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Original Research

Spatial-Temporal Characteristics and Obstacle Factors of Industry Ecology in the Lower Yellow River

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Abstract

Focusing on the implementation of the Yellow River strategy in the lower reaches of the Yellow River to achieve high-quality development of economy and ecological environment, we analyzed the spatial and temporal variation characteristics of the industrial ecological level in the lower reaches of the Yellow River from 2007 to 2020 and the main obstacle factors by using coupled coordination analysis and obstacle model. The results show that the level of industrial ecology in the lower reaches of the Yellow River has been increasing year by year during the study period, showing a trend of “decreasing first, then increasing”, and a slow increase in general, but the quality coordination still needs to be continued; there are significant differences in the level of industrial ecology in the lower reaches of the Yellow River cities, and the spatial pattern distribution shows There are significant differences in the level of industrial ecology in the lower Yellow River cities, and the distribution of spatial pattern shows the characteristics of “high in the middle and low on both sides” and “gradually decreasing from east to west”; the main obstacle factors affecting the development of industrial ecology come from the industrial system, such as the number of effective patents granted, the proportion of foreign investment in GDP, and the regional GDP growth rate have The main obstacles to the development of industrial ecology come from the industrial system. In this regard, it is proposed to reduce the energy consumption and pollution level of enterprises and improve the ability of resource recycling at the micro level; to optimize the industrial structure and layout at the macro level, to strengthen scientific and technological innovation, to enhance the level of economic opening to the outside world, and to realize the coordinated development of industry and ecosystem.

Keywords: industrial ecology, spatial and temporal characteristics, barrier factors, lower Yellow River

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Introduction

Since the ecological protection and high-quality development of the Yellow River Basin has been elevated to a major national strategy, how to promote the coordinated development of ecological environment and economy and society has become a realistic plan that provinces and regions within the Yellow River Basin need to focus on. The Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin clearly points out that the downstream areas should promote wetland protection and ecological management, build green ecological corridors, and promote the coordinated development of ecological protection and population and economy. It should be noted that the Yellow River basin is an important map for China's economic and social development, and also a key area where the contradiction between regional economic development and ecological environmental protection is more prominent [1]. In particular, after the rapid industrialization and urbanization of the lower reaches of the Yellow River, various difficult ecological and environmental problems such as water shortage, environmental pollution, and degradation of ecosystem functions have become real bottlenecks limiting the high-quality economic and social development, and it is urgent to change the development mindset and transform the development mode. On August 18, 2021, the Henan Provincial Government issued the "Henan Provincial People's Government on Accelerating the Establishment of a Sound Green The "Implementation Opinions of Henan Provincial People's Government on Accelerating the Establishment of a Sound Economic System of Green, Low-Carbon and Circular Development" has formulated a detailed plan for the province's economic and social green development. On September 02, 2022, the State Council issued the "Opinions on Supporting Shandong to Deepen the Conversion of New and Old Dynamic Energy to Promote Green, Low-Carbon and High-Quality Development" (Opinions), which pointed out that by 2027, Shandong will deepen the conversion of new and old dynamic energy to build a green, low-carbon and high-quality development pioneer area to achieve a major breakthrough, the digital transformation of industry will be fully advanced, and new technologies, new industries, new industries and new models will become the main driving force of economic development, etc., providing detailed guidance for Shandong Province to accelerate industrial restructuring and develop a green economy.

As we can see, the future high-quality economic development is bound to be coordinated with the ecological environment and to significantly reduce the stress on the resources and environment as the main direction. Industrial ecology is a research field arising from the cross-fertilization of economic and ecological systems. In 1989, scholars Frosch & Callopoulos put forward the concept of "industrial ecology" for the first time, placing traditional industries in the ecosystem. There are two definitions of industrial ecology by domestic scholars. In a narrow sense, it refers to the mode in which enterprises can save energy consumption and promote waste recycling by learning the theory related to ecosystems to guide the transmission and circulation of materials. In a broad sense, it refers to the coupling and optimization between industrial system, natural system and social system in a specific geographical space within the carrying capacity of natural system to achieve full utilization of resources, eliminate environmental damage and coordinate the sustainable development of nature, society and economy. Both definitions embody ecological protection, high-quality development, and resource coordination [2, 3]. Developing a green and low-carbon economy, changing the traditional industrial structure, and accelerating the development of industrial ecology are not only the inherent requirements for implementing the major national strategies of the Yellow River, but also the rich practice of developing the new development concepts of green, innovation, coordination, openness, and sharing. At present, the research on industrial ecology in the Yellow River basin is more extensive, and scholars have greatly enriched the theoretical system and economic practice of industrial ecology based on different perspectives. In general, the research is divided into the following aspects: firstly, from the perspective of industries including wine industry, tourism [4, 5], ethnic culture industry [6], and resource industry [7, 8], the characteristics, changes, problems, and realization paths of industrial ecology in related fields are explored. Secondly, we explore the integration path of rural development and industrial development from the perspective of rural revitalization [9, 10]; thirdly, we study the current situation [11], development trend, and optimization path of industrial ecology in each city and region [12–14]. Fourthly about the evaluation of industrial ecology, scholars mostly use dea neural envelope [15], entropy method [16], coupling model [17], and other methods, which have produced fruitful results.

