development of the Pearl River Delta region.

2 Theoretical mechanism

2.1 Connotation of urbanization and ecological resilience

Urbanization is a complex process in which fundamental and multi-faceted changes have taken place in economic structure, social structure, and patterns of production and life. Existing studies have summarized the connotation of urbanization in terms of demographic urbanization, economic urbanization, spatial urbanization, and social urbanization (Zheng *et al*., 2007; Ou *et al*., 2008; Chen *et al*., 2009). The internal logic can be understood as follows. (1) Demographic urbanization is the core, (2) economic urbanization is the driving force, (3) spatial urbanization is the carrier of demographic and economic urbanization in regional space, and (4) social urbanization is accompanied by the transformation of people's lifestyle, behavior habits, and values (Chen *et al*., 2010; Guo *et al*., 2015). In terms of ecological resilience, this paper constructed an evaluation system of urban ecological resilience based on three sub-systems, *size*, *density*, and *morphology*. Among these, size resilience refers to the relative relationship between the service scope of urban ecological infrastructure and its construction scale. Density resilience refers to the supporting capacity of urban ecosystems to human resource consumption, and morphology resilience reflects the scientific layout of ecological space in a city.

2.2 Interaction between urbanization and ecological resilience

Urbanization is linked to ecological resilience mainly through population growth, economic development, and spatial expansion. Demographic urbanization is accompanied by an increase in urban population density and the improvement of consumption level, which will lead to an increase in human demand from the ecosystem and damage to the urban density resilience. Economic urbanization affects the production scale and industrial structure of cities, and has a dual effect on density resilience (Huang and Fang, 2003). On the one hand, the expansion of non-agricultural production activities such as industry will increase resource consumption, resulting in impaired density resilience. On the other hand, economic development is always accompanied by the progress of production modes and clean technology, which significantly reduces the resource consumption and environmental pollution of enterprises and thus weakens the damage of density resilience. In addition, demographic and economic urbanization has promoted the transformation of urban and rural landscapes, namely spatial urbanization, which is mainly reflected through increases in both urban construction density and scale. The disorderly spread of construction land will inevitably encroach on the ecological space and damage the size resilience (Lu, 2007). The irrational allocation of urban construction land and ecological space will weaken the permeability of ecological elements in the built environment and reduce the level of morphology resilience. Therefore, reasonable spatial regulation is an effective means to reduce the impact of urbanization on size and morphology resilience.

It can be seen that the stress of urbanization on ecological resilience lies mainly in the processes of depletion, occupation, and governance of ecological space. The mechanism can be summarized as follows. Demographic and economic urbanization are the core driving factors of ecological resilience, which directly affect density resilience. Moreover, demographic and economic urbanization indirectly affect the size and morphology resilience of cities through spatial urbanization (Figure 1). In light of this, this paper investigates the interaction between urbanization and ecological resilience from the perspectives of demographic urbanization and economic urbanization.

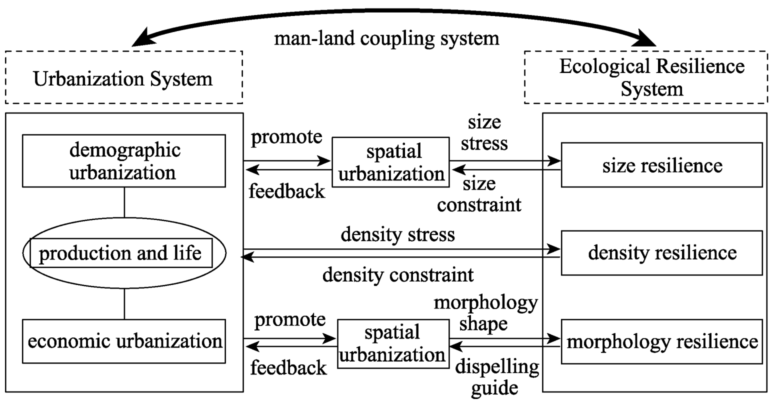

Figure 1 The theoretical mechanism of a coupling relationship between urbanization and ecological resilience

Ecological resilience also responds to urbanization. Size resilience constrains the urban scale through urban afflictions such as meteorological disasters and environmental degradation. Density resilience restricts the degree by which humans consume natural resources by providing an upper limit to the ecological carrying capacity. Morphology resilience can reflect a reasonable degree of urban ecological space allocation through the frequency and consequences of impactful environmental events and guide the adjustment of population and production layouts. In general, the research on the coupling relationship between urbanization and ecological resilience actually focuses on the fundamental contradiction between the pressure of human activities and the supporting capacity of the environment (Wu, 1991).

3 Data and methods

3.1 Study area

The Pearl River Delta includes nine prefecture-level cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, Zhaoqing, and Huizhou (Figure 2). From 2000 to 2015, the urbanization rate in the Pearl River Delta increased from 71.6% to 84.6%, which always has been 20% to 30% higher than the national average. The Pearl River Delta is one of the urban agglomerations with the largest population, the highest level of innovation, and the greatest overall strength in China. However, due to the influence of the subtropical monsoon climate, natural disasters such as typhoons and floods occur frequently in the Pearl River Delta, causing heavy direct losses. The rapid urbanization process has not only aggravated the mass occurrence of natural disasters but has also increased urban exposure and vulnerability to man-made disasters such as fires and environmental pollution. In this context, the Pearl River Delta region is challenged with discovering how to improve the level of urban disaster prevention and how to construct ecological resilience so that it catches up with the pace of urbanization.

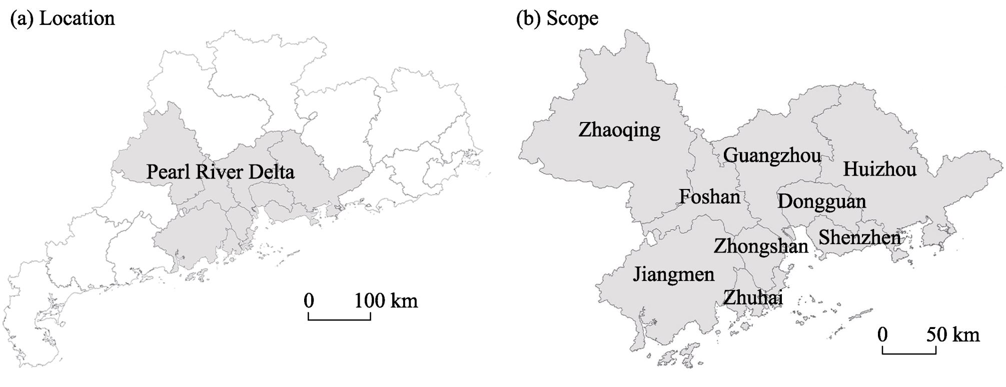

Figure 2 Location and scope of the Pearl River Delta

3.2 Data sources

The remote sensing monitoring data of land use in the Pearl River Delta in 2000, 2010, and 2015 are from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) (Xu *et al*., 2018). The data uses Landsat TM/ETM/OLI remote sensing images as the main information source. Through manual visual interpretation, the accuracy rate has reached more than 95%. The data divided the land into six categories: construction land, cultivated land, forest land, grassland, water area, and unused land. The statistical data used in this paper are from the *Guangdong Statistical Yearbook*

(*2001–2016*), *Urban Construction Statistical Yearbook* (*2001–2016*), *China Energy Statistical Yearbook* (*2001–2016*), and the *China Urban Statistical Yearbook* (*2001–2016*). The administrative regionalization data and spatial distribution data of terrestrial ecosystem service value in the Pearl River Delta are also obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) (Xu, 2018).

