

Original Research

Coupling Evolution and Spatial-Temporal Variation of Industrial Development and Ecological Efficiency under Undesirable Output Constraint

Guisheng Zhang¹, Yanna Zhu^{1,2*}, Gang He², Qingyi Tu¹

¹State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Huainan, Anhui, 232001, China

²College of Economy and Management, Anhui University of Science and Technology, Huainan, Anhui, 232001, China

Received: 8 September 2021

Accepted: 20 January 2022

Abstract

Promoting industrial ecology and greening is the fundamental requirement of the new development concept, and also the key to realizing high-quality and sustainable development of regional economy. This paper selects the relevant data of eight cities in Anhui section of Huaihe River Economic Belt from 2014 to 2018, and uses the entropy method and the undesirable SBM model to calculate the industrial development level and ecological efficiency during the study period. Moreover, based on the coupling coordination degree model, the synergistic effect between industrial development and ecological efficiency is analyzed, and the spatial-temporal evolution pattern between them is clarified by means of spatial econometric analysis model. Further research suggests that: (1) the synergistic effect between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt from 2014 to 2018 is significant, showing a steady strengthening trend. The endogenous power of industrial development keeps strengthening, and the scale effect keeps spillover diffusion. The mean value of overall coupling coordination degree is generally between 0.6 and 0.7. (2) In terms of spatial distribution, the regions with high coupling coordination degree are mainly distributed in the eastern part of Anhui Section (Bengbu and Chuzhou), the lower level area is mainly distributed in the northern part of Anhui Section (Suzhou), and the middle level area is widely distributed. (3) The agglomeration of coupling coordination degree between industrial development and ecological efficiency mainly occurs in low-high (L-H) and high-low (H-L) agglomeration areas. (4) The level of economic development, intensity of R&D and intensity of environmental regulation have significant positive effects on the coupling coordination degree of industrial ecological efficiency and industrial development, and promote the increase of coupling coordination effect. Finally, based on the research results,

*e-mail: ynzhu001@163.com

targeted suggestions are put forward in order to promote the coupling coordination between industrial development and ecological civilization construction, and walk out of a new road of high-quality development of green ecology.

Keywords: sustainable development, ecological efficiency, industrial development, coupling coordination, spatial autocorrelation

Introduction

Good ecological environment is the fairest public product and the most practical well-being of the people's livelihood [1]. Deepening the understanding of ecological environmental protection and promoting the construction of ecological civilization are also the inevitable requirements for the transformation of China's economic development from high-speed growth to high-quality growth. This change puts forward new ideas for industrial development and regional ecological protection. Huaihe River Economic Belt is located in the heart of China. With the continuous progress of industrialization of Huaihe River Economic Belt, the industrial development characteristics of high emission, high energy consumption and high pollution have lead to the depletion of resources and energy and the destruction of ecological environment in this region, which has become an important obstacle to the high-quality industrial development [2]. How to effectively promote the mutualism and highly integration of industrialization and ecological environment of the Huaihe River Economic Belt, strengthen regional cooperation, and comprehensively promote the green transformation of production and life style, has become the most critical "stick" to achieve high-quality development in the Huaihe River Economic Belt [3]. It is of great theoretical and practical significance to scientifically analyze the relationship between industrial development, resource consumption and pollution emission of Huaihe River Economic Belt and clarify the main influencing factors, so as to promote the green transformation and high-quality development of industry in the Huaihe River Economic Belt.

The research on industrial development mainly focuses on the measurement of industrial development level, the measurement of industrial efficiency and the test of its influencing factors [4]. For the evaluation of industrial development level and efficiency, many scholars put it into the category of sustainable development. Lourenco pointed out that unsustainability may be related to population growth and excessive consumption of natural resources [5]. Demiral implemented radial and non-radial Data Envelopment Analysis (DEA) models to assess eco-efficiency and eco-productivity of the 50 states in the United States in 2018. He found that the states' eco-productivity is relatively higher than the eco-efficiency levels. States with low carbon dioxide emissions had significantly higher eco-efficiency and eco-productivity levels [6]. Cortes focused on the application of LCA

+ DEA methodology to assess the eco-efficiency of 38 semi intensive shrimp farms located in the state of Sonora. The results showed that feed management and electricity consumption are the main critical points to eco-efficiency [7]. Shi constructed a comprehensive evaluation model considering the time trend, and the analysis showed that the overall level of industrial development in China is fluctuating upward trend [8]. Zhang used entropy method to measure the comprehensive level of industrial development in counties, and the results showed that the industrial development level of central urban areas in Jilin Province is significantly higher than that of surrounding county units [9]. Wang comprehensively applied Super-SBM model and Panel Tobit regression model to explore the spatial-temporal evolution characteristics and influencing factors of tourism ecological efficiency in the Yangtze River Economic Belt from 2007 to 2016 [10].

