



Identification and countermeasures of limiting factors of regional sustainable development: a case study in the Pearl River Delta of China

Zhao-Tian Li¹ · Meng-Meng Hu¹ · Miao Li¹ · Meng-Yu Jiao¹ · Bei-Cheng Xia^{1,2}

Received: 29 January 2019 / Accepted: 13 May 2019 / Published online: 18 May 2019
© Springer Nature B.V. 2019

Abstract

With the acceleration of global urbanization and the degradation of environmental resources, cities face enormous challenges in sustainable development, which is more pronounced in the Pearl River Delta (PRD) urban agglomeration of China. The influencing factors and countermeasures of the sustainable development of the PRD were identified through an ecological security assessment that was associated with the coupling coordination degree model and the BP-DEMATEL model. Three index systems were established, including socioeconomic indicators, eco-environmental indicators and both kinds of indicators; from the perspective of the ecological security and coordination degree, developing areas have better sustainability performance with a higher ecological security score on these three index systems (0.3909, 0.4210 and 0.3912, respectively). Further influencing indicator analysis suggested that the fundamental indicator that limits the regional sustainability of the PRD is the urban ecological elasticity (the “Prominence” value is 4.4713 and the “Relation” value is 3.3336), as well as driving indicators, including the normalized difference vegetation index, GDP per capita, the population density and pesticide usage per km² of cultivated area. Therefore, coordinated development among different cities should be considered. Cities with more native environments are vulnerable to external factors, and industrialized cities lack powerful ecological restoration. Ecological restoration and management measures are suggested to provide guidance for urban managers and promote regional sustainable development.

Keywords Regional sustainability · Coupling coordination degree model · BP-DEMATEL model · Ecological security · Urban ecosystems

Zhao-Tian Li and Meng-Meng Hu are co-first author.

✉ Bei-Cheng Xia
xiabch@mail.sysu.edu.cn

¹ School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China

² Guangdong Provincial Key Lab of Environmental Pollution Control and Remediation Technology, Sun Yat-sen University, Guangzhou 510275, China

1 Introduction

Over the past four decades, the rapid development of society and the economy in China have caused accelerated urbanization and urban population growth spurts. Urbanization is always accompanied by changes in land use types, given that natural landscape is gradually replaced by urban infrastructure (Larson et al. 2016; Gao et al. 2018). However, the more serious issue is ecological degradation and the accompanying complicated urban environmental problems, such as air pollution, biodiversity loss, the heat island effect, etc. (Chauvin et al. 2017), which seriously hinder urban sustainable development (Hodson and Marvin 2009; Chen et al. 2017; Dong and Xu 2019). Ecological security provides a guarantee for sustainability (Simmons et al. 2018; Gong et al. 2009; Li and Xu 2010). In the process of urbanization, the key issue that emerges is how to coordinate and balance socioeconomic development and eco-environment protection (Pulighe et al. 2016; Zulueta et al. 2017). First, it is hard but important to focus on both aspects during urbanization. Second, the interaction between socioeconomic development and eco-environment protection should promote the well-being of urban residents. Therefore, during urban planning and management, a crucial issue is how to consider the relationship between the socioeconomy and eco-environment, and how to identify the key factors that constrain urban sustainable development and guarantee urban ecological security (Gao et al. 2017).

In 1987, the World Commission on Environment and Development (WCED) published *Our Common Future*, which defined sustainability as development that meets the needs of the present without compromising the ability of future generations to meet their needs (WCED 1987). Urban ecological security is the premise and foundation of urban sustainable development. Sustainable development is actually the development of human beings and the common development of human beings with their environment (Gao 2012). Ecological security is commonly assessed using an index framework that is combined with various mathematic models (Chu et al. 2017). With increasing concerns for the ecological security, many methods have been proposed for assessing urban ecological security or sustainability ways (Su et al. 2016; Kwak et al. 2002; Rodriguez-Labajos et al. 2009; Tran et al. 2002; Mamim et al. 2009). Several conceptual frameworks and mathematical modeling approaches have been employed in this field (Shao et al. 2013). These include the widely used Press(P)–Status(S)–Response(R) model, the fuzzy assessment and gray assessment models, and so on.

Indicator selection is the first step of a security assessment, which based on the characteristics and developmental trends of a given study area. However, the biggest limitation of the current assessment method is that there is no uniform standard for the index framework, and the assessment result will change according to different indicators (Wang et al. 2003; Zhou et al. 2010), from which we could not get a stable result. To overcome the instability of the results of the index assessment, the coordination degree model and BP-DEMATEL model were introduced, which were used to measure and screen out the main indicators that influence the urban ecological security of the PDR. The urban ecological security to be discussed here includes social elements, economic elements and natural elements of the PRD region, and the roles that the socioeconomy and eco-environment play in the process of urban sustainable development form an opposing but cooperative relationship. To some extent, urbanization is the result of the trade-off between socioeconomic growth and eco-environmental protection, which comprehensively guide the urban ecological security and sustainability.