Henan and Shandong provinces in the lower reaches of the Yellow River, as large provinces with mature industrialization and urbanization and strong economic growth momentum, are facing the dilemma of fragile ecological environment and resource constraints on the way to high-quality development, and the research on industrial ecology is based on the realistic demand of industrial economic development. The study of industrial ecological development level and distribution characteristics is of great significance for promoting industrial structure adjustment and industrial layout optimization in the lower reaches of the Yellow River, and is of practical significance for building advantageous industrial clusters, promoting the integrated development of the "Central Plains City Cluster" and the "Peninsula City Cluster", and promoting regional coordination. Therefore, based on the theoretical connotation of industrial ecology, this paper constructs a multi-level industrial ecology level assessment index system from industrial and ecological dimensions, and takes 16 cities along the Yellow River in Henan and Shandong provinces in the lower reaches of the Yellow River as research objects. The study aims to provide important reference information for top-level planning and planning of high-quality economic and industrial development.

Study Area Selection

The Yellow River originated from the Yoguzonglie Basin at the northern foot of the Bayan Har Mountains in the Qinghai Plateau, through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, Shandong, a total of nine provinces and regions. According to the map of the Yellow River Conservancy Commission of the Ministry of Water Resources on the Yellow River basin, it is known that the Yellow River is upstream from its origin to the mouth of the river in Toketo County, Inner Mongolia, midstream from the mouth to Taohuayu, and downstream from Taohuayu to Kenli, Shandong. Among them, the midstream section can be divided into three parts based on the characteristics of the river, namely Jin-Shaan Valley section, Fenwei Plain section and Sanmenxia to Taohuayu section. However, considering the coordinated development of the region and the unified layout of the Central Plains urban agglomeration, Sanmenxia and Luoyang in the middle reaches of Henan were included in the study area (a number of missing data from Jiyuan City affected the completeness of the study results, so they were excluded). So far, the study area was selected as 16 cities along the Yellow River in Henan and Shandong provinces, namely Zhengzhou, Kaifeng, Luoyang, Xinxiang, Jiaozuo, Puyang, Sanmenxia, Jinan, Zibo, Dongying, Jining, Tai'an, Dezhou, Liaocheng, Binzhou, and Heze, as shown in Fig 1.

Material and Methods

Data Sources and Processing

Most of the data used in this paper come from the 2008-2021 Statistical Yearbook of Henan Province and Shandong Province, the China City Statistical Yearbook, and the statistical yearbooks, statistical bulletins, and EPS DATA of each city. In addition, the starting year is 2007 because it is the year when the idea of ecological civilization is gradually developed. Among them, the annual CO_2 emissions data were obtained from the China Carbon Accounting Database (Carbon Emission Accounts & Datasets for emerging economies, CEADs), and the annual average PM2.5 data were obtained from the annual PM2.5 data with the accuracy of 0.01°×0.01° from the Atmospheric Composition Analysis Group of Dalhousie University, Canada, and processed by ArcGIS to obtain the annual average PM2.5 values of each city. For the missing data, we use Stata17 software to fill in the missing data after multiple comparisons by interpolation and trend extrapolation method.

Evaluation Method

Evaluation Indicator System Construction

Industrial ecology is the process of mutual integration and virtuous cycle between economic activities and natural ecosystem in the process of

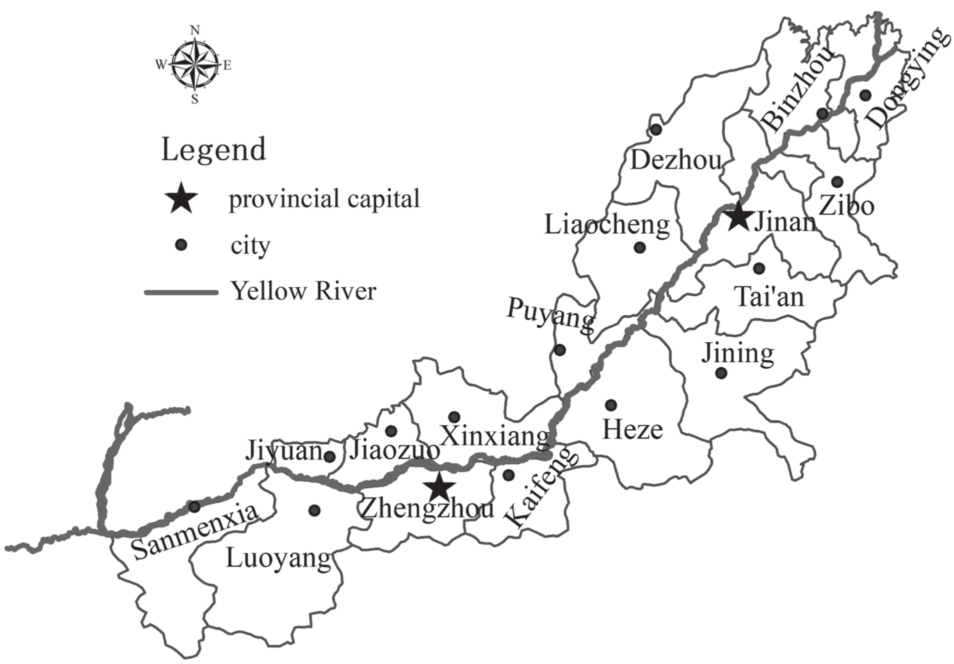

Fig. 1. Research area.

industrial development, and promoting resource-saving production technology, building resource-saving and environment-friendly industrial structure system, and promoting scientific and technological innovation are the inherent requirements of industrial ecology development [18]. In addition, industrial ecology does not mean slow and inefficient industrial economic development; on the contrary, high efficiency, green and high quality are also inevitable requirements in the process of industrial ecology. This requires that the evaluation of industrial ecology needs to build a complete and objective index system based on multiple levels from two dimensions: industrial economy and ecological environment. According to the principles of objectivity, scientificity, representativeness and data accessibility, a comprehensive evaluation index system of industrial ecological level is established based on a deep understanding of the scientific connotation of industrial ecology, including two dimensions of industrial economy and ecological environment, including development scale, scientific and technological innovation, reasonable structure, open trade, energy consumption, green production, resource recycling and environmental friendliness. 16 indicators, as shown in Table 1.