3.3 Methods

3.3.1 Data standardization

Some indicators have dimensional differences, and their effects on the corresponding system can be positive or negative. To facilitate comprehensive calculation and comparative analysis, the method of extreme value standardization was adopted to carry out dimensionless processing on the original data (Guo, 2007):

$$\text{Positive indicators: } Z_{\lambda ij} = (X_{\lambda ij} - X_{\min}) / (X_{\max} - X_{\min}) \tag{1}$$

$$\text{Negative indicators: } Z_{\lambda ij} = (X_{\max} - X_{\lambda ij}) / (X_{\max} - X_{\min}) \tag{2}$$

where λ, i, and j are year, region, and indicator respectively, $X_{\max}$ and $X_{\min}$ are the maximum and minimum of the jth indicator in all regions and years. $Z_{\lambda ij}$ and $X_{\lambda ij}$ are the standardized and original values of the jth indicator in the ith area of the λth year. After processing, all indicator values will be in the range of [0, 1]. To reduce the interference of subjective factors, this paper uses the entropy method to calculate the weighting coefficients of each indicator when constructing the comprehensive evaluation system of urbanization and ecological resilience (Bai *et al.*, 2018).

3.3.2 Evaluation indicators of ecological resilience

(1) Size resilience

According to the theory of ecological infrastructure and the landscape security pattern (Yu, 2005), the mountains, forests, and water systems surrounding cities are particular types of infrastructure that can restrain urban expansion. When the scale of the urban built-up area exceeds the service scope of ecological infrastructure, both the city's disaster response and balance recovery ability will be weakened accordingly. Therefore, the size resilience can be defined by the proportional relationship between the urban built-up area and the ecological infrastructure (Xiu *et al.*, 2008).

Ecological infrastructure (EI) includes all naturally protected area systems, forestry and agricultural systems, urban green space systems, water systems, and ecological recreation systems that can provide natural services (Yu *et al.*, 2008). Consistent with recent research (Wang *et al.*, 2017; Ma *et al.*, 2018), this paper identifies a protection red line for important ecologically functioning areas based on the spatial distribution data of ecosystem service value. Then, the protection red line and the nature reserve areas were spatially superimposed to obtain the EI boundary that meets the minimum ecological safety standards.

$$R_s = L_s / L_d \tag{3}$$

where R_s is the urban size resilience index, L_s is the suitable construction land area under the constraint of EI, and L_d is the construction land area.

(2) Density resilience

The "density" of human activities in a city directly affects the sustainability of the ecosystem. Human activities can increase pressure on the natural environment, which will lead to ecological disorder. The ecological footprint theory proposes a method to directly measure the "density" of human activities (Wackernagel and Rees, 1996; Xiong *et al*., 2003). The ecological population footprint refers to the total ecologically productive land required to provide resources and absorb waste (Xu *et al*., 2000). According to existing studies, the land for providing resources is generally cultivated land, grassland, forest land, fossil fuel land, construction land, and water areas. The actual coverage area of productive land in the city is defined as the ecological carrying capacity. By comparing a city's ecological footprint and carrying capacity, one can quantitatively assess whether its economic and social development is sustainable. If the ecological footprint overdraws the ecological carrying capacity, the city is in a state of ecological deficit; otherwise, it is in a state of ecological surplus. This article uses density resilience to calculate the gap between supply and demand. The formula of ecological footprint is as follows (Xu *et al*., 2003):

$$e_f = \sum_{i=1}^{n} r_i C_i / P_i \quad (4)$$

$$E_f = N e_f \quad (5)$$

where E_f is the total ecological footprint of the region, N is the total population of the region, e_f is the per capita ecological footprint of the region, i is the category of consumer goods, C_i is the per capita annual consumption of the ith consumer goods, P_i is the annual average productivity of the global standard land corresponding to the ith consumer goods, and r_i is a balance factor.

Consistent with the *Guangdong Statistical Yearbook* (*2001–2016*) and the *China Energy Statistical Yearbook* (*2001–2016*), we calculated the per capita annual consumption of grain, oil, meat, eggs, milk, aquatic products, vegetables, fruits, and fossil energy in the Pearl River Delta, and converted them into the corresponding productive land area. Since the productivity of cultivated land, grassland, and forest land varies greatly per unit area, it is necessary to multiply the balance factor r_i by the land area (Wackernagel and Rees, 1996). Balance factor r_i is derived from *World Ecological Footprint Report 1996* (Table 1).

Table 1 Balance factors and yield factors of the ecological footprint of the Pearl River Delta

Land type	Balance factor r_i	Yield factor m_j
Cultivated land	2.8	2.88
Grassland	0.5	1.38
Forest land	1.1	0.88
Fossil fuel land	0.2	2.01
Construction land	1.1	0.00
Water area	2.8	2.88

The formula of ecological carrying capacity is as follows:

$$E_c = (1 - 12\%) \sum_{j=1}^{n} S_j m_j \quad (6)$$

where E_c is the ecological carrying capacity of the region, j is land-use type, S_j is the area of the existing jth productive land in the region, and m_j is yield factor. Considering that the productivity of the same type of productive land varies significantly for different latitudes and longitudes (Liu *et al.*, 2010), this paper introduced the yield factor m_j to convert the land area of the Pearl River Delta into the global standard land area (Table 1). According to the initiative put forth by the World Commission on Environment and Development, 12% of the world's productive land should be set aside to protect biodiversity (Xu *et al.*, 2000). Therefore, this proportional area was deducted in calculating the ecological carrying capacity of the cities in the Pearl River Delta.

The formula of density resilience is as follows:

$$R_d = E_c / E_f \tag{7}$$

where R_d is the urban density resilience index.

(3) Morphology resilience

"Morphology" refers to the spatial organization of the built environment and ecological land within a city. According to the theory of "source-sink" in landscape ecology (Chen *et al.*, 2008), the urban landscape can be divided into a "source" and "sink." A source refers to gray landscapes such as buildings, which harm the ecological environment, and a sink is a blue (water area) or green (greenbelt) landscape that can stop or slow this negative impact. When the water, greenbelt, and built-up areas maintain a balanced layout, they can alleviate the negative impact of urban waterlogging and the tropical island effect, improving urban ecological resilience (Xiu *et al.*, 2008). Therefore, this article used the average distance between the source and sink landscapes in the city to measure the morphology resilience. In ArcGIS, we reclassified the land use raster data in the study area into sources and sinks. Source raster includes construction land, while sink raster includes cultivated land, forest land, grassland, and water area. For each source raster, we calculated its distance to the edge of the nearest sink raster and defined this measurement as the nearest neighbor distance. Next, we calculated the average of the nearest neighbor distances for all source rasters and then obtained the average distance between the source and sink landscapes. The formulas are as follows:

$$L_d = \frac{\sum_{i=1}^{m} \min(d_i)}{m} \tag{8}$$

$$R_m = L / L_d \tag{9}$$

where R_m is the urban morphology resilience index, L_d is the average distance between source and sink rasters, $min(d_i)$ is the nearest neighbor distance from *i*th source raster to sink raster, m is the number of source rasters in the study area, L is a constant whose value is the average distance of the "source-sink" landscape for the entire Pearl River Delta region in 2000.