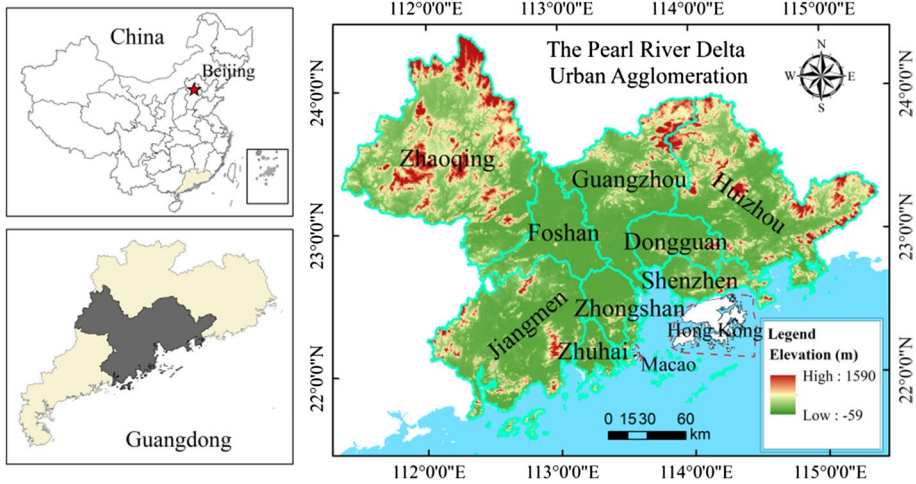


Fig. 1 The location of the Pearl River Delta urban agglomeration

Using those comprehensive methods, the urban ecological security of the PRD was assessed with respect to the role of a single element. Two index systems were established that contain a single type of element (socioeconomic indicators or eco-environment indicators) and further consider the comprehensive elements that contain mixed indicators. Based on the coupling coordination degree model (Chen and Xu 2017) and the BP-DEMATEL model (Qin and Lu 2015), the trade-offs of these two single type elements were measured in order to identify the fundamental indicator, the driving indicators and the characteristic indicators that support the urban sustainable development of the PRD. This study focuses on the limiting factors of the regional sustainable development of the PRD, considers the measures that could be taken to maintain the urban ecological security and provides suggestions to urban planners and politicians.

2 Study area

The Pearl River Delta urban agglomeration (PRD) is located in Guangdong province in southern China. It is one of the most densely urbanized regions in the world and is an economic hub of China. It encompasses a total area of more than 55,368.7 square kilometers and had a combined population of over 63.01 million at the end of 2018 (Guangdong statistics bureau 2019). The area’s growth rate was 2.38%, while the national average growth rate was only 0.39%. In 2018, the total economy of the PRD was 8104.85 billion Yuan, accounting for 80.207% of the economy of Guangdong province. The main metropolitan region of the PRD is located at (22.25°–23.5°N, 112.25°–114.5°E), including the most developed cities of Guangzhou and Shenzhen. However, the periphery of the PRD still has its original ecological environment with inadequate economic development, including Zhaoqing and Huizhou. The location of the PRD is shown in Fig. 1.

The PRD includes nine municipalities of Guangdong province, namely Guangzhou, Shenzhen, Zhuhai, Dongguan, Zhongshan, Foshan, Huizhou, Zhaoqing and Jiangmen. Among those cities, Guangzhou is the capital and the most populous city of Guangdong.

Table 1 Index system and indicator weights of different elements

Index system (C/E/S)	Indicator	Indicator weight (E/S)	Indicator weight (C)
Comprehensive elements (C)			
Eco-environment element (E)	Water area per regional unit	0.1660	0.0663
	Green land area per regional unit	0.1627	0.0661
	Shannon's diversity	0.1773	0.0693
	Biological abundance index	0.1629	0.0661
	Ecological elasticity	0.1662	0.0665
	Normalized difference vegetation index	0.1650	0.0669
Socioeconomy element (S)	GDP per capita	0.1253	0.0748
	Population density	0.1112	0.0683
	Pesticide usage per unit of cultivated area	0.1405	0.0784
	Fertilizer usage per unit of cultivated area	0.1470	0.0823
	Secondary industry proportion	0.1034	0.0661
	Anthropogenic disturbance index	0.1272	0.0741
	Construction land per unit	0.1033	0.0662
	Comprehensive management area of soil and water erosion	0.1421	0.0885

The eastern side of the PRD (Shenzhen and Dongguan) is the most economically developed area. The western areas (Foshan, Zhuhai and Zhongshan) are open for development, and the outermost areas of the PRD (Zhaoqing, Huizhou and Jiangmen) are developing with good ecological and environmental statuses.

As an important part of the Guangdong–Hong Kong–Macao Greater Bay Area (GBA), the PRD urban agglomeration has greater development space and faces more severe ecological pressure. The current urban planning aims to develop the economy without excessively damaging the environment with the ultimate goal of improving regional competitiveness and public welfare. Over the past four decades, with the rapid expansion and urbanization, the PRD is facing a series of ecological environmental problems, which are becoming key factors restricting the urban sustainable development. In view of the increasingly serious urban ecological problems, decision makers need to ensure the security of the PRD's overall ecological environment.

3 Methods

3.1 Ecological security assessment

Systematic index analysis became the mainstream method of environmental assessment after the US and EU (EEC) successively announced environmental governance policies approximately 1995 (Wang et al. 2003). The index evaluation method was used to establish three index systems, including two index systems with a single type of element (Table 1E and S) and one index system with mixed elements (Table 1C). The indicators included two types. One type of indicator included eco-environmental elements, which directly reflect

the status of the urban ecology, such as water area per unit of area, green land area per regional unit, ecological elasticity and so on. Another type of indicator included socioeconomic elements, which indirectly reflect the status of the ecological security, and include GDP per capita, population density, the anthropogenic disturbance index and so on. In addition, the degree of social and economic development also reflects the pressure on the urban ecology and environment. The selected indicators were considered based on the references (Gao et al. 2017; Li et al. 2019), and these indicators are the most frequently used and easily obtained. The indicator weight was calculated using the complex correlation coefficient method (Zou et al. 2006), and the ecological security score was calculated using the gray clustering method (He et al. 2012). Each index system was calculated using the same method.

