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Spatio-temporal Differentiation and Driving Factors of Industrial Ecology of Restricted Development Zone from Adaptive Perspective: A Case Study of Shandong, China

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Abstract: Based on the adaptive analysis paradigm, this paper constructs an evaluation index system and an evaluation model of the level of industrial ecology of a restricted development zone from the perspective of the industrial system and of the environmental system, and studies the spatial-temporal differentiation characteristics and the driving factors of the level of industrial ecology of the restricted development zone of the Shandong Province, China, by using a variety of measurement methods. The results show that: 1) In the temporal dimension, the level of industrial ecology of the research area increased from 2005 to 2017, while in the regional dimension, it was higher in the eastern coastal areas, followed by the northwestern area and the southwestern area; 2) In the spatial dimension, from 2005 to 2017 the level of industrial ecology of the research area had a clear spatial dependence, and the regional spatial agglomeration of the restricted development zones with similar industrial ecology levels become increasingly evident; 3) On the whole, the industrial ecology level in the study area had a clear spatial differentiation pattern, as it was higher in the north and in the east and lower in the south and in the west. Moreover, its evolution model changed from a 'three-core driven model' to a 'spatial scattered mosaic distribution model', and then to a 'single-core driven model'; 4) Industrial ecology was positively correlated with economic development, foreign investment, science and technology, and negatively correlated with the government role, while industrial structure and environmental regulation failed to pass the statistical significance test.

Keywords: adaptability; industrial ecology; spatio-temporal differentiation; restricted development zone; Shandong Province, China

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1 Introduction

Since the reform and opening up, China's economy grew at an average annual rate of 10%, such that its development has been hailed as 'China's miracle' (Guo et al., 2016a). However, the large-scale expansion and the total growth of China's economy were driven by traditional industries. The development model of heavy industry hinders intensive technological innovation and technological progress. At present, most regions in China are still on the left side of the Environmental Kuznets Curve (EKC) (Zhao et al., 2016), that is, eco-

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nomic growth is positively correlated with environmental degradation. The current production model has increased the industrial stress on resources and environment, and a series of ecological problems have been emerging. The industrial system is an important manifestation of the economic level of the human-land relationship system; accordingly, its structural type and organizational scale affect to a great extent the economic development efficiency and resource utilization efficiency. At the same time, the industrial development model also directly determines its antagonistic stress or its coupling, symbiotic effect on the ecological system (Ren and Shang, 2005; Liu et al., 2007; Wang et al., 2020). Therefore, it is of urgent practical significance to explore the mechanism of influence of regional development on resources and environment from the perspective of industry.

Industrial ecology aims to build a bridge between the economic system and the ecological system by adjusting and reforming the traditional industrial production organization model, so as to intensify resource utilization and minimize environmental disturbance in the process of economic operation, thus realizing the organic unity of economic, social, and environmental benefits (Gao et al., 2011; Liu et al., 2018). At present, research on industrial ecology mainly focuses on the following aspects. In terms of connotation interpretation, industrial ecology is the result of the interaction between the industrial system and the environmental system. Moreover, industrial ecology is a symbiotic network formed by different industries, their products, and their surrounding environment including its spatial manifestation (Smith et al., 2015). From the point of view of the industrial system, the industrial system is an organic part of the biosphere. According to the principles of ecology, industrial ecology aims to optimize the structure, and to restructure the function, of the industrial ecosystem, so as to achieve a centralized input and efficient output of the industrial ecosystem (Shao et al., 2016). From the perspective of the ecosystem, industrial ecology aims to integrate material production and industrial activities into a circular, closed ecosystem, so as to promote economic growth and ecological protection (Huang and Wang, 2000). In terms of research contents and methods, foreign scholars mainly focused on utilizing energy and materials (von Hauff and Wilderer, 2008), constructing ecological industry symbiosis networks (Lambert and Boons, 2002) and industrial ecological parks (Korhonen and Snäkin, 2005). However, Chinese scholars mainly employed methods such as the data envelopment analysis (DEA) model, ecological efficiency, environmental adaptability efficiency of the industrial system, and impulse response analysis, to conduct an empirical analysis of urban agglomeration in the middle reaches of the Yangtze River (Ma and Liu, 2015), of an industrial demonstration park in Fujian Province (Xu et al., 2019), of the Songhua River Basin in Jilin Province (Guo et al., 2016a), of the Dongting Lake area (Yan et al., 2017), and others. In terms of influencing factors and driving mechanism, at present, scholars generally analyze the regional differences in industrial ecology, looking at aspects such as regional resource endowment and regional division of labor (Liu et al., 2018), industrial structure and economic development level (Kuai et al., 2015; Guo et al., 2019; Li and Jin, 2019), energy structure and inter-industry technology spillover (Patchell and Hayter, 2013), science and technology (Wang et al., 2017; Diao et al., 2019), and government regulation intensity (Zuindeau, 2007) and path dependence (Guo et al., 2016b). With the continuous development of big data and information technology, the identification of the influencing factors of industrial ecology will be more accurate and diversified.