3.3.3 Indicator system of urbanization and ecological resilience

This article selected both demographic and economic urbanization as first-level indicators to evaluate urbanization. In accordance with scientific principles and data availability, nine secondary indicators were selected to establish a comprehensive urbanization evaluation indicator system, e.g., urbanization rate, urban population density, and the proportion of non-agricultural industry employees (Table 2). The comprehensive evaluation indicator system of ecological resilience was composed of size resilience, density resilience, and morphology resilience (Table 3).

Table 2 The comprehensive indicator system for urbanization

First-level indicator	Weight	Secondary indicators	Weight	Effect
Demographic urbanization	0.3316	Urbanization rate	0.0548	+
		Urban population density	0.1334	+
		Proportion of non-agricultural industry employees	0.0317	+
		Urban permanent population	0.1117	+
Economic urbanization	0.6684	GDP per capita	0.1311	+
		Proportion of secondary industry in GDP	0.0412	+
		Proportion of tertiary industry in GDP	0.0582	+
		Urban economic density	0.1428	+
		Fixed asset investment	0.2059	+

Table 3 The comprehensive indicator system for ecological resilience

Indicator	Weight	Effect
Size resilience	0.4473	+
Density resilience	0.3331	+
Morphology resilience	0.2197	+

3.3.4 Coupling coordination degree model

Coupling coordination is a concept from physics, which refers to the interaction between different systems under the combined influence of themselves and the outside world. This paper introduced a coupling coordination degree model to explore the interaction between urbanization and ecological resilience. The formulas are as follows:

$$C = \sqrt{\left[(U_1 \times U_2) / \left(\frac{U_1 + U_2}{2} \right)^2 \right]} \tag{10}$$

$$D = \sqrt{C \times T} \tag{11}$$

$$T = \alpha U_1 + \beta U_2 \tag{12}$$

where C is the coupling degree, D is the coupling coordination degree, T is the comprehensive evaluation index, U_1 is the comprehensive evaluation index of the urbanization system, U_2 is the comprehensive evaluation index of the ecological resilience system. The coupling coordination degree, D, can comprehensively evaluate the relationship between the two systems (Wang and Tang, 2018). The parameters α and β can be explained as the relative importance of the two sub-systems (Wang *et al*., 2015). The authors of this paper believe that urban ecological resilience is equally as important as urbanization, so α=β=0.5. Drawing lessons from the classification standards of physics (Li *et al*., 2012), the coupling coordination degree between urbanization and ecological resilience was divided into four major categories and 12 sub-categories (Table 4).

3.3.5 Coordination influence

To analyze the influence of the three types of resilience on the coupling coordination degree, the coordination influence (*CI)* was introduced (Wang *et al*., 2019). The formula is as follows:

$$CI = W_x(D_x - D_y) \tag{14}$$

where D_x (x=1, 2, 3) is the coupling coordination degree between urbanization and size resilience, density resilience and morphology resilience, respectively, D_y is the coupling coordination degree between urbanization and ecological resilience, and W_x is the weighting coefficient corresponding to the resilience. The coordination influence (*CI*) can measure the influence of sub-category coordination upon the overall coordination, and its positive and negative values represent the promoting and blocking effects, respectively; the magnitude of these values represents the degree of influence.

Table 4 Classification of coupling coordination degree for urbanization and ecological resilience

Type	Coupling coordination degree	Sub-type	
High coordination	$0.8<D\leqslant1$	High coordination – urbanization lag	$U_2-U_1>0.1$
		High coordination – ecological resilience lag	$U_1-U_2>0.1$
		High coordination	$0\leqslant\lvert U_1-U_2\rvert\leqslant0.1$
Basic coordination	$0.5<D\leqslant0.8$	Basic coordination – urbanization lag	$U_2-U_1>0.1$
		Basic coordination – ecological resilience lag	$U_1-U_2>0.1$
		Basic coordination	$0\leqslant\lvert U_1-U_2\rvert\leqslant0.1$
Basic imbalance	$0.3<D\leqslant0.5$	Basic imbalance – urbanization blocked	$U_2-U_1>0.1$
		Basic imbalance – ecological resilience blocked	$U_1-U_2>0.1$
		Basic imbalance	$0\leqslant\lvert U_1-U_2\rvert\leqslant0.1$
Severe imbalance	$0<D\leqslant0.3$	Severe imbalance – urbanization blocked	$U_2-U_1>0.1$
		Severe imbalance – ecological resilience blocked	$U_1-U_2>0.1$
		Severe imbalance	$0\leqslant\lvert U_1-U_2\rvert\leqslant0.1$

4 Results

4.1 Analysis of urbanization level in the Pearl River Delta

From 2000 to 2015, the urbanization level gap of the cities in the eastern, central, and western regions of the Pearl River Delta gradually widened, indicating that the development imbalance within the region has increased. Guangzhou and Shenzhen were the two cities with the highest level of urbanization in the Pearl River Delta during the study period (Figure 3). Except for Jiangmen, the urbanization level of other cities showed a steady upward trend.

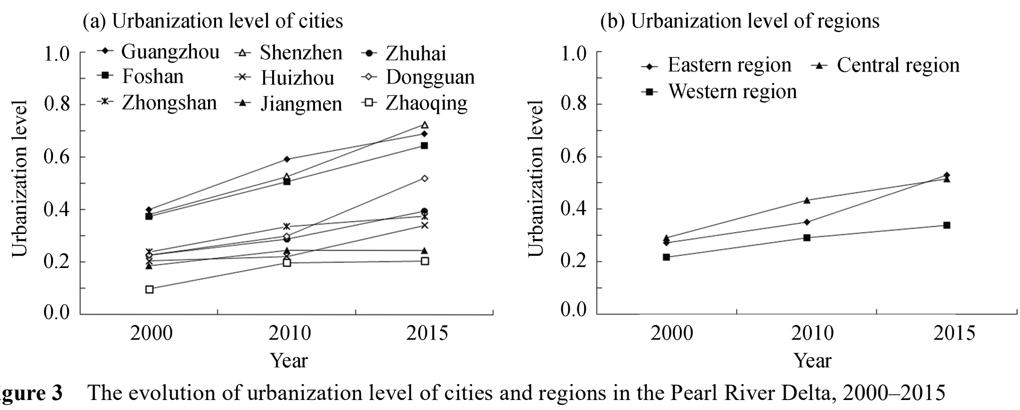

Figure 3 The evolution of urbanization level of cities and regions in the Pearl River Delta, 2000–2015

The urbanization level of Jiangmen declined after 2010. The main reason was that Jiangmen, a traditional industrial city in the Pearl River Delta, has a poor agglomeration effect regarding its population and enterprises. Based on the further analysis of the Shenzhen-Dongguan-Huizhou, Guangzhou-Foshan-Zhaoqing, and Zhuhai-Zhongshan-Jiangmen metropolitan areas, the urbanization level of Guangzhou-Foshan- Zhaoqing metropolitan area increased the most between 2000 and 2010. Over the period 2010–2015, the urbanization level of Shenzhen-Dongguan-Huizhou metropolitan area increased significantly, surpassing that of the Guangzhou-Foshan-Zhaoqing metropolitan area. The urbanization of Zhuhai-Zhongshan-Jiangmen was always the lowest among the three metropolitan areas.