The PRD was divided into 35 areas (counties or districts of the 9 municipals). The data of the socioeconomic indicators were taken from the Statistic Yearbook of each area. The data of the landscape indicators were acquired using ENVI 5.1 and ArcGIS 10.2 based on the remote sensing images (<https://glovis.usgs.gov>) of the PRD in 2017, or they were calculated using Fragstats 4.2. The ecological elasticity indicator is taken from Costanza et al. (1997), and the anthropogenic disturbance index is taken from Gong et al. (2008). The ecological security results are divided into five levels according to the Natural Breaks (Jenks) method of ArcGIS 10.2, and we set each level to *Unsafe*, *Relatively unsafe*, *Generally safe*, *Relatively safe* or *Safe*. The five levels of ecological security reflect the relative state of the urban ecology rather than the absolute value. The higher the safety level is, the better the ecological status of the corresponding county or district. For example, *Safe* represents a good environmental status.

3.2 Coordination degree model

The coordination degree model is used to measure the balance between the socioeconomic growth and eco-environmental protection of each city. The coupling coordination degree is used as the standard value, and the strategy types of each element are divided according to the level of each element’s deviation from the coupling coordination degree.

The coordination degree model of the urban socioeconomic level and eco-environmental level is represented as follows:

$$C = \left[(F_A \times F_B) / (F_A + F_B)^2 \right]^{1/2} \tag{1}$$

In formula (1), C is the coordination degree of the urban socioeconomic and eco-environment ($0 \leq C \leq 1$). F_A represents the urban eco-environment, and F_B represents the urban socioeconomic. Here, $F = \sum_1^n (A_n \times W_n)$, where A_n is the standard indicator value, and W_n is the indicator weight (refers to Table 1E), which was calculated using the complex correlation coefficient method.

When C cannot reflect the coordination degree of the two elements, we further introduced the following coupling coordination degree model:

$$D = (C \times T)^{1/2} \tag{2}$$

In formula (2), D is the coupling coordination degree of the urban eco-environment and socioeconomic; T is the coupling coordination coefficient, where $T = \alpha F_A + \beta F_B$; and α and β are the undetermined coefficients, which, respectively, represent the contribution rates of

the urban eco-environment and socioeconomy to the overall coordinated development, where $\alpha = \frac{1}{n} \sum_1^n \frac{F_{An}}{F_{An}+F_{Bn}}$ and $\beta = \frac{1}{n} \sum_1^n \frac{F_{Bn}}{F_{An}+F_{Bn}}$.

3.3 BP-DEMATEL model

DEMATEL (Decision-Making Trial and Evaluation Laboratory) is a method of systematic analysis based on graph theory and matrix theory that was proposed by the Battelle Institute of the United States (Tseng 2009). By constructing the direct influence matrix through the logical relations among the factors in the system, the central degree and causal degree of each indicator are calculated, the status and system function of each indicator are defined, and then, the key indicators of the system are further identified (Lee et al. 2008; Liu et al. 2012; Li et al. 2012). It uses the BP neural network to replace the traditional method to calculate the weight value and form the direct correlation matrix between each indicator. Therefore, a BP-DEMATEL model that conforms to the study of urban ecological security is constructed, which improves the objectivity and reliability of the analytical results of the influential factors of ecological security.

1. Construction of BP neural network model.

A total of 16 indicators are used as input layer neurons, which includes socioeconomic indicators, natural environment indicators and landscape ecological indicators. The BP neural network with hidden layers is established using MATLAB 2016a, and the nonlinear mapping model is created. The BP neural network is trained using the gradient descent method of the adaptive rate of the momentum term. The weight matrix (W)_{n×k} of the input layer and hidden layer and the weight matrix (w)_{k×k} of the hidden layer and output layer were obtained, respectively.

2. Total weight vector (ω)

$\omega = |W| \times |w|$ and $\omega = \omega_{n \times k}$, where $|W|$ and $|w|$ are the absolute weight matrices. When $k > 1$, the vectors are weighted as follows:

$$\omega_{n \times k} = \left(\sum_{j=1}^k \sum_{g=1}^k \alpha_{1g} \omega_{1j}, \sum_{j=1}^k \sum_{g=1}^k \alpha_{2g} \omega_{2j}, \dots, \sum_{j=1}^k \sum_{g=1}^k \alpha_{ng} \omega_{nj} \right) \tag{3}$$

where α_{ng} represents the weight and $g = 1, 2, \dots, k$.

3. Direct relation matrix of each indicator (B)

$$B = (b_{ij})_{n \times n} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \tag{4}$$

where $b_{ii}=0$, and $b_{ij}=\frac{w_i}{w_j}$ (if $w_j=0$, then $b_{ij}=0$), which is the weight of indicator i for indicator j .

4. Normalized direct correlation matrix (X)

$$X = (x_{ij})_{n \times n} = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n b_{ij}} \cdot B \tag{5}$$

5. Full incidence matrix (T)

$$T = (t_{ij})_{n \times n} = X(I - X)^{-1} \tag{6}$$

where $(I - X)^{-1}$ is the inverse matrix of $(I - X)$, and I is the unit matrix.

6. The degree of influence (R) and the influenced degree (D)

$$R = \sum_{i=1}^n t_{ij} \tag{7}$$

$$D = \sum_{j=1}^n t_{ij} \tag{8}$$

7. Analysis of influence factors

The horizontal axis vector $(D + R)$ named ‘‘Prominence’’ is made by adding D to R , which represents the importance and magnitude of a single indicator. The vertical axis $(R - D)$ named ‘‘Relation’’ is made by subtracting D from R , which may group criteria into a causal group. Conversely, if $(D - R)$ is negative, the criterion is grouped into the effect group. According to the ranking of the relative importance of the ecological security indicators in the PRD, the main influencing factors are determined and analyzed. $(D - R)$ is used to distinguish between the causal factors and effect factors.