Although, in general, the research results of industrial ecology are relatively rich, previous studies suffer from several shortcomings. First, several studies exist at the scale of a whole country, province, or city; however, there are objective differences in resources and environment conditions, social and economic basis, development density and development potential in the above regions, and the actual guiding value of the research results is relatively weak. Second, these studies mainly employ traditional measurement methods and ignore adaptation research, which provides a new research perspective on the coupling relationship and spatio-temporal mechanism between industrial and ecological systems in relation to theoretical introduction and method selection. Using the adaptation research paradigm to analyze the characteristics of 'process-pattern-mechanism' of regional industrial ecology is the current frontier of research, and a hot issue in the fields of geography, economics, and social sciences. Third, the majority of existing studies analyze only the spatio-temporal evolution characteristics and the coupling mechanism of industrial ecology at the macro scale, while there is little research on the regular characteristics of the specific influencing factors, and on industrial ecology development at different scales. The restricted development zone is one of the four main functional areas in China. It focuses on the protection of the main agricultural areas and ecological functional areas in accordance with the concept of 'protective development' (Guo et al., 2018; 2020). Therefore, it is of great practical value to study the spatio-temporal pattern and driving mechanism of industrial ecology in the restricted development zone.

As an important economic province and a strong industrial province in China, the Shandong Province is dominated by heavy chemical industry, and contradictions within its industrial structure are prominent. Its long-term extensive economic and industrial development model has brought serious resource and environmental problems. In 2018, the State Council approved the 'Overall Plan for the Construction of Old and New Kinetic Energy Conversion Comprehensive Experimental Zones in the Shandong Province'. As the first pilot area for the conversion of old and new driving forces in China, Shandong Province inevitably faced new opportunities for the rapid regional development. However, several questions are worth further discussion. It is interesting to investigate the spatio-temporal change of the industrial ecology of the restricted development zone in the Shandong Province, and where the efficiency increase originates. Based on this, according to the two-dimensional perspective of industrial system adaptability and environmental system adaptability, this paper evaluates the spatio-temporal evolution characteristics of industrial ecology in Shandong Province's restricted development zone and reveals its driving mechanism, hoping to provide a reference for sustainable development in the restricted development zone.

2 Materials and Methods

2.1 Study area and data source

The main functional area, which is a special achievement in the spatial planning system, is divided into an optimized development zone, a key development zone, a restricted development zone, and a prohibited development zone. The restricted development zone includes two types of areas: the main agricultural production area, with the main function of ensuring the safety of the supply of agricultural products; and the key ecological function area, with the main function of maintaining the stability of the ecosystem. The main purpose of restricting the development area is not to restrict its development, but to better protect the agricultural and ecological productivity, and achieve its sustainable development. According to the 'Major Function-Oriented Zones Planning of the Shandong Province', the restricted development zones in the Shandong Province include 77 counties and 40 towns; they cover an area of 102 400 km^2, accounting for 65.20% of the total land area of the Shandong Province. Considering the possibilities of data acquisition and the need for regional comparison, the scope of this paper was determined as follows. If the number of towns listed as restricted development zones in a county (city or district) accounts for more than 50% of the total number of towns in the area, and the GDP of these towns accounts for more than 50% of the GDP of the whole county (city or district), then the county-level units these towns belong to, shall be classified as restricted development zones (Guo et al., 2018). After the merger, the study area included 80 county units (Fig. 1). In order to further reveal the spatio-temporal characteristics of industrial ecology in different regions, following previous research (Liu and Ren, 2019), the 80 county units were divided into three areas: northwestern Shandong; southwestern Shandong; and eastern coastal region. In 2017, the GDP of the study area reached 3.39 trillion yuan (RMB), with a total population of 59.65 million, accounting for 47.25% and 59.74% of the total of the Shandong Province, respectively. The research data were obtained from the China City Statistical Yearbook (2005–2018) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of China, 2005–2018), the Shandong Statistical Yearbook (2005–2018) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of Shandong, 2005–2018). Other missing data are supplemented by using the average growth rate method.

2.2 Methodology

2.2.1 Construction of the evaluation index system

The concept of adaptation originated from ecology; it refers to the fact that a population adapts to environmental changes by altering its structure and function in order to continue its viability (Hu and Hassink, 2017). It was then gradually extended to the fields of sociology,