4.2 Analysis of ecological resilience level in the Pearl River Delta

4.2.1 Size resilience

The size resilience index of the Pearl River Delta region continued to decline during the research period. The decline was rapid from 2000 to 2010, before it slowed down from 2010 to 2015. Future development of the Pearl River Delta will be constrained by size security (Table 5). In terms of spatial distribution, the size resilience of the Pearl River Delta displayed a pattern that was low in central cities and high in peripheral cities, and the gap between central cities and peripheral cities was distinct. These results were closely related to the extensive spatial development model generally adopted by the Pearl River Delta cities. After 2010, the central cities of the Pearl River Delta faced a severe shortage of development space. In particular, the size resilience index of Shenzhen and Dongguan approached the critical level of 1 (Table 5).

Table 5 Size resilience index of cities in the Pearl River Delta, 2000–2015

City	Construction land area (km^2)			Suitable construction land area (km^2)	Size resilience		
	2000	2010	2015		2000	2010	2015
Guangzhou	708.054	1183.540	1257.113	4417.095	6.238	3.732	3.514
Shenzhen	493.923	746.907	772.350	1346.315	2.726	1.803	1.743
Zhuhai	127.323	183.679	193.981	1129.710	8.873	6.150	5.824
Foshan	491.504	967.901	1046.979	2483.358	5.053	2.566	2.372
Jiangmen	458.461	595.465	665.087	6248.908	13.630	10.494	9.396
Zhaoqing	249.645	331.106	358.134	7838.219	31.397	23.673	21.886
Huizhou	359.835	597.613	645.415	5928.079	16.474	9.920	9.185
Dongguan	553.752	1041.234	1079.704	1892.422	3.417	1.817	1.753
Zhongshan	185.572	423.043	445.965	1242.172	6.694	2.936	2.785
Average	3628.070	6070.488	6464.728	32526.277	8.965	5.358	5.031

4.2.2 Density resilience

The ecological footprint of the Pearl River Delta was higher than the carrying capacity during the study period, and the ecological deficit was substantial. This fact reflected hidden ecological dangers such as high population density, unreasonable energy consumption, and food insecurity in the Pearl River Delta. The difference in density resilience between cities remained significant, noting that low-density resilience indexes have been typical of central cities for a long time. In light of this, Shenzhen had the most severe ecological deficit problem (Table 6).

Table 6 Density resilience index of cities in the Pearl River Delta, 2000–2015

City	Ecological footprint (10^4 hm^2)			Ecological carrying capacity (10^4 hm^2)			Density resilience		
	2000	2010	2015	2000	2010	2015	2000	2010	2015
Guangzhou	828.335	1600.175	1830.351	187.383	204.888	211.433	0.226	0.128	0.116
Shenzhen	583.898	1305.864	1542.616	85.245	114.950	124.777	0.146	0.088	0.081
Zhuhai	102.959	196.610	221.536	26.824	27.562	28.101	0.261	0.140	0.127
Foshan	444.685	906.387	1007.370	105.719	117.128	117.789	0.238	0.129	0.117
Jiangmen	329.102	560.368	612.711	149.367	151.862	151.554	0.454	0.271	0.247
Zhaoqing	281.183	493.816	550.362	179.090	181.967	183.276	0.637	0.368	0.333
Huizhou	267.951	579.291	644.706	156.574	165.470	166.350	0.584	0.286	0.258
Dongguan	536.935	1035.526	1119.012	90.103	98.743	98.375	0.168	0.095	0.088
Zhongshan	196.900	393.157	435.127	47.506	50.535	50.971	0.241	0.129	0.117
Average	3571.948	7071.194	7963.791	1027.811	1113.105	1132.627	0.288	0.157	0.142

As the government prioritized environmental protection measures, the deterioration of the ecological deficit in the Pearl River Delta cities eased from 2010 to 2015. This change was largely dependent upon ‘city’ control of the ecological footprint (Table 6). The developmental practice of the Pearl River Delta showed that the natural environment exerted a strong constraint on ecological carrying capacity in the rapid urbanization area. Therefore, it is not easy to increase the urban ecological carrying capacity by expanding the ecological space. In the future, important actions which favor the successful construction of an ecological civilization in the Pearl River Delta will be to transform production and lifestyles, save resources, and reduce energy consumption.

4.2.3 Morphology resilience

Over the study period, the morphology resilience index of the Pearl River Delta first decreased and then increased (Table 7). From 2000 to 2010, the morphology resilience index of all cities decreased significantly. However, from 2010 to 2015, the morphology resilience index of Guangzhou, Zhuhai, Foshan, Zhaoqing, and Huizhou rose slightly, while that of Shenzhen, Jiangmen, Dongguan, and Zhongshan continued to decline. Combined with

Table 7 Morphology resilience index of cities in the Pearl River Delta, 2000–2015

City	Average distance between “source-sink” landscape			Morphology resilience		
	2000	2010	2015	2000	2010	2015
Guangzhou	304.297	315.923	315.239	0.815	0.785	0.786
Shenzhen	560.833	562.260	569.518	0.442	0.441	0.435
Zhuhai	235.261	249.900	246.287	1.054	0.992	1.006
Foshan	212.443	316.319	314.872	1.167	0.784	0.787
Jiangmen	122.806	136.230	140.238	2.019	1.820	1.768
Zhaoqing	98.173	119.432	118.569	2.525	2.076	2.091
Huizhou	131.281	148.569	147.647	1.888	1.668	1.679
Dongguan	180.442	294.512	297.585	1.374	0.842	0.833
Zhongshan	239.535	307.397	310.544	1.035	0.806	0.798
Average	247.884	295.297	294.746	1.000	0.839	0.841

remote sensing images, the change of urban morphology resilience in the Pearl River Delta was closely related to its urban spatial expansion pattern. From 2000 to 2010, the spatial expansion of cities in the Pearl River Delta had the characteristic of an outward spreading core. After 2010, the layout of each city had been optimized, with various forms of urban expansion. Cluster development increased the accessibility of construction land to ecological space. With the gradual exhaustion of construction land in central cities, future spatial expansion of the Pearl River Delta will mainly be in Jiangmen, Zhaoqing, and Huizhou. These three peripheral cities have rich ecological landscape resources. Future development should fully recognize the relationship between construction land and ecological space and actively create a highly-coupled urban morphology representative of a previously discussed "source-sink" landscape (Section 3.3.2).

4.2.4 Ecological resilience

It can be seen from Table 8 that the ecological resilience index of cities in the Pearl River Delta continued to decrease from 2000 to 2015, posing significant threats to regional ecological security. From 2000 to 2010, the ecological resilience index of all cities decreased sharply, with an average decline of nearly 50%. After 2010, the Pearl River Delta began to attach importance to ecological protection in its urban planning and construction practices. Although rapid urbanization was ongoing, the declining trend of the ecological resilience index for each city weakened. The urban ecological resilience degree and urbanization level of the Pearl River Delta resembled a core-periphery structure. The difference is that the development of urbanization was the fastest in central cities, while the ecological resilience degree was relatively high in peripheral cities (Figure 4). Therefore, in future rounds of urbanization, if the urban expansion scale and development intensity are not actively controlled, the ecological resilience level of cities in the Pearl River Delta will likely decrease further.