Based on the above calculation results, the influencing factors of ecological security in the PRD urban agglomeration were classified as follows

- a. The fundamental indicator: One indicator whose central degree value is greater than all others shows significant importance.
- b. The driving indicator: The central degree and causal degree are higher than the average values of all indicators, but obviously weaker than the fundamental indicator.
- c. The characteristic indicator: As the result factor $R - D < 0$, there is a high degree of centrality and the result is closely related to other indicators. Such indicators are the result of the combined action of other indicators in the system, which represents the core problem to be solved in the ecological security system. However, because the characteristic indicators are the result of the comprehensive influence of many other indicators, it is difficult to improve and influence them directly.

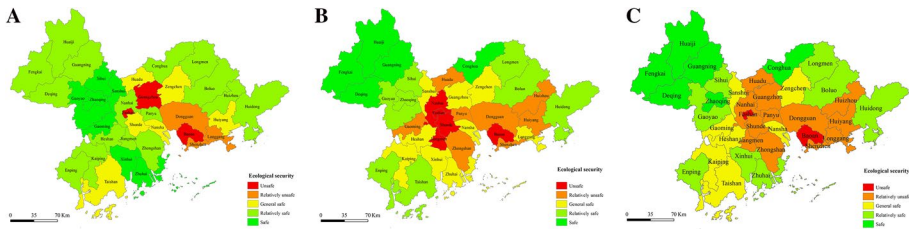


Fig. 2 Ecological security pattern of the PRD as evaluated by different index systems. **a** eco-environmental elements, **b** socioeconomic elements and **c** comprehensive elements

4 Results

4.1 Eco-environmental element

The eco-environmental index system includes six indicators, which consider the situation of each type of landscape and the ecological factors of water, green land, biodiversity and ecological elasticity, and exclude the influence of economic and social factors. The weight of each indicator ranges from 0.1627 to 0.1773 (Table 1E). The indicator with the highest weight is Shannon's biodiversity, and the indicator with the lowest weight is green land area per unit of area. The ES score of the 35 regions ranges from 0.2306 to 0.3909. Seven areas possess safety with respect to ecological security, sixteen areas possess relative safety, six areas possess general safety, three areas possess relative unsafety, and the last three areas possess unsafety (Fig. 2a).

Not surprisingly, those areas that were highly developed had a poor performance on urban ecological security. Especially, the areas such as Foshan, Guangzhou and Baoan received low ES scores for their eco-environments, as well as Dongguan, Longgang and Shenzhen areas. All of those areas are located on the central region or on the east bank of the PRD. However, some other areas around the central region have better performance on the ES evaluation, such as Zhaoqing, Xinhui, Huizhou and others. Although the developing counties in the PRD have good ecological environments, they are threatened by the environment pressure of surrounding regions. In addition, those areas have weaker economic capacities, and their ecological security prospects are not optimistic. In this case, a welcome ecological status provided a safe environment for economic development, and an advanced economy will guarantee the security of the urban ecology.

4.2 Socioeconomic element

Next, we assess the second index system in which all indicators are socioeconomic factors. The weight of each indicator ranges from 0.1033 to 0.1470 (Table 1S). The indicator with the highest weight is fertilizer usage per unit of cultivated area, and the indicator with the lowest weight is construction land per unit of area. The further ES assessment scores of the 35 counties and districts range from 0.2419 to 0.4210 in five levels (Fig. 2b). Among them, five areas possessed safety with respect to ecological security and were mainly located in the less developed area with the native environment. Eight areas possessed relative safety, and these areas were mainly distributed in the periphery of the core region of the PRD with lower economical pressure. Nine areas possessed general safety with a certain degree of

urbanization. Seven areas possessed relative unsafety with higher environmental pressure. Finally, five areas possessed unsafely due to their high economic pressure and low environmental protection.

Economic growth promotes urbanization and results in various environmental problems for cities. Meanwhile, after a certain degree of urbanization, an advanced economy is conducive to improving urban environmental restoration. Based on this view, the economic development level has played an important role in the ecological security of cities. However, according to the ES result, the counties and districts with lower human activities performed better overall than those regions with higher urbanization. To some extent, the lesser the economic pressure that an urban area suffers, the better ecological security the urban area will possess, regardless of the urbanization level of the city.

4.3 Comprehensive elements

From the third index system, we obtained a very similar ecological security pattern to the former two results. This indicator system considered both the ecological status and economic pressure of each county or district. The evaluation result showed that most areas have good urban ecology, but Foshan is still the worst, along with Baoan.

The weight of each indicator ranges from 0.0661 to 0.0885 (Table 1C). The anthropogenic disturbance index and comprehensive management area of soil and water erosion are the indicators with the lowest and the highest weights, respectively. The ES scores of the 35 areas range from 0.2528 to 0.3912 in five levels (Fig. 2c). Compared with the former two results, under the comprehensive influence of the socioeconomic and eco-environmental indicators, the city's ecological security classification is more obvious. Apart from Foshan and Baoan, there are twelve areas that possessed general unsafety, seven areas that possessed general safety, eight areas that possessed relative safety and six areas that possessed safety. The number of cities possessing safety and relative safety was reduced to fourteen, and more cities show the limitations of ecological security as affected by the socioeconomy and eco-environment.