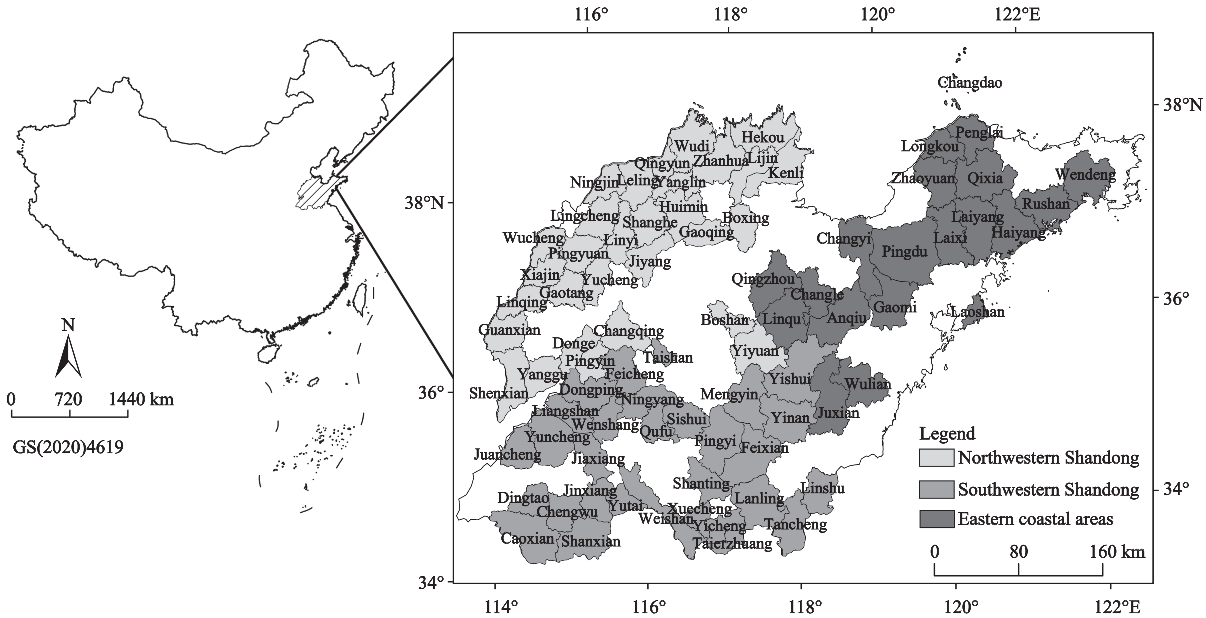

Fig. 1 The location of Shandong Province and study area

economics, and geography, where it refers to the fact that, in order to cope with external interference and stress, a system effectively adjusts or transforms itself into a new system. Based on the adaptation perspective, the analysis of industrial ecological issues in restricted development zones is normally based on the carrying capacity of regional resources and environment. Accordingly, through the measurement of the materials and energy input-output relationship between regional industrial systems and ecological systems, the ecological characteristics of industrial development were analyzed. The final aim of this type of research is to assess the coupling and co-existence relationship between the industrial system and the environmental system, and the level and state of sustainable development of the industrial ecosystem. However, as the external manifestation of the interaction and restrictions between the industrial system and the ecological system, the continuous improvement of the industrial ecological level also reflects the evolution process of the industrial and ecological systems from low-level antagonism to high-level symbiosis (Liu and Han, 2017). Studying the spatial-temporal differentiation characteristics of industrial ecology based on the adaptation perspective can better reveal the degree of interaction between the industrial system and the ecological system. It is also an inevitable choice to introduce the adaptation analysis paradigm into the field of industrial ecological research.

Based on the connotation of adaptability and following previous research (Huber, 2000; Brooks et al., 2005; Korhonen and Snäkin, 2005; Smit and Wandel, 2006; Guo et al., 2019), this paper constructs a comprehensive evaluation index system of the industrial ecology of the Shandong restricted development zones from the perspective of adaptability (Table 1). The first layer is the target layer, that is, the adaptability of the industrial ecosystem, which comprehensively reflects the level of regional industrial ecology. The second layer is the system layer, that is, the industrial system adaptability and the ecological adaptability, which comprehensively reflects the subsystem adaptability. The third layer is the element layer, which is mainly based on the adaptive elements, including the three indicators of sensitivity, stability, and elasticity. Sensitivity refers to the changes in the system caused by the internal and external environmental disturbances imposed on the industry ecosystem. Stability refers to the ability of the system to maintain its original state when responding to environmental disturbances. Elasticity refers to the system's response to disturbances through the system's own structure to absorb disturbances and ensure no fundamental change of system functions (Guan et al., 2018; Li et al., 2020; Tan et al., 2020). Generally speaking, adaptability is negatively correlated with sensitivity, but positively correlated with stability and elasticity.

2.2.2 Evaluation model of the industrial ecological level

To avoid the influence of dimensionality on the accur-

Table 1 Evaluation index system of the industrial ecological level in the Shandong restricted development zones

System layer	Element layer	Index layer	Weight
Industrial system adaptability (0.3516)	Sensitivity (0.1996)	Actual foreign investment / GDP (%) (+)	0.1001
		Value added of the secondary sector / GDP (%) (+)	0.0591
	Stability (0.1675)	Industrial system structure entropy (+)	0.0947
		Agriculture and forestry economy / GDP (%) (–)	0.0611
		Per capita GDP (yuan) (+)	0.0789
	Elasticity (0.0841)	Industrial structure advanced index (%) (+)	0.0614
		Industrial structure conversion rate (+)	0.0393
Environmental system adaptability (0.6484)	Sensitivity (0.1123)	Per capita industrial wastewater discharge (ton) (+)	0.0668
		Fertilizer application intensity (kg/ha) (+)	0.0591
	Stability (0.1411)	Per capita arable land area (mu) (+)	0.0769
		Per capita public green area (m^2) (+)	0.0661
	Elasticity (0.2953)	Comprehensive utilization rate of general industrial solid waste (%) (+)	0.0521
		Environmental protection expenditure/financial expenditure (%) (+)	0.0583
		Energy consumption per unit of GDP (–)	0.1261

Notes: + means positive indicator; – means negative indicator

acy of the evaluation results, we used the extreme value processing method to standardize the data. In addition, the weights of the evaluation index were calculated according to the entropy method. At the same time, in order to improve the objectivity of the evaluation results, a linear weighted summation method was used to calculate the weight coefficients of the system layer and of the element layer. Finally, the hierarchical and multilevel comprehensive evaluation method was used to obtain the industrial and environmental system adaptability index, and the linear weighted summation method was used to calculate the level of industrial ecology. For the positive indicators, the following standardized formula was used (Guo et al., 2016b):

$$x'_{ij} = \frac{x_{ij} - \min\{x_{ij}\}_{1\le i\le n}}{\max\{x_{ij}\}_{1\le i\le n} - \min\{x_{ij}\}_{1\le i\le n}} \quad (1)$$

For the negative indicators, the following standardized formula was used:

$$x'_{ij} = \frac{\max\{x_{ij}\}_{1\le i\le n} - x_{ij}}{\max\{x_{ij}\}_{1\le i\le n} - \min\{x_{ij}\}_{1\le i\le n}} \quad (2)$$