Table 8 Ecological resilience index of cities in the Pearl River Delta, 2000–2015

City	Ecological resilience		
	2000	2010	2015
Guangzhou	0.195	0.095	0.084
Shenzhen	0.055	0.006	0.000
Zhuhai	0.280	0.161	0.149
Foshan	0.221	0.078	0.068
Jiangmen	0.569	0.391	0.355
Zhaoqing	1.000	0.675	0.629
Huizhou	0.676	0.376	0.349
Dongguan	0.176	0.053	0.046
Zhongshan	0.234	0.085	0.076
Average	0.378	0.213	0.195

4.3 Analysis of coupling coordination degree between urbanization and ecological resilience in the Pearl River Delta

4.3.1 Spatiotemporal distribution of coupling coordination degree

In terms of temporal distribution, the coupling coordination degree between urbanization and ecological resilience in the Pearl River Delta declined from basic coordination to basic imbalance. The average urban coupling coordination decreased from 0.51 to 0.45 (Figure 5). In 2000, the coupling coordination degree of each city was between [0.38, 0.61], and they were all in the stage of basic coordination or basic imbalance. In 2010, the coupling coordination degree of each city was between [0.23, 0.61]. Except for Zhaoqing, the coupling coordination degree of the other eight cities showed various degrees of decline. The stage of

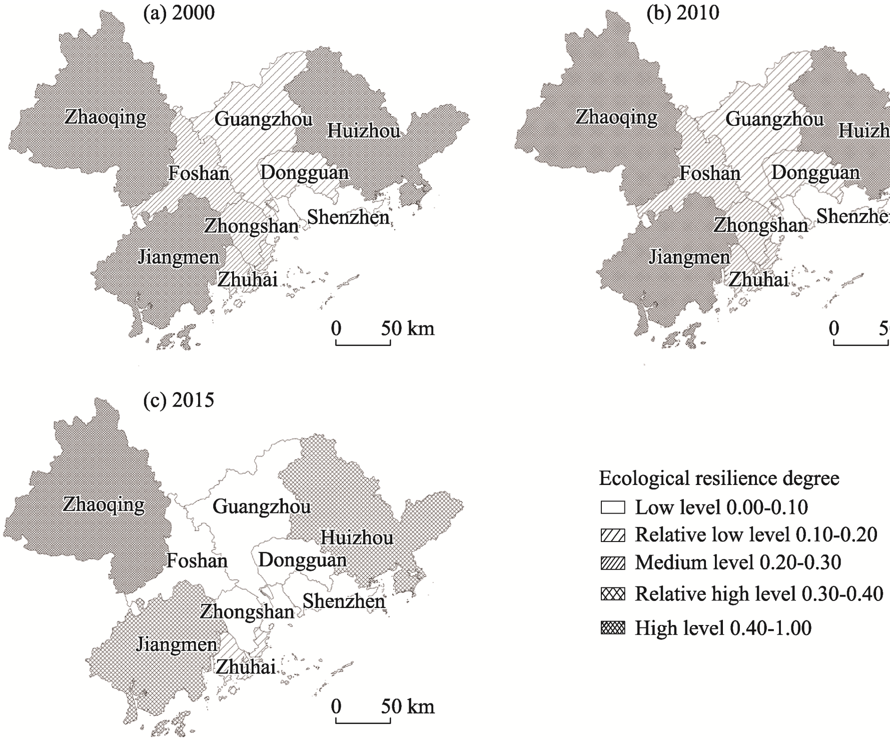

Figure 4 Spatial distribution of ecological resilience level of cities in the Pearl River Delta, 2000–2015

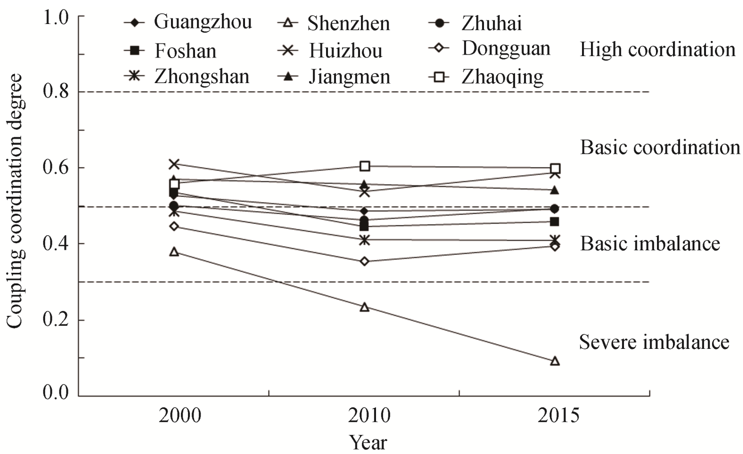

Figure 5 Temporal evolution of coupling coordination degree between urbanization and ecological resilience of cities in the Pearl River Delta, 2000–2015

coupling coordination in Shenzhen decreased from basic imbalance to severe imbalance. The declines in Guangzhou, Foshan, and Zhuhai were relatively small, but they still decreased from the basic coordination to the basic imbalance stage. In 2015, the coupling coordination degree of each city was between [0.09, 0.60].

The coupling coordination degree in Guangzhou, Foshan, Zhuhai, Huizhou, and Dongguan increased, while that in Zhongshan, Jiangmen, and Zhaoqing decreased, and the decline degree in Shenzhen was the largest. Jiangmen, Zhaoqing, and Huizhou maintained their status in the basic coordination stage. This change was caused by the continuous improvement of the urbanization level and a simultaneous reduction of the ecological resilience level, which reflected the fact that urbanization in the Pearl River Delta comes at the expense of the land, resources, and the environment. The Pearl River Delta attracted foreign investment due to its large amounts of cheap land, which resulted in the blind expansion of construction land. The subsequent development of the manufacturing industry caused increasingly serious ecological deficits and environmental pollution problems in the region. As the limiting effect of ecological resilience becomes more and more obvious, the urbanization model that emphasizes speed over quality is no longer sustainable.

In terms of spatial distribution, the coupling coordination degree between urbanization and ecological resilience in the Pearl River Delta region presented as a circular pattern increasing from the core to its periphery (Figure 6). This spatial characteristic is related to the differences in the ecological endowment and developmental timing of each city. Shenzhen, located in the *inner circle*, was the pilot demonstration area for the economic construction of the Pearl River Delta. However, the foundation of ecological resilience was poor and rapidly degraded during the study period, and this triggered a severe dislocation with the level of urbanization. In the *middle circle*, Guangzhou, Foshan, Zhuhai, Zhongshan, and Dongguan had relatively high levels of urbanization. The rapid urbanization process also exerted a negative impact on their ecological resilience to varying degrees. Although the cities restrained and guided urban development through policy intervention and planning means, the coupling coordination degree did not rebound significantly. In the *outer circle*, Jiangmen, Zhaoqing, and Huizhou had good ecological background conditions, with sufficient reserves