Industrial economy dimension, first of all, we need to consider the scale of development, high-quality economic development is the development of quality and efficiency at the same time, only the scale of development continues to grow to support the continuation of high quality. Therefore, the regional GDP growth rate and the total value added of secondary and tertiary industries are selected as representative indicators for measurement respectively. Secondly, science and technology innovation is a necessary path in the process of industrial economy development, and strengthening investment in science and technology innovation and transformation of scientific and technological achievements is not only beneficial to the industrial economy towards high-end, but also to enhance the core competitiveness in the globalized industrial division of labor, so we use The intensity of R&D investment and the number of effective patents granted are the two indicators. Again, optimizing industrial structure, adjusting industrial layout, and gradually eliminating and upgrading resource-dependent industries are the inevitable trends of industrial economy towards high quality and high efficiency, so it is more appropriate to consider the index of rationalization of industrial structure (Thiel index) [19] and index of advanced industrial structure [20]. Finally, the strengthening of economic openness in the global industrial division of labor system is conducive to enhancing the vitality of industrial and economic growth, as well as to globalization and internationalization, and the proportion of foreign

Table 1. Industrial ecology level evaluation index system.

Target layer	Program layer	Criteria layer	Indicator layer	Code	Attribute	Weights
Industrial ecology	Industrial economic system (IS)	Scale of development	Regional GDP growth rate/%	x1	+	0.0412
			Total added value of secondary and tertiary industries/billion yuan	x2	+	0.1194
		Science and technology innovation	R&D investment intensity/%	x3	+	0.2484
			Number of effective patents granted/piece	x4	+	0.0579
		Reasonable structure	Industrial structure Rationalization index	x5	-	0.0248
			Index of advanced industrial structure	x6	+	0.0279
		Open trade	Foreign investment in GDP/%	x7	+	0.1383
			Total imports and exports as a proportion of GDP/%	x8	+	0.1726
	Ecological system (ES)	Energy Consumption	Energy consumption per ten thousand yuan GDP / ton. ten thousand yuan	x9	-	0.0197
			Electricity consumption per ten thousand yuan GDP / million yuan. Kilowatt-hour	x10	-	0.0086
		Green Production	Industrial wastewater emissions / million tons	x11	-	0.0375
			Industrial sulfur dioxide emissions / million tons	x12	-	0.0153
		Resource Recycling	General industrial solid waste comprehensive utilization rate / %	x13	+	0.0166
			Harmless treatment rate of domestic waste/%	x14	+	0.0065
		Environmentally friendly	CO_2 annual emission/million tons	x15	-	0.0120
			Annual average value of PM2.5 ug/m^3	x16	-	0.0533

investment in GDP and the proportion of total import and export in GDP are chosen as representative indicators for evaluation. Ecological environment dimension, comprehensive consideration of the whole process of economic production activities. First, the energy consumption and electricity consumption of ten thousand yuan GDP are used to consider the degree of energy consumption in the process of industrial economy, and industrial wastewater and industrial sulfur dioxide emissions are selected as the reverse indicators to evaluate the level of green production in the process of industrial development. Secondly, if the waste materials generated in the process of economic activities cannot be recycled and used as useful materials in production and life, they will flow into the ecological environment system to produce problems such as soil cadmium pollution and form great hidden dangers to human beings. Therefore, the comprehensive utilization rate of general industrial solid waste and the harmless treatment rate of domestic waste are selected to reflect the level of resource recycling in the process of industrial development. Finally, industrial ecology aims at the coordinated development of economic society and ecological environment, and the development of low-carbon green economy is the main way, which requires the process of economic production activities to minimize the degree of environmental stress and develop an environmentally friendly economy, therefore, two indicators of CO_2 annual emissions and PM2.5 annual average value are selected for consideration.

Entropy Weight TOPSIS Method

Among the multi-objective comprehensive evaluation and decision-making methods, the entropy-weighted TOPSIS method is a comprehensive evaluation method using the modified TOPSIS model combined with the entropy-weighted method, which has the advantages of strong objectivity and maturity, and can effectively avoid errors caused by subjective factors and complicated index information, and is widely used in many fields of economics, management, ecology and other research. The basic idea of entropy TOPSIS method is to first construct the original data matrix and adopt the polarization method for standardization, and the standardization formula is as follows: the positive indicator is $x_{ij} = (X_{ij} - X_{ij}^{min})/(X_{ij}^{max} - X_{ij}^{min})$, the negative indicator is $x_{ij} = (X_{ij}^{max} - X_{ij})/(X_{ij}^{max} - X_{ij}^{min})$, x_{ij}, X_{ij}, X_{ij}^{max}, X_{ij}^{min} represent the standardized value, original value, maximum value, and minimum value of the *j*th index, respectively. Secondly, weights are calculated based on the coefficient of variation of each index. Finally, the weighted normalization matrix is constructed according to the indicator weights, the positive and negative ideal solutions are determined, the euclidean distance and the closeness are calculated, and the score of each system in each evaluation year is represented by the closeness progress, and the larger the value indicates the higher level of each system, and the specific calculation formula and steps are detailed in references [21-23].