Among the three index systems, some areas retain the same security level in urban ecological security assessment among the different index systems. For example, Foshan and Baoan still possess unsafety, and Longmen, Boluo, Huidong and Enping still possess relative safety. Although most areas exhibited different security levels among the three index systems, the whole ecological security pattern of the PRD is relatively formed (Fig. 3). According to the ecological security of each area, the PRD region was divided into three subregions, including the central and east subregion, the west subregion and the peripheral subregion. The central and east subregion is very developed, and the ecological security is poor with respect to both socioeconomic and eco-environmental conditions. The areas in the west subregion are good with respect to eco-environmental conditions but have poor socioeconomic conditions. The areas in the peripheral subregion have both good eco-environmental and socioeconomic conditions.

4.4 Coupling coordination degree model

According to the coordination degree model, eight areas show lower coordination of their socioeconomy and eco-environment. Those areas all located in the center region and on the east bank of the PRD, and this is basically similar to the ecological security

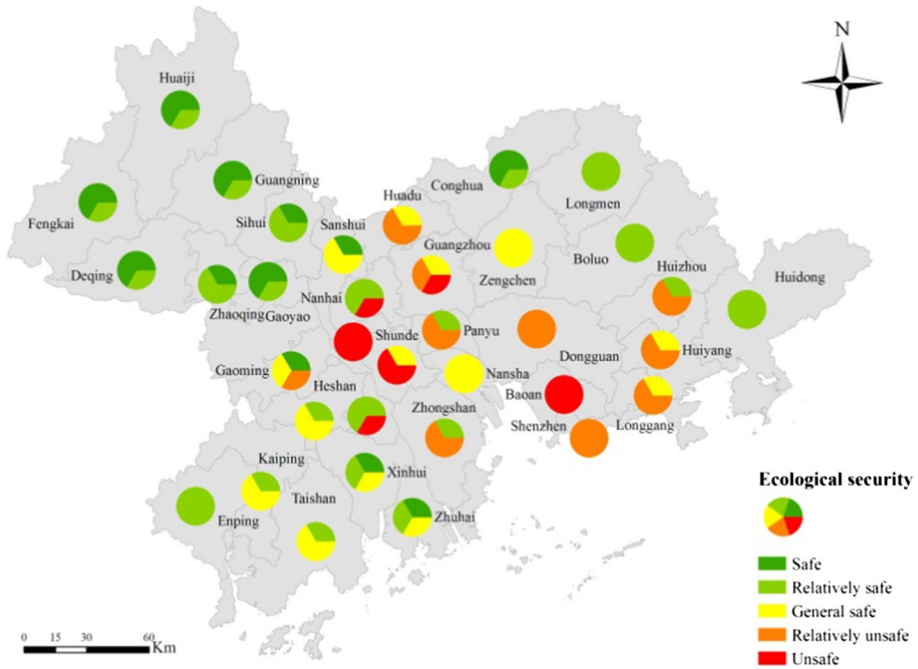


Fig. 3 The change of the ecological security level of each county (district) in the PRD under the three evaluation systems

patterns of those developed areas. Nine cities show higher coordination of their socioeconomy and eco-environment, which include areas with poor ecological security, such as Shenzhen and Longgang, and areas with good ecological security, such as Guangning, Longmen and Boluo (Fig. 4). However, most areas have high coordination and balance their socioeconomic and eco-environmental development. It is proven that only cities that reached a balance between their economic development and environmental protection can be sustainable (Figs. 2, 4).

4.5 BP-DEMATEL model

According to the BP-DEMATEL model, three kinds of influencing factors were selected from the fifteen indicators (Table 2). The fundamental influencing factor is the ecological elasticity index; the driving influencing factors include the normalized difference vegetation index, GDP per capita, population density and pesticide usage per unit of cultivated area; and the other eight indicators are the characteristic influencing factors (Fig. 5). The fundamental influencing factor was the most important factor that affected urban ecological security and limited urban sustainable development.