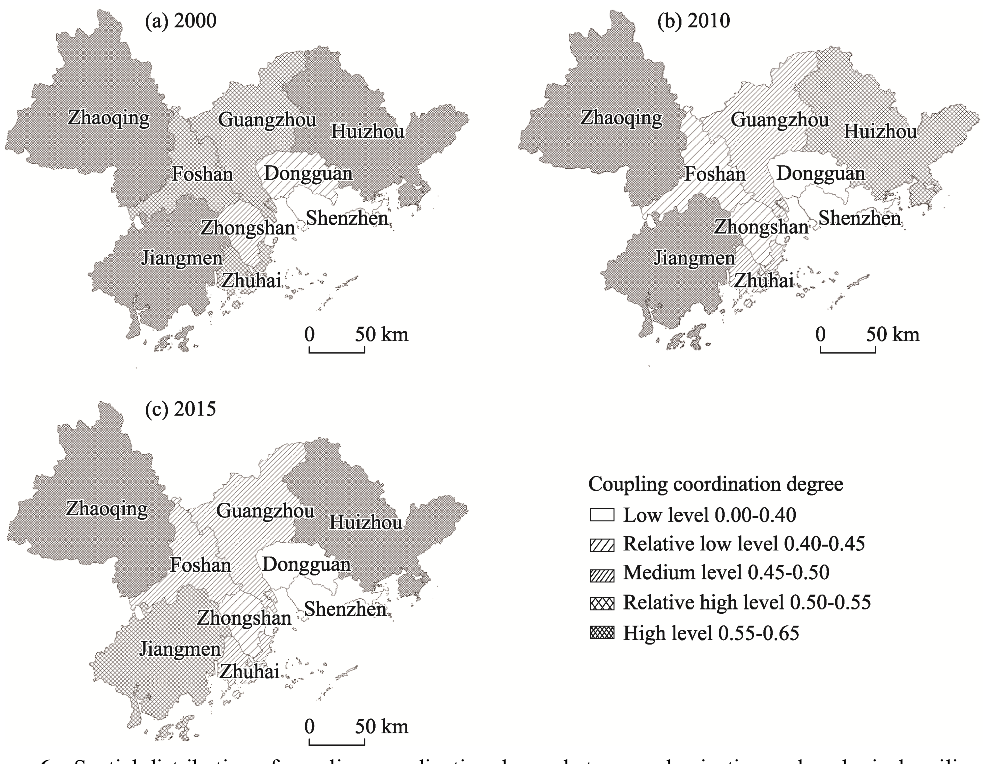

Figure 6 Spatial distribution of coupling coordination degree between urbanization and ecological resilience of cities in the Pearl River Delta, 2000–2015

of ecological space such as cultivated land and grassland; and the process of urbanization was slow. Therefore, ecological resilience supported a robust carrying capacity for the stress of urbanization.

4.3.2 Analysis of coupling coordination types

From the perspective of the evolution of the coupling coordination types between urbanization and ecological resilience (Figure 7), it was found that the coupling coordination types of the three peripheral cities have not changed during the study period, showing that urbanization lagged behind ecological resilience. The coupling coordination types of the other six central cities regressed to various degrees, and their ecological resilience was blocked. The evolution characteristics of urban coupling coordination types in the Pearl River Delta were still consistent with three types of circular structures.

Year	2000	2010	2015
Guangzhou	High coordination-ecological resilience lag	Basic imbalance-ecological resilience blocked	Basic imbalance-ecological resilience blocked
Shenzhen	Basic imbalance-ecological resilience blocked	Severe imbalance-ecological resilience blocked	Severe imbalance-ecological resilience blocked
Zhuhai	High coordination	Basic imbalance-ecological resilience blocked	Basic imbalance-ecological resilience blocked
Foshan	High coordination-ecological resilience lag	Basic imbalance-ecological resilience blocked	Basic imbalance-ecological resilience blocked
Huizhou	High coordination-urbanization lag	High coordination-urbanization lag	High coordination
Dongguan	Basic imbalance	Basic imbalance-ecological resilience blocked	Basic imbalance-ecological resilience blocked
Zhongshan	Basic imbalance	Basic imbalance-ecological resilience blocked	Basic imbalance-ecological resilience blocked
Jiangmen	High coordination-urbanization lag	High coordination-urbanization lag	High coordination-urbanization lag
Zhaoqing	High coordination-urbanization lag	High coordination-urbanization lag	High coordination-urbanization lag

Severe imbalance-ecological resilience blocked | Basic imbalance-ecological resilience blocked | Basic imbalance | High coordination-urbanization lag | High coordination-ecological resilience lag | High coordination

Low coupling coordination level ⇨ High coupling coordination level

Figure 7 Classification of coupling coordination degree between urbanization and ecological resilience of cities in the Pearl River Delta, 2000–2015

Shenzhen, in the *inner circle*, regressed to a severe imbalance stage during the study period. Its ecological resilience continued to be blocked, showing the characteristics of a *low coupling-low coordination condition*. Shenzhen completed its demographic urbanization in 2004, becoming the first city in China without a rural area. Motivated by the momentum of the urbanization process, a more radical policy of agricultural land nationalization was implemented to promote the demand for industrial land (SASS, 2015). Subsequent rapid industrialization caused a severe imbalance in the ratio of construction land and ecological space in Shenzhen. By 2015, construction land in Shenzhen was almost exhausted. In addition, decreases in cultivated land area and ecological carrying capacity led to an extreme decoupling between urbanization and ecological resilience. In the *middle circle*, the coupling coordination types of Guangzhou, Foshan, and Zhuhai changed from basic coordination-ecological resilience lag to basic imbalance-ecological resilience blocked, respectively. Zhuhai, in particular, regressed from a harmonious state of *high coupling-high coordination* to a separate state of *low coupling-low coordination*. This happened because Zhuhai was mainly positioned as a livable city in its early stage of urban development and did not vigorously develop a high-polluting manufacturing industry, thus maintaining a high level of ecological resilience.

Since the strategy of strengthening cities by industry was put forward in the 11th Five-Year Plan (2006–2010), the process of economic urbanization significantly stressed ecological resilience. Due to lacking ecological space in Dongguan and Zhongshan, these cities were already in the stage of basic imbalance in 2000. After 2010, they also changed to basic imbalance-ecological resilience blocked. In the *outer circle* cities of Jiangmen, Zhaoqing, and Huizhou, the urbanization was relatively slow due to location factors, so their coupling coordination type stabilized at basic coordination-urbanization lag during the study period. However, as the double-transfer strategy of Guangdong province was put forth in 2008, Jiangmen, Zhaoqing, and Huizhou successively established high-standard industrial transfer parks. These cities continuously promoted the transfer of the rural labor force, effectively driving the urbanization process. As a result, Huizhou entered the basic coordination stage at the end of the study period.

4.3.3 Effects of ecological resilience sub-systems on coupling coordination

This paper used the *CI* index to reflect upon the direction and magnitude of the ecological resilience sub-systems' effect on the coupling coordination degree (Figure 8).

From 2000 to 2015, the *CI* of the urban size resilience in the Pearl River Delta was generally negative, indicating that it had a negative effect on the coupling coordination degree. In contrast, the morphology resilience of each city, with the notable exception of Shenzhen, had a positive effect on the coupling coordination degree; and the intensity of this effect increased over time. The effect of density resilience on coupling coordination degree exerted both positive and negative effects during the study period. Early density resilience generally played a positive role, but after 2010, its *CI* continued to decline; and after falling below a zero value, it declined further, obtaining increasingly negative values. In general, the size resilience and morphology resilience strongly influenced the urban coupling coordination degree. Changes in the coupling coordination degree of cities were largely determined by the checks and balances of these two resilient sub-systems. One reason for this is that the scale expansion of urban construction land had not been strictly restrained. From 2000 to 2015, the Pearl River Delta entered a period of accelerated industrialization and a real estate boom, leading to a rapid increase in the demand for construction land. Due to political achievements and financial pressures, local governments had accelerated the construction of suburban industrial parks to stimulate urban expansion. In addition, after the 2008 financial crisis, cities in the Pearl River Delta began to emphasize the quality of urbanization; and the urban spatial organization was also adjusted accordingly. By planning and guiding the accessibility of ecological space, the urban "source-sink" landscape pattern was constantly improved. Shenzhen is a classic example of this process. Since the 21st century, the government has taken the construction of a garden city as a strategic goal. With the advancement of urban renewal and the improvement of the green space system, gardens have become the urban