Based on the above-mentioned analysis, the standardization matrix was constructed as follows:

$$Y = \{y_{ij}\}_{m\times n},\ y_{ij} = x'_{ij} / \sum x'_{ij} \quad (3)$$

Therefore, the value of entropy, as well as the difference coefficient and the weight, were obtained as follows:

$$e_j = (-1/\ln m)\sum y_{ij}\ln y_{ij},\ g_j = 1 - e_j,\ w_j = g_j / \sum g_j \quad (4)$$

Finally, the sensitivity, stability, and responses cores could be calculated using the following formula:

$$D_j = \sum w_j \times y_{ij} \quad (5)$$

where D_j is the sensitivity, stability, or responses core of index j; x_{ij} is the indictor value of index j in city i; x'_{ij} is the standardized indictor value of index j in city i; Y is the standardized matrix; e_j is the entropy of index j; g_j is the difference coefficient of index j; and w_j is the weight of index j; y_{ij} means the standardization indictor value of index j in city i; $m \times n$ means m row n column matrix.

2.2.3 Exploratory spatial analysis method

Global spatial autocorrelation reflects the regional distribution effect through the approximation of the attribute values of spatial neighboring units (Huang et al., 2020). Therefore, the global spatial autocorrelation was used to explore the industrial ecology of restricted development zones in the Shandong Province. The global spatial autocorrelation was calculated as follows:

$$I = \sum_{i=1}^{n}\sum_{j=1}^{n}(X_i - \overline{X})(X_j - \overline{X}) / S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \quad (6)$$

$$S^2 = \sum_{i=1}^{n}(X_i - \overline{X}) / n \quad (7)$$

where n is the total number of areas; W_{ij} is the spatial weight linking areas i and j, W_{ij} can be obtained by inverse distance ; X_i, X_j is the industrial ecology value for areas i and j, respectively; and $\overline{X}$ is the mean of the industrial ecology values.

The Getis-Ord G_i^* statistic in the Hot Spot Analysis tool of ArcGIS was used to indicate the clustering of high or low industrial ecology value areas. The spatial agglomeration characteristics were identified through the Hot Spot Analysis to analyze the future evolution trend in the restricted development zones. G_i^* was calculated as follows:

$$G_i^*(d) = \frac{\sum_i \sum_{j \neq 1} W_{ij}(d) X_i X_j}{\sum_i \sum_{j \neq 1} X_i X_j} \tag{8}$$

where d is the critical distance between each area.

2.2.4 The Tobit Regression Model

Because the value of the industrial ecology is within the range [0, 1], the Tobit Regression Model can solve the problem of limited dependent variables; as such, it is widely used in multiple linear regression models. The Tobit regression analysis was performed using the EViews software, to determine the action direction and the response degree of the factors affecting the industrial ecology of the restricted development zones in the Shandong Province. The following Tobit regression Model was used:

$$\text{Tobit}(Y_i) = \alpha_0 + \alpha_1 x_{j_1} + \alpha_2 x_{j_2} + \alpha_3 x_{j_3} + \cdots + \varepsilon_j \tag{9}$$

where Y_i is the industrial ecology value of city i; x_j is the explanatory variable of index j; ε_j is the disturbance term of index j, assumed to be normally distributed with mean μ and standard deviation σ; and α is the Tobit coefficient, which indicate show a unit change in an independent variable x alters the latent dependent variable y (Martey et al., 2012).

3 Results and Analysis

3.1 Temporal evolution characteristics of industrial ecology

As shown in Fig.2a, the industrial system adaptability of the restricted development zones in Shandong Province showed an initial decline from 0.0294 (2005) to 0.0225 (2011), and then an increase to reach 0.0247 (2017). Throughout the period investigated, the average level of industrial system adaptability was 0.0247. Looking at the regional scale, industrial system adaptability was higher in the eastern coastal areas, followed by the southwestern Shandong and the northwestern Shandong. At the same time, the industrial system adaptability of the southwestern and northwestern Shandong was lower than the average, suggesting that the eastern coastal region was an important driving force for the improvement of the industrial system adaptability of the restricted development zones in the Shandong Province. In the future, improving the industrial system adaptability of the southwestern and northwestern Shandong will be key to the industrial ecological development of the restricted development zones in the Shandong Province. At the same time, the adaptive time-series evolution characteristics of the regional industrial system also showed clear differences. In the northwestern Shandong, industrial adaptability fell from 0.0240 (2005) to 0.0198 (2008), and then rose to 0.0227 (2017). In the southwestern region, it fell from 0.0287 (2005) to 0.0209 (2014), and then rose to 0.0228 (2017), while in the eastern coastal areas, it fell from 0.0354 (2005) to 0.0253 (2008), and then rose to 0.0287 (2017). From the analysis of the change in the growth rate of the element layer, we can see that the largest growth rates in the

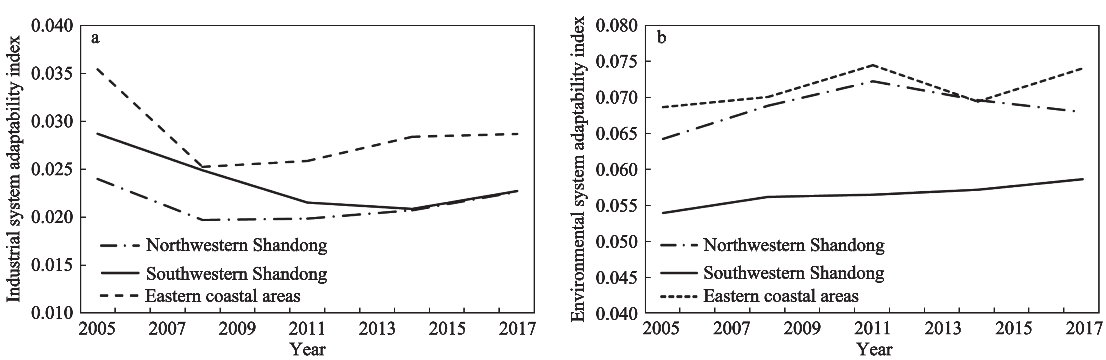

Fig. 2 Adaptability index of the industrial system and of environmental system in Shandong restricted development zones, a. industrial system adaptability; b. environmental system adaptability