Coupled Coordination Method

Industrial ecology is the process of integrating industrial system into ecological environment system, forming a virtuous cycle with natural ecological system and then interacting with each other. Therefore, according to the connotation of coordinated development between industry and ecological environment system, the coupled coordination analysis method is introduced to measure the development change of industrial ecology level by the coupled coordination degree between industrial economy and ecological environment. Drawing on relevant research results [12, 24], the calculation formula is defined as follows:

$$\begin{cases} C = \dfrac{(IS \times ES)^k}{(aIS + bES)^{2k}} \\ D = \left[C \times (aIS + bES)\right]^{\frac{1}{2}} \end{cases} \tag{1}$$

In the above equation, *IS* and *ES* represent the industrial economic system and ecological environment system respectively, *C* represents the coupling degree between the two systems, *D* is the coupling coordination degree which is the level of industrial ecology, *a, b, k* are the corresponding parameters, *k* generally takes the value of 5, $a + b = 1$, but in view of the same importance of industrial economic system and ecological environment system, so in this paper, *a* and *b* are assigned the value of 0.5, and the coordination degree is divided into 10 levels (see Table 2) [25, 26].

Table 2. Classification of industry-ecosystem coupling and coordination level.

Coupling coordination	Status	Type	Coupling coordination	Status	Type
0<D≤0.1	Extreme disorder	I	0.5<D≤0.6	Barely coordinated	VI
0.1<D≤0.2	Severe disorder	II	0.6<D≤0.7	Primary coordination	VII
0.2<D≤0.3	Moderate disorder	III	0.7<D≤0.8	Intermediate coordination	VIII
0.3<D≤0.4	Mild disorder	IV	0.8<D≤0.9	Good coordination	IX
0.4<D≤0.5	Nearly dysfunctional	V	0.9<D≤1.0	Quality coordination	X

Barrier Factor Analysis Method

After using the coupling coordination degree to evaluate the evolution of the level of industrial ecology, it is necessary to understand the size of the barriers of each indicator to the development of the coupling coordination degree changes, in order to clarify the key powering points of the level of industrial ecology. For this purpose, the barrier degree model identification is introduced, and the model is defined according to relevant studies as [27–29]:

$$O_{ij} = \frac{\left(1 - x_{ij}\right) \times w_j \times 100\%}{\sum\left(1 - x_{ij}\right) \times w_j} \tag{2}$$

Where O_{ij} denotes the degree of obstacle of single indicator i to the level of industrial ecology, and x_{ij}, w_j denote the standardized values of individual indicators and weights.

Results and Discussion

Overall Characteristics of the Temporal Evolution of the Ecological Level of Industries in the Lower Yellow River

Based on the industrial system, ecosystem, coupling degree and coupling coordination degree of the lower Yellow River cities, which is the level of industrial ecology, the overall characteristics of the temporal evolution of the level of industrial ecology in the lower Yellow River are plotted (Fig. 2). From 2007 to 2020, the overall level of industrial ecology in the lower reaches of the Yellow River basin shows a trend of "decreasing first, then increasing", and the overall trend is slowly increasing, from 0.2560 in 2007 to 0.3497 in 2020. The average annual increase is 2.62%. The coupling degree between the two systems shows a small increase, from 0.2787 to 0.3011 after three "up-downs" during the study period, with a relatively small average annual increase of 0.57%. Among them, the first 2 huge changes were from 2007-2011 and 2011-2015, reaching a maximum value of 0.3519 in 2015, which on the whole is more consistent with the fluctuating trend of the level of industrial ecology. The industrial system and ecosystem are the most outstanding, both of which have increased rapidly at a high rate during the study period. Among them, the industrial system score increased rapidly from 0.1394 to 0.2645, with an average annual increase of 6.41%, while the ecosystem increased from 0.4270 to 0.7303, with an average annual increase of 5.07%, indicating that while the lower reaches of the Yellow River Basin are striving to develop various industries to promote rapid economic growth, the ecosystem system has not been abandoned, but focuses on the improvement of the quality of natural ecological environment. The improvement of natural ecological environment quality.

On the whole, the ecological level of industries in the lower Yellow River basin has increased year by year, which reflects the continuous promotion of ecological civilization construction and the deepening of ecological civilization thought, and the benign coordination between industrial development and natural ecological environment has been strengthened gradually, but the analysis of the specific coupling coordination status between the two systems in combination with Table 2 shows that the coordination type has been alternating between III and IV during the study period, and the coordination status has been moderate and Mild disorder, indicating that the development of industry