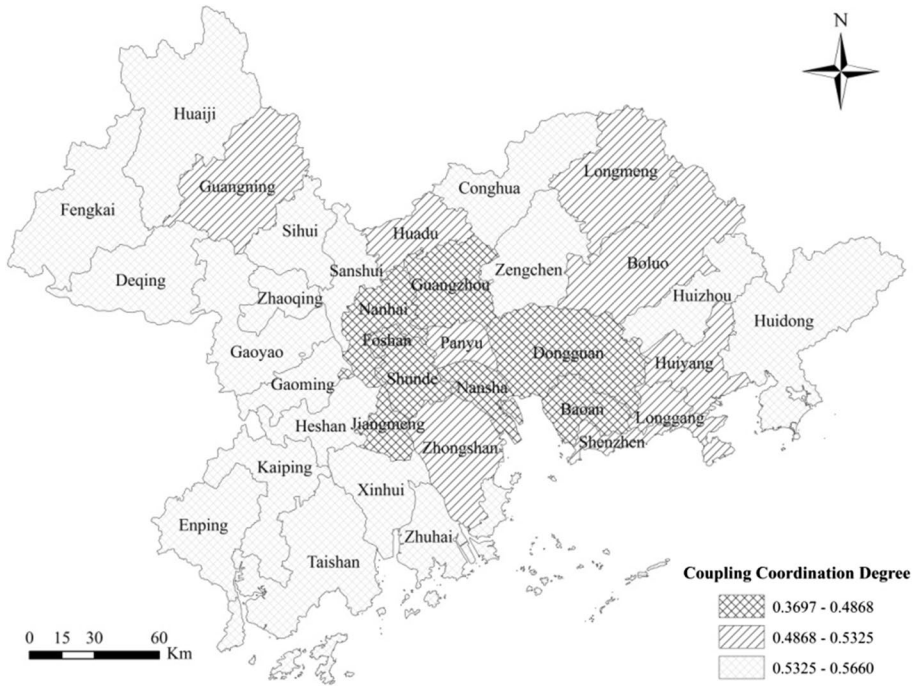


Fig. 4 Coupling coordination degree of each county (district) in the PRD

Table 2 Influencing factors of the urban ecological security of the PRD

Influence factor	$(D + R)^a$	$(D - R)^b$	Indicator
Fundamental influencing factor	4.4713	3.3336	Ecological elasticity
Driving influencing factor	3.7063	2.1740	Normalized difference vegetation index
	3.1413	0.8718	GDP per capita
	3.0759	0.5850	Anthropogenic disturbance index
	3.0735	0.5723	Population density
	3.0243	0.1380	Pesticide usage per unit of cultivated area
Characteristic influencing factor	3.0977	-0.6933	Water area per unit of area
	3.1895	-1.0364	Green land area per unit of area
	3.2087	-1.0955	Shannon's diversity
	3.3149	-1.3822	Biological abundance index
	3.2476	-1.2072	Secondary industry proportion
	3.1569	-0.9279	Fertilizer usage per unit of cultivated area
	3.1613	-0.9433	Construction land per unit of area
3.0455	-0.3889	Comprehensive management area of soil and water erosion	

^a $(D + R)$ reflects the importance of a criterion

^bIf $(D - R) > 0$, the indicator is grouped into the cause group; and if $(D - R) < 0$, the indicator is grouped into the effect group

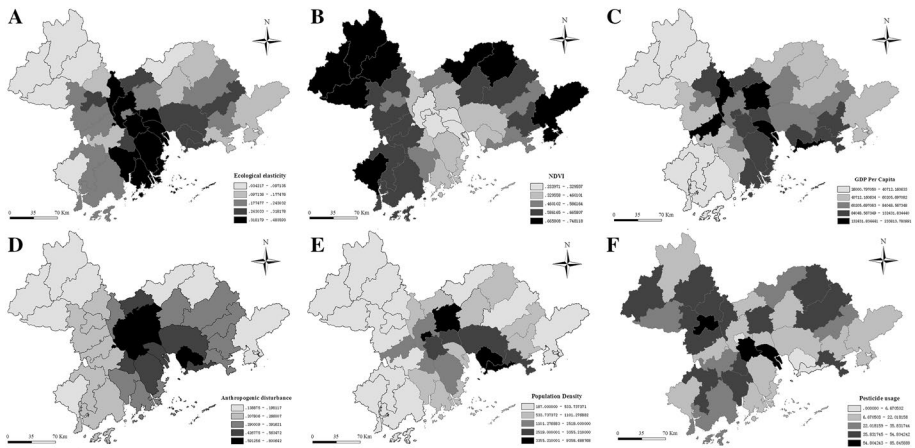


Fig. 5 The performance of each county (district) on the six main indicators of the PRD. **a** Ecological elasticity index, **b** normalized difference vegetation index, **c** GDP per capita, **d** anthropogenic disturbance index, **e** population density and **f** pesticide usage per unit of cultivated area

5 Discussion

Ecological security is the foundation and premise of urban sustainable development. With rapid urbanization, environmental problems are affecting the safety and orderly operations of cities. Therefore, the accurate assessment of urban ecological security becomes increasingly more important. However, the identification of the main factors affecting the urban ecological security is more conducive to the sustainable development of urban managers and to maintaining scientific development.

5.1 Urban ecological security and coordination degree

In the process of urbanization, the social and economic activities of human beings promote the development of cities. A city originates from a single natural system, which combines the subjective social system and economic system of human beings, and finally grows into a complex ecosystem. The ecological foundation of a city suffers irreversible damage in the process of urbanization, which results in the biggest obstacle to the sustainability of a city. Especially, many cities have been hit hard in the process of industrialization, which has resulted in socioeconomic development while destroying the cities. It can be said that the eco-environment provides the foundation for social and economic development and advanced society and economy, thereby providing support for the eco-environmental restoration of the problems that were caused by the rapid development. Modern urban development should avoid the old way of “destruction first, protection later” since the urban ecology is the primary element.

Taking the Pearl River Delta urban agglomeration as an example, it can be seen from the results that urban development is restricted by both socioeconomic elements and eco-environmental elements. However, whether based on eco-environmental elements or socioeconomic elements, the ecological security situation that is faced by developed counties or districts is more serious. On the one hand, rapid economic growth will inevitably cause

ecological environmental degradation. On the other hand, the degraded ecological environment can only be restored by a developed society and economy. The two elements both play important roles in the urban ecosystem. Furthermore, whether from the perspective of urban ecological security or the perspective of urban coordinated development, the PRD region has shown a similar pattern with poor ecological security and poor coordination in developed areas. It is ultimately reflected in the poor sustainable developmental capacity of those counties and districts.

5.2 Limiting factors of urban sustainable development

The fundamental factor influencing the ecological security of each county and district in the PRD region is the ecological elasticity. As the basis of the self-regulation ability of the natural ecosystem, the ecological elasticity supports the ecological carrying capacity (Tian and Zhang 2018). The ecological elasticity is reflected in the self-maintenance and self-regulation of an ecosystem and its ability to resist external pressures and disturbances (Gao 2001). Moreover, an urban ecosystem's uniqueness is embodied in the complex components with large disturbances and instability. Therefore, the fundamental factors of the PRD region's ecological security are the maintenance of the ecosystem's stability and increasing the ecosystem's elasticity. The ecological elasticity of developed areas is greater, and the ecological connectivity between the developed areas and the less developed areas will help balance the ecological level of the whole region.