northwestern, southwestern, and eastern coastal areas of Shandong were to elasticity, stability, and sensitivity. Therefore, there are evident differences in the key promotion paths of industrial system adaptability in different regions. In the northwestern Shandong, the optimization and upgrading of the industrial structure should be accelerated. In the southwestern Shandong, industrial scale expansion and total growth is still the key to the improvement of industrial system adaptability. In the eastern coastal areas, it is necessary to strengthen the screening of foreign investment, and improve the scientific and technological level of industrial development. As shown in Fig.2b, the environmental system adaptability of the restricted development zones in the Shandong Province showed an increasing trend from 0.0622 (2005) to 0.0668 (2017), with an average annual increase rate of 0.60%. Looking at the regional scale, there were clear differences in the environmental system adaptability index, which was higher in the eastern coastal areas, followed by the northwestern Shandong and southwestern Shandong. This confirms that the improvement of the environmental system adaptability index in the eastern coastal areas is the key driving factor for the improvement of the environmental system adaptability index in the restricted development zones of the Shandong Province. Compared to the southwestern Shandong and the northwestern Shandong, the eastern coastal areas followed a low-consumption and high-efficiency green development model, while the southwestern Shandong and the northwestern Shandong still followed the scale expansion model driven by extensive industrialization, and the resource and environment bottleneck constraint effect of industrial development was relatively prominent. At the same time, the time-series evolution characteristics of environmental system adaptability showed clear differences across regions. In the eastern coastal areas, it raised from0.0686 (2005) to 0.0744 (2011), and then to 0.0740 (2017). In the northwestern Shandong, it followed an inverted 'V-type' trend from 0.0642 (2005) to 0.0722 (2011), and then to 0.0679 (2017), while in the southwestern Shandong it increased from 0.0539 (2005) to 0.0586 (2017). The contribution rate analysis of the element layer shows that the largest contribution in the values for the northwestern and southwestern Shandong was from elasticity and stability, while for the eastern coastal areas it was from stability and elasticity. With the passage of time, the influences of the leading factors on environmental system adaptability passed from a single-factor influence to a multi-element mixed action.

As shown in Fig.3, the industrial ecology level in the restricted development zones of the Shandong Province increased from 0.0507 (2005) to 0.0520 (2017), with an average annual growth rate of 0.21%. The construction of the Shandong ecological province effectively improved the system development of industrial ecology. The regional scale analysis showed clear regional differences in the environmental system adaptability index, which was higher in the eastern coastal areas, followed by the northwestern Shandong and the southwestern Shandong. On the one hand, this reflects the fact that industrial economy and ecological environment in the eastern coastal areas had a relatively coordinated development; in particular, the marine science and technology, innovation-driven strategy continuously promotes the transformation and upgrading of the marine industry, and promotes the diversification of the marine industry ecosystem. On the other hand, regional differences in industrial ecology and environmental systems adaptability showed consistent characteristics, reflecting the fact that the improvement of environmental systems adaptability was the key to industrial ecology. Compared to more developed resource-based industries and heavy industrial structures, 'clean' industrial development was easier than 'light' industrial development, which also implies that environmental systems adaptability was the main influencing factor of industrial ecology.

The evolution characteristics of industrial ecology in different regions also had clear differences. More into detail, the eastern coastal areas followed a 'W-type' development of 'decrease-increase-decrease-increase'; the northwestern Shandong presented an inverted 'V-fall'; and the southwestern Shandong showed a continuous in-

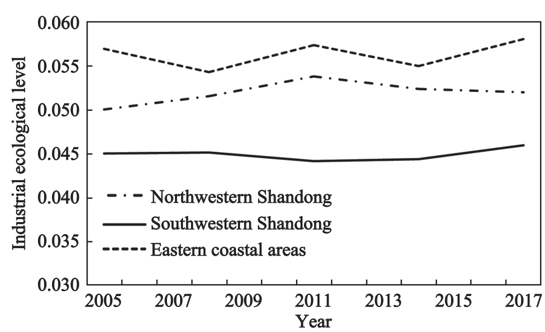

Fig. 3 Industrial ecology level of the Shandong restricted development zones from 2005 to 2017

crease. However, from the growth rate analysis we can see that the eastern coastal areas had the lowest growth rate (0.16%) and appeared to be more advanced; the northwestern Shandong was growing at a rate of 0.31%, whereas the southwestern Shandong had a growth rate of 0.18%. The regional differences were continuously shrinking, and the convergence characteristics of the industry's ecologically stable clubs begun to be optimized.

3.2 Spatial differentiation characteristics of industrial ecology

The evaluation results of the industrial ecology of 83 evaluation units in 2005, 2011, and 2017 were imported into the Geoda software, and the Euclidean Distance was used as the evaluation weight to calculate the Global Moran's I index. The results were 0.3579, 0.4778, and 0.5461, respectively. Furthermore, all the results passed the significance test at the 1% level; therefore, the original hypothesis can be rejected. It can be concluded that there was a relatively clear spatial dependence relationship between the restricted development zones of the Shandong Province from 2005 to 2017. The Moran's I index was greater than 0, indicating that the spatial agglomeration was evident in areas with similar industrial ecology levels, and the spatial spillover effect of industrial ecology was significant.