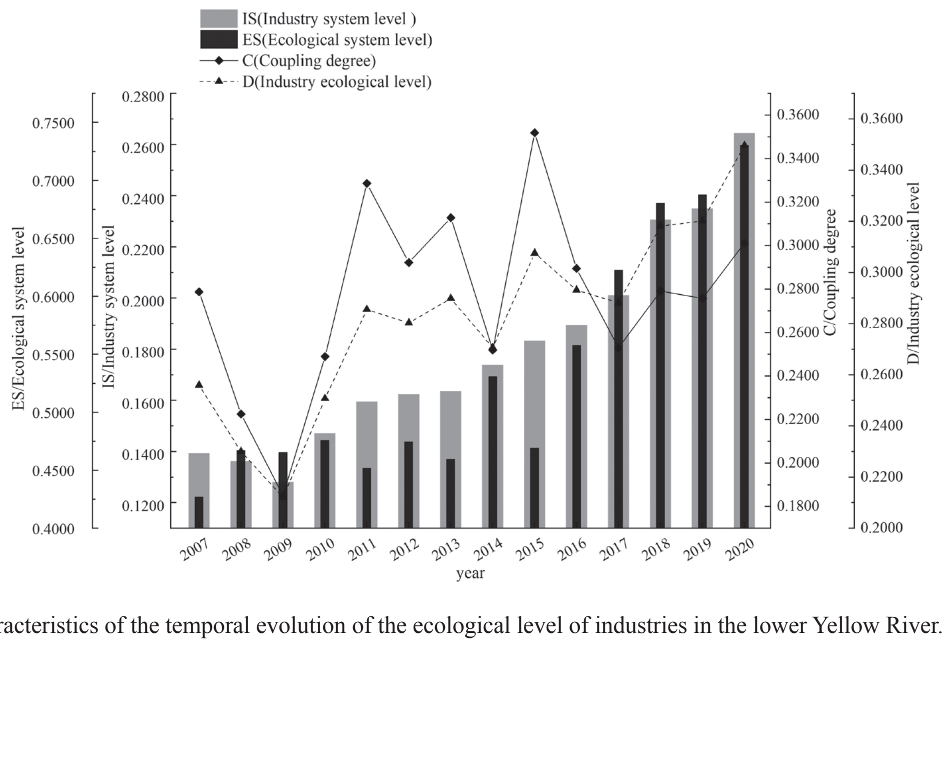

Fig. 2. Overall characteristics of the temporal evolution of the ecological level of industries in the lower Yellow River.

and ecological environment system needs to be improved and improved, and the development towards good and high-quality coordinated transformation still needs to be continued.

Spatial Characteristics of the Level of Industrial Ecology in the Lower Yellow River

Table 3 shows the detailed development evolution of industrial ecology level of cities in the lower reaches of the Yellow River from 2007 to 2020, and it can be seen that the industrial ecology level of most of the cities improved rapidly during the study period, and only three cities, Kaifeng, Jiaozuo and Puyang, showed a decreasing trend, reflecting that some regions will pay less attention to the ecological environment while pursuing rapid economic growth It is necessary to further change the thinking of economic growth and optimize the industrial development. In addition, among the 16 cities in the lower reaches of the Yellow River, Zhengzhou and Jinan as the regional capital cities have also played a leading role in the demonstration. Zhengzhou has increased from 0.3361 in 2007 to 0.8519 in 2020, with an average annual increase of 10.96%, becoming the No. 1 city in the lower reaches of the Yellow River, while Jinan has increased by 7.78% annually, and is No. 2 with 0.7589.

According to the analysis of the spatial characteristics of the industrial ecology of the lower Yellow River cities during the study period (Fig. 3), the industrial ecology level of 16 cities varied significantly during the first period from 2007 to 2011, and could be divided into 4 echelons in general, the first echelon being Zibo, Binzhou and Jinan, whose industrial ecology level was significantly higher than the rest of the cities, representing The first echelon is Zibo, Binzhou and Jinan, whose industrial ecology level is significantly higher than the rest of the cities, representing the highest level of cities in the lower reaches of the Yellow River. The second echelon is Zhengzhou, Liaocheng, Dongying and Jining, which have a strong economic foundation and also bear the important responsibility of protecting the ecological environment. The third tier is Xinxiang, Jiaozuo, Tai'an, Dezhou, Heze, and Luoyang, which have rapid industrial development but need to improve the quality of ecological environment. The fourth echelon is Sanmenxia, Puyang and Kaifeng, which urgently need to develop a green economy and reduce the negative effects of rapid industrial development; in the second period from 2012 to 2016, Jinan and Zhengzhou, as provincial capital cities, had to play an exemplary leading role in economic development and ecological environment management, so they continued to promote the virtuous cycle of industry and ecosystem and gradually developed The first echelon, followed by Zibo, Dongying, Jining, Liaocheng and Binzhou, with only a slight gap between them in the second echelon; the third echelon includes Xinxiang, Tai'an, Heze, Luoyang, Dezhou and Jiaozuo; Puyang, Kaifeng and Sanmenxia belong to the fourth echelon because of the large gap with the rest of the cities; in the third period (2017-2020), Zhengzhou and Jinan still In the third period (2017-2020), Zhengzhou and Jinan are still in the first echelon, while Dongying is in the first echelon because of its rich resources and natural ecosystem has not been seriously damaged, and the wetland restoration project has been effective for many years, which makes the relationship between industry and ecosystem more coordinated, Binzhou, Zibo, Jining, Xinxiang, Liaocheng and Luoyang are in the second echelon, Dezhou, Heze, Tai'an and Jiaozuo are in the third echelon because of their poor performance, Sanmenxia, Puyang and Kaifeng are still in the fourth echelon due to their relatively slow economic development and not yet in harmony with the natural ecosystem. In conclusion, there are significant differences in the level of industrial ecology in the lower reaches of the Yellow River, and there are certain patterns in the distribution of spatial patterns, with Henan Province and Shandong Province showing the characteristics of "high in the middle and low on both sides" and "gradually decreasing from east to west" respectively. In addition, the coordinated development of provincial capitals in urban clusters not only promotes the industrial development of neighboring cities, but also promotes some cooperative governance in the field of ecology and environment, which is important for the improvement of industrial ecology level.