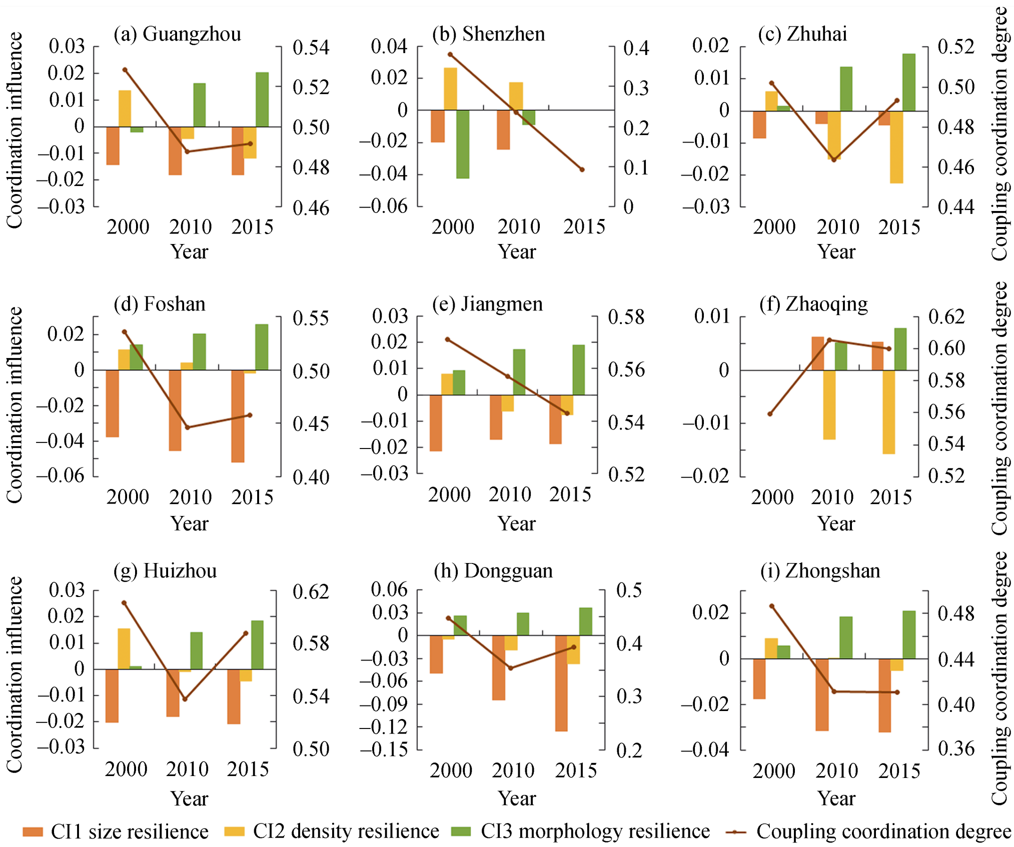

Figure 8 Coordination influence of ecological resilience sub-system in the Pearl River Delta, 2000–2015

business card of Shenzhen, and the negative impact of morphology resilience has decreased accordingly. It is worth noting that the directional change of *CI* and density resilience has sounded the alarm for the Pearl River Delta region. The ecological deficit problem has become a significant threat to the Pearl River Delta, and the adaption to low-carbon life and the commensurate transformation industry should become the focus of future urban development.

5 Conclusion and discussion

5.1 Conclusion

Based on the theoretical perspective of urban resilience, this paper constructed a size-density-morphology ecological resilience evaluation system. The coupling coordination degree between urbanization and ecological resilience of cities in the Pearl River Delta was calculated using a physical coupling model. The spatial and temporal differentiation characteristics were then analyzed. The main conclusions are as follows.

From 2000 to 2015, the urbanization level of cities in the Pearl River Delta continued to increase, while the ecological resilience level continued to decrease. The coupling coordination degree between urbanization and ecological resilience showed a declining trend from basic coordination to basic imbalance. The spatial distribution of urbanization and ecological resilience formed a distinct dislocation relationship, and their coupling coordination degree presented a circular pattern. Shenzhen in the *inner circle* had a high level of urbanization and a low level of ecological resilience, and the coupling coordination degree between the two was in severe imbalance. The urbanization level of Guangzhou, Foshan, Zhuhai, Dongguan, and Zhongshan, in the *middle circle*, was relatively high, but the ecological resilience was low and blocked. The coupling coordination degree between the two dropped to the basic imbalance stage by the end of the study period. Jiangmen, Zhaoqing, and Huizhou, in the *outer circle*, had a high level of ecological resilience, but the urbanization level lagged, and their coupling coordination degree was in the basic coordination stage. Different resilience sub-systems exerted different effects on the coupling coordination degree between urbanization and ecological resilience. Size resilience played a negative role in coupling coordination. Morphology resilience had a positive effect on coupling coordination, and this effect increased with time. The effect of density resilience on coupling coordination degree changed from positive to negative during the study period.

On the whole, the coupling coordination degree between urbanization and ecological resilience in the Pearl River Delta is still in the stage of constant adjustment, facing the critical inflection point from decline to rebound. Under the requirements of new urbanization, there are two main pathways to improve the coupling coordination degree in the future. The first is to continue prioritizing the leading role of core cities, improving the urbanization level of peripheral cities, and promoting coordinated regional development. The second is to strengthen the ecological resilience of core cities through legal constraints and planning guidance. Size resilience can be improved through the strict delineation of three areas and three lines and by strengthening the controls of construction land. Density resilience can be improved by setting an upper limit for resource utilization, implementing a low-carbon lifestyle, and encouraging cleaner means of production. Morphology resilience may be improved through the rational arrangement of urban green spaces. For the typical city, Shenzhen, we should focus on seeking innovative means to break the constraints of resilience, such as gradually clearing construction land, increasing the secondary development of extensive industrial land, and reducing population and industrial density.

5.2 Discussion

The ecological resilience involved in this paper focuses on the impact of human activities on ecological space and is discussed from the perspective of urban material space. Under this research system, this article focuses on selecting indicators related to the scale of ecological space, but gives less consideration to the quality of ecological space. However, the service value of different ecosystems varies greatly. This difference is not considered in this paper’s calculations of size resilience and morphology resilience, which makes the evaluation result incomplete. In the future, the research system can be improved to conduct more in-depth research. In addition, recently, diversified quantitative indicators of spatial forms have been established in the field of landscape ecology such as landscape vulnerability index and landscape security adjacency index. These can also be fused into future ecological resilience research to obtain more instructive conclusions.

References

Ahern J, 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning*, 100(4): 341–343.

Bai L, Feng X, Sun R *et al*., 2018. Coupling analysis of urban resilience level and urbanization quality in Jilin province. *Urbanism and Architecture*, 15(35): 19–23. (in Chinese)

Chen F, Zhang H, Wu Q *et al*., 2010. A study on coordinated development of population urbanization and land urbanization in China. *Human Geography*, 25(5): 53–58. (in Chinese)

Chen L, Fu B, Zhao W, 2008. Source-sink landscape theory and its ecological significance. *Frontiers of Biology in China*, 3(2): 131–136.