In order to visually display the spatial pattern characteristics of industrial ecology, the spatial visualization analysis of the industrial ecology in 2005, 2011 and 2017 was carried out by ArcGIS 10.4. Using ArcGIS software, Natural Breaks was adopted to divide the data into four categories of high-value areas, second-high-value areas, second-low-value areas, and low-value areas (Fig. 4).

As shown in Fig.4, in 2005, 2011, and 2017, the industrial ecology level was higher in the east and in the north, and lower in the west and in the south. There was a significant spatial differentiation between the high-value eastern and northern regions of Huangdao, Jiaozhou, Jimo, Gaomi, and Anqiu, and the low-value southwestern regions of Liangshan, Wenshang, Jiaxiang, Jinxiang, Yutai, Weishan, Qufu, and Sishui. The regional evolution analysis shows that the number of areas in the four types named high-value areas, second-high-value areas, second-low-value areas, and low-value areas changed significantly during the period investigated. More into detail, the number of low-value areas, second-low-value areas, second-high-value areas, and high-value areas evolved from 11, 26, 21, and 22 in 2005 to 19, 21, 24, and 16 in 2017, respectively. In fact, the number of low-value areas and second-high-value areas increased, while the number of second-low-value areas and high-value areas decreased, and the proportion of low-value areas and second-low-value areas increased from 47.5 % in 2005 to 50% in 2017. This indicates that, to a certain extent, the industrial ecology process in the restricted development zones of the Shandong Province was slow, and it was a long and arduous road to improve industrial ecology quality.

In addition, the spatial evolution model analysis shows that the industrial ecology in high-value areas evolved from a three-core driving model in 2005 to a spatial clustering distribution in 2011, and then to a single-core driving model in the eastern coastal areas in 2017, where these high-value areas were concentrated. The economic development and the mature market mechanism of the eastern coastal areas generated a strong spillover effect to enhance the industrial capacity and the industrial chain of the surrounding areas, promoting the innovation of the industrial system. However, the vast southwestern and northwestern regions of the Shandong Province were still facing the increasingly acute problems caused by intensive human activit-

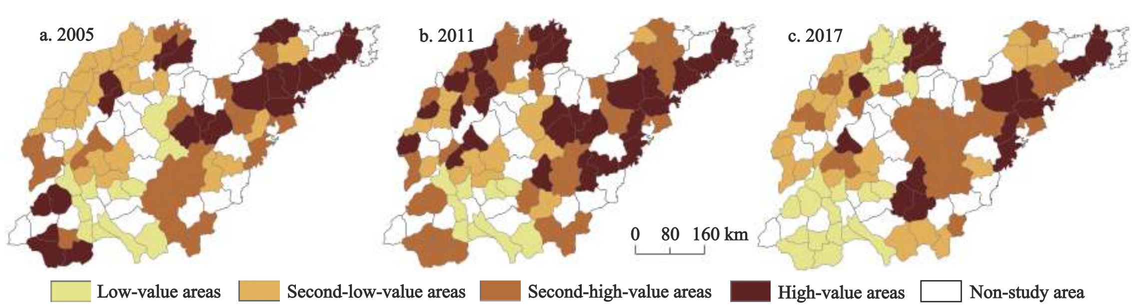

Fig. 4 Spatial pattern evolution of industrial ecology in restricted development zones of Shandong Province

ies, such as the contradictions between man and land, between water and soil, and between supply and resources demand.

However, the analysis of the above-mentioned spatial differentiation characteristics of industrial ecology ignored the spatial increase and decrease changes in the restricted development zones. To better reveal the spatial pattern characteristics of the industrial ecology, based on the growth rate of the industrial ecology in 2005–2011 and 2011–2017, this part also adopted Natural Breaks to divide the data into four categories of high-value areas, second-high-value areas, second-low-value areas, and low-value areas by using ArcGIS software (Fig. 5).

As shown in Fig. 5, from 2005 to 2011, the areas with a high growth rate of industrial ecology were concentrated in the northwestern and central regions of the Shandong Province, including Qingyun, Leling, Ningjin, Lingcheng, Linyi, Wucheng, Xiajin, Yucheng, Boshan, Yiyuan, and Mengyin. The areas with a low value were mainly concentrated in southwestern Shandong, including Tancheng, Dingtao, Chengwu, Caoxian, and Shanxian. From 2011 to 2017, the areas with a high growth rate of industrial ecology underwent a spatial-transition, whereby the southwestern Shandong becomes a hot spot. On the other side, the northwestern Shandong and the eastern coastal areas become low-value areas. It can be seen that, with the continuous implementation of the 'Development plan for the economic circle of provincial capital city groups' and the 'Development plan of the western economic uplift belt', the industrial ecology development of the southwestern and northwestern Shandong ushered good development opportunities and broke the lock-in effect of regional path dependence, such that the spatial pattern of industrial ecology has been continuously optimized.