The driving factor that mainly affects the PRD is the normalized difference vegetation index. The vegetation coverage is still an important indicator that promotes the ecological security in the PRD region. The vegetation coverage is the foundation of the ecological conditions, and the natural habitat is still the main factor. The second driving factor is GDP per capita. Once urban development reaches a certain stage, the major form of the urban ecosystem is the social economic system. The social economy is also a main factor supporting the natural ecosystem's recovery. On the one hand, it is important to promote the ecosystem protection consciousness of urban residents. On the other hand, it is necessary to enhance the recovery of the ecological system, and GDP is the main factor of the PRD's ecological security. Furthermore, the anthropogenic distribution index, population density and pesticide use per unit of area also reflect the impacts of human activities on the urban ecology of the PRD. The PRD region is facing the pressure of population growth, which leads to the expansion of the urban space and greater ecological pressure. It is important to coordinate the ecological environmental protection and socioeconomic development in the urban complex ecosystem.

5.3 Urban sustainable development pattern of the PRD

The overall ecological security pattern of the PRD shows a trend of gradual deterioration from inland areas to estuary areas, which is similar to the economic development level of each district and county. The more developed the country or district is, the lower the ecological security level. The results reveal that there are many problems from blind development and the lack of environmental protection in the process of urbanization. Moreover, the developed social economic system plays a certain but very limited role in urban ecological restoration. The traditional urban development idea of "destruction first, protection

later” is very unfavorable to the sustainable development of cities, and sustainable urban development should be based on ecological priority and economic moderation.

The development of each area in the PRD is very different, and the ecological security problems of each county or district are also different. Under the unified evaluation method, the different index systems reflect the relatively stable influencing factors of the ecological security problems of each district and county. The cities exist due to social and economic development, and the ecological system will inevitably suffer from damage in this process. Controlling the urban ecosystem security falls within urban sustainable development, which provides support for urban sustainability.

For city managers, balancing the relationship between the socioeconomy and eco-environment in the process of urban development is crucial in improving the comfort level of urban residents. To this end, the specific measures should include the following: (1) control the population, thereby reducing the pressure of the urban population; (2) increasing the environmental awareness of urban residents and improving the urban environment; (3) changing the economic growth model and developing environmentally friendly enterprises; and (4) increasing the financial investments in environmental protection and green GDP.

6 Conclusions

The index assessment method was used to measure the ecological security status of the PRD region under different influencing factors, and the restrictive factors and countermeasures affecting the regional sustainable development are obtained through the coordination degree model and the BP-DEMATEL model. By comparing the results of different research methods, the sustainable development of the regional ecological security is comprehensively analyzed. The index assessment method can establish different index systems, and they are assessed using different influencing factors of the PRD regional ecological security pattern. However, due to the instability of the index assessment result, it is difficult to directly show the limiting factors of the identification on the regional sustainable development. Under this condition, the developmental level and the importance of the influencing factors of the counties and districts of each city were determined using a mathematical model of the different influencing factors. Through the combination of the above methods, the limiting influencing factors of regional sustainable development and the countermeasures of urban sustainable development are suggested from the perspective of urban ecological security.

Ecological security and coordinated development are the primary conditions of urban sustainable development. The main threat to the sustainable development of the PRD comes from the population and economic growth. The economic “regurgitation-feeding effect” on the eco-environment has a limited effect on the restoration of the urban ecosystem. On this basis, the overall ecological security of the PRD shows a tendency of deterioration from inland areas to estuary areas. The city managers face the problems of how to maintain the sustainable development of developing areas and promote ecological recovery in developed areas. It is suggested that the overall planning and scientific design should be done well in the early stage of urban development, which would ensure the coordinated development of the regional ecology and economy.

Acknowledgements This research was financially supported by the National Key R&D Program of China (2016YFC0502803). The authors are grateful to the editor and the anonymous reviewers and Y-F Wang for their insightful comments and suggestions.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