Evolutionary Characteristics of the Ecological Level of Urban Industries

In order to further analyze the spatial variability characteristics of the industrial ecology of cities in the lower reaches of the Yellow River and grasp the regular distribution between regions and areas, ArcGIS10.7 was used to visualize the industrial ecology levels of cities in 2007, 2013 and 2020 and analyze the spatial variability of urban industrial ecology levels by combining the division of coordination levels in Table 2, the specific results are shown in Fig. 4. The distribution pattern of industrial ecological level among cities is obviously different, and the overall pattern is decreasing from east to west, and the industrial ecological level of cities in the eastern region is significantly higher than that in the western region, and the industrial ecological level of cities in the western region is improving slowly. In addition, the spatial spillover effect of the provincial capital cities is well played in the province, showing the distribution characteristics of "high in the middle and low on both sides".

In 2007, most of the cities along the Yellow River in Henan Province were in serious and moderate disorders, and no city reached the coordinated level, while only Zhengzhou, the capital city of Henan Province, performed better and was in a mild disorder. On the contrary, four cities in Shandong Province have a high level of coordination and are in mild,

Table 3. Levels of industrial ecology in lower Yellow River cities.

City/year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Zhengzhou	0.3361	0.2841	0.2877	0.3371	0.4518	0.4839	0.5073	0.6474	0.6255	0.7097	0.7298	0.7837	0.7903	0.8519
Kaifeng	0.0771	0.0658	0.0696	0.0680	0.1119	0.1011	0.1408	0.0996	0.0999	0.0619	0.0713	0.0767	0.0768	0.0731
Luoyang	0.1626	0.1404	0.1501	0.1659	0.2151	0.2129	0.1924	0.1932	0.2225	0.2117	0.2229	0.2502	0.2600	0.2945
Xinxiang	0.2669	0.2025	0.1958	0.2085	0.2540	0.2349	0.2418	0.2779	0.2968	0.2247	0.2135	0.5488	0.2283	0.2696
Jiaozuo	0.2878	0.1898	0.1930	0.2007	0.2258	0.2075	0.1973	0.1859	0.2072	0.1782	0.1660	0.1754	0.1666	0.1849
Puyang	0.1425	0.0900	0.0777	0.0796	0.0920	0.1042	0.1518	0.1150	0.1304	0.1024	0.0876	0.0693	0.0985	0.0869
Sanmenxia	0.1421	0.0949	0.0761	0.1021	0.1170	0.1118	0.0914	0.0960	0.0928	0.1063	0.1143	0.1179	0.1606	0.1672
Jinan	0.3633	0.3965	0.3498	0.4118	0.4713	0.4961	0.4807	0.4400	0.5388	0.5237	0.5339	0.5611	0.6383	0.7589
Zibo	0.4182	0.3925	0.3645	0.4150	0.4421	0.4315	0.4080	0.3618	0.4130	0.3650	0.3637	0.4069	0.4109	0.4330
Dongying	0.2248	0.2476	0.2547	0.3543	0.3766	0.3973	0.4088	0.3842	0.4161	0.4399	0.4597	0.4584	0.5813	0.5280
Jining	0.2982	0.2742	0.2476	0.3180	0.3310	0.3313	0.3329	0.2840	0.3734	0.3235	0.3099	0.3073	0.2922	0.3850
Tai’an	0.1981	0.1677	0.1800	0.1843	0.1963	0.2252	0.2452	0.2264	0.2766	0.2386	0.2159	0.1787	0.1883	0.2059
Dezhou	0.2425	0.2099	0.1953	0.2169	0.1846	0.1897	0.2241	0.1901	0.2114	0.1928	0.1767	0.1863	0.2384	0.2910
Liaocheng	0.3199	0.3557	0.2771	0.3499	0.4346	0.3317	0.3357	0.2838	0.3012	0.2953	0.2824	0.2445	0.2636	0.3156
Binzhou	0.4206	0.4227	0.3257	0.4071	0.4475	0.4122	0.4497	0.3718	0.4721	0.4789	0.4548	0.4770	0.5162	0.5296
Heze	0.1947	0.1464	0.1483	0.1923	0.2173	0.2136	0.2297	0.1732	0.2440	0.2374	0.2085	0.2484	0.2133	0.2203

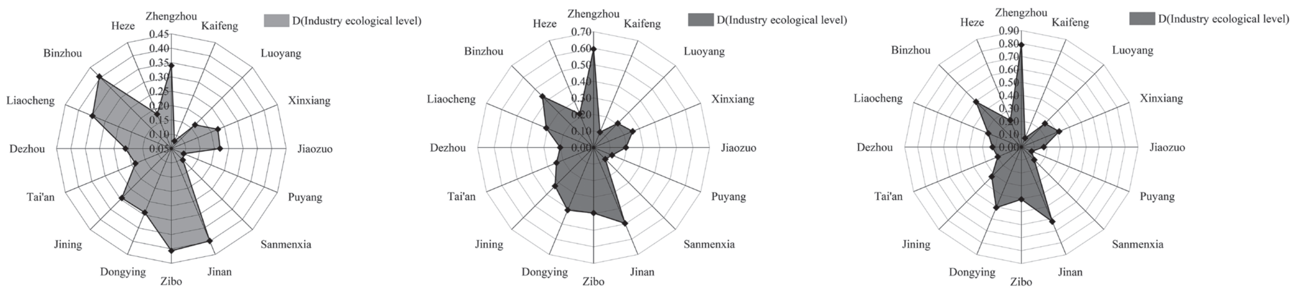

Fig. 3. Spatial characteristics of industrial ecology in the lower Yellow River cities.