3.3 Driving factors of industrial ecology in the Shandong restricted development zones

Industrial ecology focuses on the construction of industrial activities in accordance with the laws of ecological economy. It aims to achieve the coordinated and sustainable development of industrial activities and of the natural environment through the improvement of resource utilization efficiency, cleaner production processes, and terminal control efficiency. Industrial ecology is the advanced form of industrial development. As such, it is a manifestation of the interactions between multiple factors, and its ultimate pursuit is to maximize the economic, social, and ecological benefits of the industrial ecosystem. At present, research on industrial ecology mainly focuses on qualitative descriptions, while research on the strength of specific influencing factors needs to be further developed. According to relevant research results (Tong et al., 2012; Wang and Ding, 2017; Zhang et al., 2018; Guo et al., 2019), and in combination with the actual situation of the study area, this paper selected economic development, industrial structure, foreign investment, science and technology, government regulation, and environmental regulation to perform a quantitative analysis of the driving factors of industrial ecology.

3.3.1 Theoretical analysis

(1) Economic development

The EKC theory claims that economic development and environmental quality present an inverted U-shaped relationship. More into detail, the environment shows a process of deterioration and improvement along with economic development. Per capita GDP was selected to represent economic development (ED), and the quadratic term of the per capita GDP was included in the empirical model to test whether there was an inverted 'U-shape' relationship between economic development and

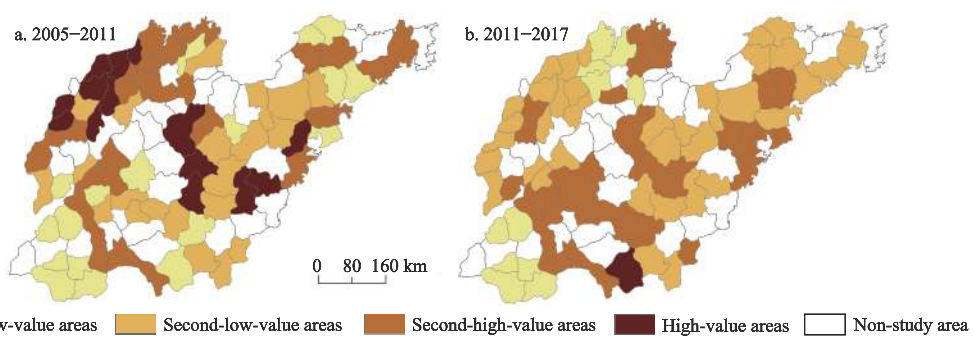

Fig. 5 Spatial pattern evolution of industrial ecological growth rate in Shandong restricted development zone

industrial ecology.

(2) Industrial structure

The structural-bonus hypothesis states that industrial restructuring plays an important role in regional development. The industrial restructuring process may be accompanied by multiple effects, such as increased resource utilization efficiency, clean productivity, energy conservation, pollutant emissions reduction. The proportion between the added value of the secondary sector and the added value of the tertiary sector was selected to represent the industrial structure (IS).

(3) Foreign business investment

The hypotheses of 'pollution halo' and 'pollution haven' concern the influence of foreign investment on regional development. In fact, foreign investment may have dual and complex interactive effects on industrial ecological development. The ratio of the actual utilization of foreign investment to GDP was selected to represent foreign investment (FI), and it was tested whether foreign investment had a 'pollution halo' or a 'pollution haven' effect on industrial ecological development.

(4) Science and technology

Science and technology can directly encourage enterprises to innovate production technology, change traditional equipment and production technology, and promote the optimization and upgrading of traditional industries. At the same time, they can also directly create high-efficiency and low-consumption emerging industries, and apply new technologies, new methods, and new processes to specific production activities to improve industrial ecology. The number of personnel engaged in key enterprises' scientific and technological activities per 10 000 inhabitants was selected to represent scientific and technological (TF).

(5) Government regulation

Under a decentralized fiscal system, government regulation has unparalleled advantages in terms of free factors flow and optimal resources allocation, which can effectively break the path-dependent effect of regional industrial development. However, an industrial development strategy that relies too much on government regulation may affect industrial structure optimization and upgrading. Therefore, the ratio of fiscal expenditure to GDP was selected to represent government regulation (GA).

(6) Environmental regulation

Strict environmental regulation (EM) forces polluting industries to relocate, and can also encourage companies to improve energy-saving technologies. However, loose environmental regulation is conducive to fulfilling the 'pollution haven' hypothesis. The attainmentrate of industrial waste water was selected to represent environmental regulation.

3.3.2 Empirical analysis

The specific regression results using the EViews software are shown in Table 2. Table 2 shows that economic development played a positive role in promoting industrial ecology. However, the square coefficient of the GDP per capita was significantly negative, which indicates that there was an inverted 'U-shape' relationship between industrial ecological and economic development in the restricted development zones of the Shandong Province, which at this stage was still on the left side of the inverted U-shaped curve. Both foreign investment and scientific and technological factors played a positive role in promoting industrial ecology, implying that there was no 'pollution haven' effect on industrial ecology development. Through the 'spillover effect', 'demonstration effect', and 'competition effect' of foreign capital and advanced technology, the input-output efficiency of resource elements in the restricted development zones can be improved.