- Chauvin, J. P., Glaeser, E., Ma, Y., & Tobio, K. (2017). What is different about urbanization in rich and poor countries? Cities in Brazil, China, India and the United States. *Journal of Urban Economics*, 98, 17–49.
- Chen, M., & Xu, C. (2017). Study on the coupling coordination degree between metropolitan economic system and water environmental system-taking Beijing as an example. *MATEC Web of Conferences*, 100, 05080.
- Chen, L., Xu, L., & Yang, Z. (2017). Accounting carbon emission changes under regional industrial transfer in an urban agglomeration in China's Pearl River Delta. *Journal of Cleaner Production*, 167, 110–119.
- Chu, X., Deng, X., Jin, G., Wang, Z., & Li, Z. (2017). Ecological security assessment based on ecological footprint approach in Beijing–Tianjin–Hebei region, China. *Physics & Chemistry of the Earth Parts*, 101, 43–51.
- Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, 387, 253–260.
- Dong, Y., & Xu, L. (2019). Aggregate risk of reactive nitrogen under anthropogenic disturbance in the Pear River Delta urban agglomeration. *Journal of Cleaner Production*, 211, 490–502.
- Gao, J. (2001). *Exploration of sustainable development: theory, method and application of ecological carrying capacity*. Beijing: China Environmental Science Press.
- Gao, L. (2012). Research on urban sustainable development based on ecological security. *Program Design and Research*, 133, 10–15.
- Gao, P. P., Li, Y. P., Sun, J., & Li, H. W. (2018). Coupling fuzzy multiple attribute decision-making with analytic hierarchy process to evaluate urban ecological security: A case study of Guangzhou, China. *Ecological Complexity*, 34, 23–34.
- Gao, Y., Zhang, C., He, Q., & Liu, Y. (2017). Urban ecological security simulation and prediction using an improved cellular automata (CA) approach—A case study for the City of Wuhan in China. *International Journal of Environmental Research & Public Health*, 14(6), 643.
- Gong, J. Z., Liu, Y. S., Xia, B. C., & Zhao, G. W. (2009). Urban ecological security assessment and forecasting, based on a cellular automata model: A case study of Guangzhou, China. *Ecological Modelling*, 220(24), 3612–3620.
- Gong, J. Z., Xia, B. C., & Chen, J. F. (2008). Spatially fuzzy assessment of regional eco-security in Guangzhou, a fast urbanizing area: A case study in Guangzhou City. *Acta Ecologica Sinica*, 28(10), 4992–5001.
- Guangdong statistics bureau (2019). *Guangdong statistical yearbook*. Guangzhou.
- He, T., Zhang, L., Zeng, Y., Zuo, C., & Li, J. (2012). Water quality comprehensive index method of Eltrix River in Xin Jiang Province using SPSS. *Procedia Earth & Planetary Science*, 5, 314–321.
- Hodson, M., & Marvin, S. (2009). Urban ecological security: A new urban paradigm? *International Journal of Urban and Regional Research*, 33(1), 193–215.
- Kwak, S. J., Yoo, S. H., & Shin, C. O. (2002). A multiattribute index for assessing environmental impacts of regional development projects: A case study of Korea. *Environmental Management*, 29, 301–309.
- Larson, K. L., Nelson, K. C., Samples, S. R., Hall, S. J., Bettez, N., et al. (2016). Ecosystem services in managing residential landscapes: Priorities, value dimensions, and cross-regional patterns. *Urban Ecosystem*, 19, 95–113.
- Lee, Y. C., Hu, H. Y., Yen, T. M., et al. (2008). Kano's model and decision making trial and evaluation laboratory applied to order winners and qualifiers improvement: A study of the computer industry. *Information Technology Journal*, 7(5), 702–714.
- Li, C.-R., Geng, Y., Xue, B., Ren, W.-X., & Dong, H.-J. (2012). Analysis on barriers of urban sustainable development based on DEMATEL. *Chinese Journal of Applied Ecology*, 23(10), 2836–2842.
- Li, Z. X., & Xu, L. Y. (2010). Evaluation indicators for urban ecological security based on ecological network analysis. *Procedia Environmental Sciences*, 2, 1393–1399.
- Li, Z.-T., Yuan, M.-J., Hu, M.-M., Wang, Y.-F., & Xia, B.-C. (2019). Evaluation of ecological security and influencing factors analysis based on robustness and BP-DEMATEL model: A case study of Pearl River Delta urban agglomeration. *Ecological Indicators*, 101, 595–602.

- Liu, L., Shen, Y., Cao, X., He, J., & Li, S. (2012). Research on early-warning model of unconventional emergencies based on key information. *Management Review*, 24(10), 166–176.
- Mamim, L., Spangenberg, J., & O'Connor, M. (2009). The DPSIR framework for biodiversity assessment. *Ecological Economics*, 69(1), 12–23.
- Pulighe, G., Fava, F., & Lupia, F. (2016). Insights and opportunities from mapping ecosystem services of urban green spaces and potentials in planning. *Ecosystem Services*, 22, 1–10.
- Qin, X., & Lu, X. (2015). A BP-DEMATEL model based research of the factors that affect coastal urban ecological security system. *Management Review*, 27, 48–58.
- Rodriguez-Labajos, B., Binimelis, R., & Monterroso, I. (2009). Multi-level driving forces of biological invasions. *Ecological Economics*, 69, 63–75.
- Shao, C., Tian, X., Yang, G., Ju, M., & Xie, Q. (2013). Development and application of a new grey dynamic hierarchy analysis system (GDHAS) for evaluating urban ecological security. *International Journal of Environmental Research & Public Health*, 10(5), 2084.
- Simmons, G., Giraldo, J. E., Truong, Y., & Palmer, M. (2018). Uncovering the link between governance as an innovation process and socio-economic regime transition in cities. *Research Policy*, 47(1), 241–251.
- Su, Y., Chen, X., Liao, J., Zhang, H., Wang, C., Ye, Y., et al. (2016). Modeling the optimal ecological security pattern for guiding the urban constructed land expansions. *Urban Forestry & Urban Greening*, 19, 35–46.
- Tian, M., & Zhang, Y. (2018). An ecological elasticity measurement model and its calculation regarding Guanzhong area of Shaanxi province. *Journal of Zhejiang University (Science Edition)*, 45(2), 226–233.
- Tran, L. T., Knight, C. G., O'Neill, R. V., Smith, E. R., Riitters, K. H., & Wickham, J. (2002). Fuzzy decision analysis for integrated environmental vulnerability assessment of the Mid-Atlantic Region I. *Environmental Management*, 29, 845–859.
- Tseng, M. L. (2009). A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. *Expert Systems with Applications*, 36(4), 7738–7748.
- Wang, G., Cheng, G. D., & Qian, J. (2003). Several problems in ecological security assessment research. *Chinese Journal of Applied Ecology*, 14, 1551–1556.
- World Commission on Environment & Development. (1987). *Our common future* (Vol. 43). Oxford: Oxford University Press.
- Zhou, F., Guo, L. Z., Chen, S. Y., & Wu, X. B. (2010). Evaluation on ecological security of land resource and its limiting factors in Zhanjiang city. *Research of Soil and Water Conservation*, 17(5), 202–206.
- Zou, Z. H., Yi, Y., & Sun, J. N. (2006). Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. *Journal of Environmental Sciences*, 18(5), 1020–1023.
- Zulueta, Y., Rodriguez, R. M., Bello, R., & Martinez, L. (2017). A hesitant heterogeneous approach for environmental impact significance assessment. *Journal of Environmental Informatics*, 29(2), 74–87.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.