on the verge of disorder, but the performance of Jinan, the provincial capital city, is not in the first place, perhaps because Jinan city has a strong economic foundation and bears the important task of promoting the common development of the regional economy, so the development of the industrial system has become a top priority; observing 2013, it can be seen that the level of industrial ecology in Zhengzhou City, Henan Province, has significantly improved towards the primary In 2020, the number of cities in coordination in Shandong Province is 3 and 1 in Henan Province, which also reflects that Henan Province still needs to coordinate the relationship between industrial development and ecological environment. strengthen. From the perspective of urban clusters, cities in the lower reaches of the Yellow River are experiencing a gradual deepening of regional integrated development, in which the proportion of extremely and severely dysfunctional cities decreases from 37.50% in 2007 to 25.00% in 2020, indicating that the development trend of industrial ecological level is gradually improving, but also reflecting that the level of urban industrial ecological has relative stability and there is a sacrifice of ecological environment in exchange, However, it also reflects that the ecological level of urban industry is relatively stable, and there is a possibility of sacrificing ecological environment for the development of high-efficiency and high-value-added industries. In addition, the spatial distribution pattern of industrial ecological level of provincial capital cities and neighboring cities also shows that the spatial spillover effect is limited when it is bound by administrative division barriers, and it cannot drive the coordinated development of industry and ecosystem of other cities in the region.

Analysis of Barriers to Industrial Ecology

According to the barrier degree model to measure the barrier degree of each single indicator for the level of industrial ecology, in order to identify the main barrier factors affecting the level of industrial ecology in the lower reaches of the Yellow River cities in 2007, 2013 and 2020, the calculation results of the top 5 barrier factors and obstacle degree(O) in 2020 are used as an example for analysis, and the results are shown in Table 4. observing Table 4, it can be seen that most of the barrier factors belong to the indicators of industrial economic system, accounting for 98.75%, and the indicators of ecosystem account for 1.25%, reflecting that the industrial economic system is still the main aspect that restricts the level of industrial ecology in each city, and how to get rid of the resource dependence in the process of industrial

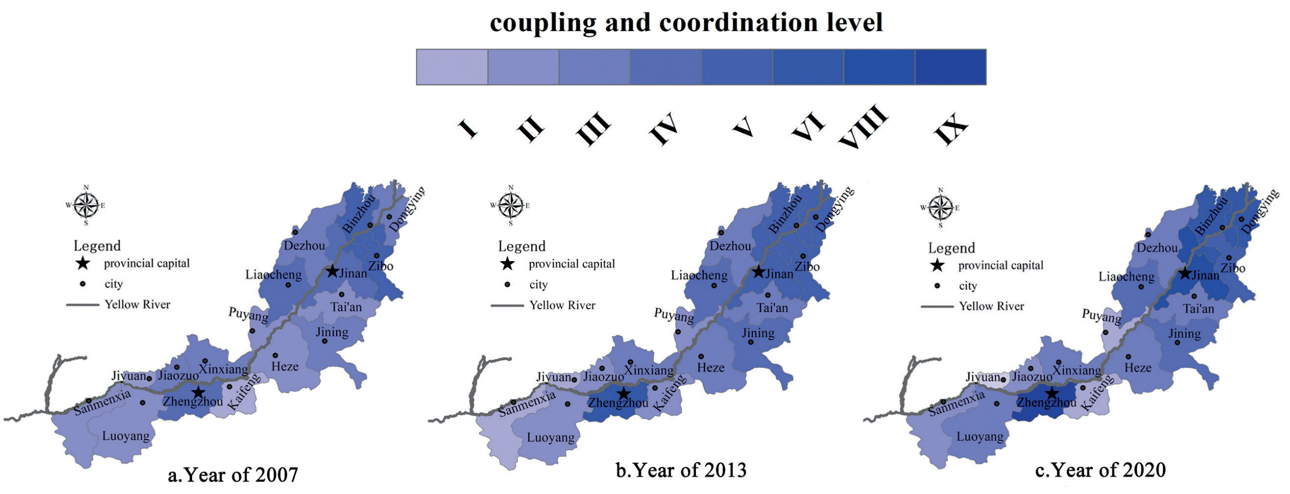

Fig. 4. Evolutionary characteristics of the ecological level of urban industries.

development and develop green and low-carbon industrial economy is a major development problem faced at present. Analyzing the primary obstacle factors of each city, it is found that the number of effective patents authorized (x3) with 87.50% of the index is the most important influence factor affecting the level of industrial ecology in the lower Yellow River cities, and the proportion of foreign investment in GDP (x7) and total import and export in GDP (x8) are the biggest factors restricting the provincial capital cities Zhengzhou and Jinan, indicating that strengthening scientific and technological innovation, promoting scientific and technological research and development results transformation, and increasing the pulling power of high-tech industries to economic growth are crucial for most cities to enhance industrial ecology, while provincial capitals need to pay more attention to the level of openness in the division of labor in the global industrial chain and expand the influence of the industrial system in global trade. In addition, among the top 5 barrier factors, regional GDP growth rate (x1) and total value added of secondary and tertiary industries (x2) appear several times with 16.25% and 18.75% respectively, which also indicates that the development scale size of industrial economy plays a certain supporting role for the coordinated and benign development of industrial system and ecosystem, after all, economic foundation is fundamental to determine all the rest activities.