Chen M, Lu D, Zhang H, 2009. Comprehensive evaluation and the driving factors of China's urbanization. *Acta Geographica Sinica*, 64(4): 387–398. (in Chinese)

Cui M, 2015. The relationship of coupling coordination between urbanization and ecological environment: A case of urban cluster in the Central Plains. *Economic Geography*, 35(7): 72–78. (in Chinese)

Cui X, Fang C, Liu H *et al*., 2019. Dynamic simulation of urbanization and eco-environment coupling: A review on theory, methods and applications. *Acta Geographica Sinica*, 74(6): 1079–1096. (in Chinese)

Du Z, Zhang H, Ye Y, 2019. Urban shrinkage and growth: Measurement and determinants of economic resilience in the Pearl River Delta. *Journal of Geographical Sciences*, 29(8): 1331–1345.

Guo F, Li C, Chen C *et al*., 2015. Spatial-temporal coupling characteristics of population urbanization and land urbanization in Northeast China. *Economic Geography*, 35(9): 49–56. (in Chinese)

Guo Y, 2007. Theory, Method and Application of Comprehensive Evaluation. Beijing: Science Press, 70–73. (in Chinese)

Holling C S, 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4(1): 1–23.

Huang J, Fang C, 2003. Analysis of coupling mechanism and rules between urbanization and eco-environment. *Geographical Research*, 22(2): 211–220. (in Chinese)

Li Y, Li Y, Zhou Y *et al*., 2012. Investigation of a coupling model of coordination between urbanization and the environment. *Journal of Environmental Management*, 98: 127–133.

Li Y, Zhai G1 2017. China's urban disaster resilience evaluation and promotion. *Planners*, 33(8): 5–11. (in Chinese)

Liu K, 2014. Emergence and theory construction of resilient planning in the background of socialist market economy: Based on urban planning practice in Shenzhen (1979–2011). *City Planning Review*, 38(11): 59–64. (in Chinese)

Liu M, Li W, Xie G, 2010. Estimation of China ecological footprint production coefficient based on net primary productivity. *Chinese Journal of Ecology*, 29(3): 592–597. (in Chinese)

Liu Y, Li R, Song X, 2005. Grey associative analysis of regional urbanization and eco-environment coupling in China. *Acta Geographica Sinica*, 60(2): 237–247. (in Chinese)

Lu D, 2007. Urbanization process and spatial sprawl in China. *Urban Planning Forum*, (4): 47–52. (in Chinese)

Lu D, Yao S, Li G *et al*., 2007. Comprehensive analysis of the urbanization process based on China's conditions. *Economic Geography*, 27(6): 883–887. (in Chinese)

Ma Q, Liu K, Liu W *et al*., 2018. Zoning the ecological red-line in arid and semiarid regions: Taking Yulin City as an example in the context of an integrated multi-planning. *Geographical Research*, 37(1): 158–170. (in Chinese)

Najjar W, Gaudiot J L, 1990. Network resilience: A measure of network fault tolerance. *Computers IEEE Transactions on*, 39(2): 174–181.

Omer M, Nilchiani R, Mostashari A, 2009. Measuring the resilience of the trans-oceanic telecommunication cable system. *IEEE Systems Journal*, 3(3): 295–303.

Ou X, Zhen F, Qin Y *et al*., 2008. Study on compression level and ideal impetus of regional urbanization: The case of Jiangsu Province. *Geographical Research*, 27(5): 993–1002. (in Chinese)

Park R E, Mckenzie R D, 1987. Urban Sociology. Song Junling *et al*. trans. Beijing: Huaxia Publishing House.

Shao Y, Xu J, 2015. Understanding urban resilience: A conceptual analysis based on integrated international literature review. *Urban Planning International*, 30(2): 48–54. (in Chinese)

Shenzhen Academy of Social Sciences (SASS), 2015. Practice in empirical research of Shenzhen urbanization. https://max.book118.com/html/2017/0808/126668775.shtm. (in Chinese)

Shi T, 2016. From comprehensive defense to resilient cities: Strategic conception of Shanghai's city security in the new normal. *Shanghai Urban Planning Review*, (1): 13–18. (in Chinese)

Wackernagel M, Rees W E, 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriela Island: New Society Publishers, 192–210.

Walker B, Holling C S, Carpenter S R *et al*., 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, 9(2): 5.

Wang C, Tang N, 2018. Spatio-temporal characteristics and evolution of rural production living-ecological space function coupling coordination in Chongqing Municipality. *Geographical Research*, 37(6): 1100–1114. (in Chinese)

Wang L, Zou C, Wang Y *et al*., 2017. Methods to identify the boundary of ecological protection red line regions using GIS: A case study in Changping, Beijing. *Acta Ecologica Sinica*, 37(18): 6176–6185. (in Chinese)

Wang S, Fang C, Wang Y, 2015. Quantitative investigation of the interactive coupling relationship between urbanization and eco-environment. *Acta Ecologica Sinica*, 35(7): 2244–2254. (in Chinese)

Wang S, Liu Z, Zhang T *et al*., 2019. The coupling relationship between multi-dimensional urbanization and the service industry: A case study of Guangzhou. *Tropical Geography*, 39(3): 450–460. (in Chinese)

Wu C, 1991. The core of geographical study: Regional system of man-land relationship. *Economic Geography*, 11(3): 1–6. (in Chinese)

Xinhua News Agency (XNA), 2019. China's urbanization rate has risen significantly over the past 70 years. http://www.gov.cn/xinwen/2019-08/15/content_5421538.htm, 2019-08-15. (in Chinese)

Xiong D, Xian X, Jiang Y, 2003. Discussion on ecological footprint theory applied to regional sustainable development evaluation. *Progress in Geography*, 22(6): 618–626. (in Chinese)

Xiu C, Wei Y, Wang Q, 2008. Evaluation of urban resilience of Dalian city based on the perspective of "Size-Density-Morphology". *Acta Geographica Sinica*, 73(12): 2315–2328. (in Chinese)

Xu X, 2018. Chinese terrestrial ecosystem service value of spatial data set. Chinese Academy of Sciences, Resources and Environment Science Data Center data registration and publication system. (in Chinese)

Xu X, Liu J, Zhang S *et al*., 2018. China's multi-period land use land cover remote sensing monitoring dataset (CNLUCC). Chinese Academy of Sciences, Resources and Environment Science Data Center data registration and publication system. (in Chinese)

Xu Z, Zhang Z, Cheng G *et al*., 2003. Ecological footprint calculation and development capacity analysis of China in 1999. *Journal of Applied Ecology*, 14(2): 280–285. (in Chinese)

Xu Z, Zhang Z, Cheng G, 2000. The calculation and analysis of ecological footprints of Gansu Province. *Acta Geographica Sinica*, 55(5): 607–616. (in Chinese)

Yu K, 2005. "Anti-planning" Approach. Beijing: China Architecture & Building Press. (in Chinese)

Yu K, Li B, Li D, 2008. Ecological infrastructure approach for regional protection of natural and cultural heritage: A case study of Fujian Wuyi Mountain. *City Planning Review*, 32(10): 88–91, 96. (in Chinese)

Zhang M, Feng X, 2019. A comparative study of urban resilience and economic development level of cities in Yangtze River Delta urban agglomeration. *Urban Development Studies*, 26(1): 82–91. (in Chinese)

Zhang Y, Yang Q, Min J, 2016. An analysis of coupling between the bearing capacity of the ecological environment and the quality of new urbanization in Chongqing. *Acta Geographica Sinica*, 71(5): 817–828. (in Chinese)

Zheng W, Wang X, Li C, 2007. The spatial disparities of regional comprehensive urbanization level of vice provincial city in China from 1997. *Economic Geography*, 27(2): 256–260. (in Chinese)