From 2005 to 2017, the number of personnel engaged in key enterprises' scientific and technological activities per 10 000 inhabitants rose from 6 to 50. Scientific and technological factors played an important role in promoting the industrial ecology of the restricted development zones in the Shandong Province. However,

Table 2 Regression results of influencing factors of industrial ecology in restricted development zone of Shandong Province

Variable	Coefficient	*SE*	*z*-Statistic	*P*
ED	0.0086^{***}	0.0000	3.7079	0.0002
ED^2	-0.0002^{*}	0.0000	–1.9203	0.0548
IS	0.0031	0.0025	1.2575	0.2086
FI	0.0966^{***}	0.0193	5.0180	0.0000
TF	0.0317^{***}	0.0093	3.4254	0.0006
GA	-0.0032^{*}	0.0019	–1.6735	0.0942
EM	–0.0008	0.0012	–0.6851	0.4933
C	0.0460^{***}	0.0023	19.6081	0.0000

Note: *** means significance levels of 0.01; ** means significance levels of 0.05; * means significance levels of 0.1; *ED*, economic development; *IS*, industrial structure; *FI*, foreign investment; *TF*, scientific and technological; *GA*, government regulation; *EM*, environmental regulation the proportion of expenditure in scientific and technological education to GDP in the northwestern, southwestern, and eastern coastal regions of Shandong increased by 4.33%, 3.16%, and 4.29%, respectively. To a certain extent, the lack of scientific and technological investment in southwestern Shandong also caused the regional spatial differentiation of industrial ecology. Government regulatory factors played a negative role in restraining industrial ecology. Restricted development zones are vulnerable areas with a sharp conflict between socioeconomic development and environmental resources. Large-scale government regulation will cause rapid regional development, and may brought serious regional resource consumption and environmental pollution problems, thus hindering the improvement of industrial ecology.

Neither industrial structure factors nor environmental regulatory factors passed the statistical significance test. It was possible that the ratio of the added value of the secondary sector to the added value of the tertiary sector in the study area was declining from 2005 to 2014. In fact, a clean and service-oriented sector, the tertiary sector improved the industrial ecology level to a certain extent. However, this ratio increased from 2014 to 2017. The slow development of the tertiary sector hindered the improvement of the industrial ecology level. In the future, it will be necessary to further optimize the industrial structure and vigorously promote modern service industries. Driven by GDP performance, local governments often have a strong desire for regional development, but strong environmental regulations will restrict regional-scale expansion and development to a certain extent. Environmental regulatory factors did not pass the statistical significance tests, which also reflect the reciprocating characteristics of environmental regulatory factors in the study area.

Table 2 also shows that the industrial ecological development was typically foreign investment-driven. Economic development, industrial structure, science and technology, government regulation, and environmental regulatory factors had a small effect coefficient. It can be concluded that the improvement of industrial ecology in the study area requires a multi-dimensional and multi-channel sequential advancement. On the one hand, it is necessary to further optimize the industrial structure to achieve complementary advantages, resource sharing, and the integrated development of traditional and emerging industries. On the other hand, enhancing the regional scientific and technological development, formulating reasonable and scientific pollution supervision programs, and achieving a high-quality and low-consumption regional economic development is also an important way to improve the industrial ecology level.

4 Conclusions

(1) From 2005 to 2017, the industrial ecological level of the restricted development zones in the Shandong Province recorded an increase. The regional-scale analysis shows that the industrial ecological level was higher in the eastern coastal areas, followed by the northwestern Shandong and the southwestern Shandong. There were clear differences in the evolution characteristics of industrial ecology across regions. More into detail, the eastern coastal areas showed a ‘W-type’ development characteristic of ‘decrease-increase-decrease-increase’, while the northwestern Shandong presented an inverted ‘V-fall’, and the southwestern Shandong recorded a continuous increase.

(2) There was a relatively clear spatial dependence relationship in the restricted development zones of the Shandong Province during the study period. The industrial ecology level was close to the regional spatial agglomeration, and the spatial spillover effect was significant. On the whole, there was a clear pattern of spatial differentiation of industrial ecology in the study area, with higher levels in the north and in the east, and lower levels in the south and in the west. Moreover, its evolution pattern also evolved from a ‘three-core drive’ model in 2005 to a spatial cluster mosaic distribution in 2011 and to a single-core driving model in 2017.

(3) Economic development, foreign investment, and scientific and technological factors played a positive role in improving the industrial ecology; government regulatory factors played a negative role; and industrial structure and environmental regulatory factors did not pass the statistical significance test. In addition, the industrial ecological development had a typical foreign investment-driven characteristic. Economic development, industrial structure, science and technology, government regulation, and environmental regulatory factors had relatively small effect coefficients. In the future, measures should be adopted in the study area according

to local conditions, to enhance the multi-driving development effect of industrial ecology and improve the regional industrial ecology development.

Based on the obtained results, several policy implications can be proposed. The way to improve the quality of industrial ecology in restricted development zones needs to be advanced step by step considering multiple perspectives and scales. First, it is necessary that enterprises engage in clean production at the micro-scale, that Eco-Industrial Parks are constructed at the meso-scale, and that the development model is changed at the macro-scale. Second, the regional radiation effect of the eastern coastal areas should be further enhanced. Moreover, the integration and network development with the surrounding areas should be promoted. Third, the level of industrialization and urbanization in the southern Shandong and the southwest Shandong should be upgraded, and both industrial development and the spatial distribution should be optimized. At the same time, the competition and cooperation relationship between restricted development zones in the Shandong Province should be emphasized. The development from north to south should be promoted, and extended from east to west, to comprehensively improve the level of industrial ecology in the Shandong Province.

As the lifeblood of national economic development, the industrial system plays a leading role in maintaining the normal operation of various economic and social elements. The ecological system, as the material carrier for human survival and development, is the foundation for building a resource-saving and environmentally friendly society. This paper presented the results of a comprehensive study of the industrial and ecological systems of a restricted development zone with prominent human-land contradictions, using the adaptation research paradigm. Our results reveal the process-pattern-mechanism characteristics of the restricted development zone at the county level. However, due to limits in data acquisition, we only selected the key indicators representing the adaptive elements, and the evaluation index system should be further extended in the future. In addition, as the industrial ecology of restricted development zones is affected by the interaction of several factors, future studies should try to reveal the driving factors and mechanism of specific typical cases from a micro perspective.

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