Discussion

Industrial ecology is an inevitable stage of economic development to a certain period, and is an inevitable demand of human society when facing a series of ecological and environmental problems such as global resource depletion, ecosystem degradation and global warming [30], and is also an inherent requirement of the current Yellow River strategy for the high-quality development of the lower reaches of the Yellow River. The development of industrial ecology is a huge project of systemic and complexity, which requires the joint action of multiple factors in multiple dimensions. It requires not only microscopic industrial development process to reduce the energy consumption and pollution level of enterprises and improve the ability of resource recycling, but also macroscopic industrial structure adjustment and layout optimization. At present, the Yellow River Strategy has pointed out the direction and path of high-quality economic development for the lower reaches of the Yellow River. Vigorously developing a green and low-carbon economy, promoting a significant improvement in the quality of the ecological environment, and improving the level of industrial ecology are the challenges that must be solved for future cities in the lower reaches of the Yellow River to move toward high-quality development, and require more in-depth research.

Table 4. Identification of barriers to the level of industrial ecology in the lower Yellow River cities in 2020.

City	1		2		3		4		5	
	Indicators	O	Indicators	O	Indicators	O	Indicators	O	Indicators	O
Zhengzhou	x7	47.2311	x8	17.9400	x1	14.8788	x4	7.6096	x16	5.6454
Kaifeng	x3	30.6812	x8	21.5718	x7	16.1135	x2	13.4822	x1	5.2561
Luoyang	x3	31.5864	x8	26.3316	x7	17.8582	x2	11.8748	x1	6.1609
Xinxiang	x3	28.2555	x8	23.3825	x7	16.8950	x2	13.6996	x1	5.3444
Jiaozuo	x3	32.1894	x8	21.9049	x7	16.7709	x2	14.7888	x4	3.8122
Puyang	x3	31.6192	x8	20.8922	x7	15.6178	x2	14.5197	x4	5.3570
Sanmenxia	x3	35.3362	x8	19.6899	x2	16.0095	x7	14.1727	x1	5.4407
Jinan	x8	31.3512	x7	30.9620	x3	11.0488	x1	7.9420	x2	5.1608
Zibo	x3	31.5853	x7	21.5141	x8	15.8389	x2	13.9978	x1	6.2522
Dongying	x3	37.4384	x7	22.9892	x2	16.4757	x1	6.2494	x8	5.9109
Jining	x3	26.8615	x8	19.8874	x7	19.0659	x2	12.0711	x1	5.3317
Tai’an	x3	30.7401	x8	21.2803	x7	18.0653	x2	13.9610	x1	5.2132
Dezhou	x3	31.0279	x7	20.1190	x8	20.0683	x2	14.2060	x1	5.4352
Liaocheng	x3	30.4274	x7	19.2363	x8	17.0892	x2	14.7496	x1	5.4611
Binzhou	x3	33.0763	x7	20.5702	x2	15.6251	x8	11.3173	x1	5.6368
Heze	x3	29.0839	x8	18.6518	x7	18.6488	x2	12.5964	x4	6.6598

Conclusions

Focusing on the harmonious development of industrial system and ecological environment system, based on the coupled coordination model and barrier degree model, the evaluation index system of industrial ecological level is constructed to scientifically assess the level of industrial ecological level and barrier factors in the lower reaches of the Yellow River cities in the context of the implementation of the Yellow River Strategy, and the following conclusions are drawn.

(1) The level of industrial ecology in the lower reaches of the Yellow River has been increasing year by year, showing the trend of "decreasing first, then increasing" and a slow increase in general, indicating that the industrial system and the ecological environment system are developing in the direction of a harmonious and virtuous cycle, but there is still a need to continue to work towards quality coordination. In addition, the trend also reflects that with the deepening of ecological civilization, it has become a consensus to reduce the intensity of environmental stress in the process of industrial development and protect the ecological environment.

(2) There are significant differences in the level of industrial ecology in the lower reaches of the Yellow River, and there is a certain pattern in the distribution of spatial pattern, with Henan Province and Shandong Province showing the characteristics of "high in the middle and low on both sides" and "gradually decreasing from east to west". The spatial spillover effect of the provincial capital cities, represented by Zhengzhou and Jinan, in the process of coordinated development of urban agglomerations is also limited when they are bound by administrative barriers, and their effectiveness in promoting the coordinated development of industries and ecosystems is low for the rest of the cities in the region. The evolution of industrial ecological level in some cities reflects the relative stability of industrial ecology and the possibility of sacrificing ecological environment for the development of high economic efficiency industries in some areas.

(3) The results of barrier factor identification show that the industrial system is the main dimension affecting the development of industrial ecology in the lower reaches of the Yellow River cities. The number of effective patents granted, the proportion of foreign investment in GDP, the proportion of total import and export in GDP, the regional GDP growth rate, and the total value added of secondary and tertiary industries have the greatest influence on the scores of industrial ecology level in the lower reaches of the Yellow River cities, indicating that scientific and technological innovation and improving high-tech industry's ability to pulling capacity of economic growth, improving the level of economic openness, and promoting further development of economic scale and quality are particularly important for improving the level of industrial ecology.

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Conflict of Interest

The authors declare no conflict of interest.

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