Aiming at these problems existing in research, scholars used different econometric models to empirically analyze the efficiency of industrial development efficiency and industrial ecological efficiency. Shi used entropy-weight TOPSIS and undesired output slacks-based model (SBM) to conduct empirical analysis on the industrial development level and efficiency in Inner Mongolia from 2010 to 2016, and on this basis studied the coordination degree of industrial development performance by using coupling coordination degree model [11]. Wu used the entropy-weight TOPSIS method to evaluate the industrial development level of the Yangtze River Economic Belt from 2011 to 2015, utilized the undesired output global SBM model to measure the industrial development efficiency, and analyzed the synergistic effect of industrial development level and efficiency based on the coupling coordination degree model [12].

Among them, scholars put emphasis on principal component analysis, factor analysis and entropy weight method when evaluating the level of industrial development [13-14], and they applied DEA-Malmquist, super-efficiency DEA model, input-output method combined with DEA method when measuring industrial ecological efficiency [15-17].

In the light of the existing research, the main research perspective of industrial ecological efficiency could be got. Huang and Ding used the super-efficiency SBM involving undesirable output to calculate the ecological efficiency of 30 provinces in China from 2008 to 2017, they found that there is in fact a threshold effect of technological innovation

and industrial-structure upgrading on ecological efficiency due to the mismatch of periods [18]. Based on the super-efficiency DEA model, Song evaluated the industrial ecological efficiency of cities in the Yellow River Basin from 2008 to 2017. The research results showed that the industrial ecological efficiency (IEE) exhibited an elongated S-shaped evolutionary trend [19]. By using the SBM-DEA model, the Malmquist-Luenberger (ML) index, and the spatial Durbin model (SDM) under different weight matrices, Zhang explored the spatial pattern of ecological efficiency [20]. Zhang applied the weight super data envelopment analysis and slacks-based measure considering undesirable outputs (W-S-DEA-SBM-UO) to evaluate the ecological efficiency of industrial enterprises [21]. Wu used interprovincial panel data from 2012 to 2016 to calculate and analyze the industrial ecological efficiency of 31 provinces in China, and then discussed the factors that influence efficiency [22]. Liu collected and processed the data of industrial production system in a unified dimension from the perspective of energy, and built a date driven eco-efficiency optimization decision to improve eco-efficiency and production benefits in industrial production [23].

In summary, scholars have done fruitful research on industrial development or ecological efficiency. However, due to regional heterogeneity and industrial heterogeneity, there are still some deficiencies in the coupling study of industrial development and ecological efficiency. First of all, most studies are conducted from the perspective of industrial development level or industrial ecological efficiency, but the analysis of spatial heterogeneity and synergistic effect of spatial evolution mechanism from the two dimensions of industrial development level and ecological efficiency is relatively rare. Secondly, the traditional model ignores the influence of input-output relaxation variables on the results, which leads to the deviation of the measurement results of industrial ecological efficiency, and it is difficult to solve the problem of multiple inputs and multiple outputs. Thirdly, there are few studies on the coupling coordination and spatial differentiation of industrial development and industrial ecological efficiency in Huaihe River Economic Belt.

Materials and Methods

Construction of Index System

The selection of evaluation indexes should not only prove the results of industrial economic development, but also consider the impact of industrial development on the environment. The higher the efficiency of industrial development is, the smaller the negative impact on the environment. Following the principles of data availability, scientificity, systematicness, comprehensiveness and comparability, and combining with existing research results, this paper selects

ten indexes from three aspects of industrial scale, industrial structure and industrial potential to construct the evaluation index system of industrial development level. The scale of industrial development reflects the absolute scale level of industry. The structure of industrial development directly reflects the allocation of production factors and the degree of coordinated development of various industries. The industrial development potential is the fundamental support for the industrial development of Huaihe River Economic Belt, which reflects that the industry has innovation ability and innovation stamina. In view of the important supporting role of each indicator and the subjective assumption of the role of a certain indicator, the entropy method is an objective method to determine the weight of indicators, which can fully mine the data utility and reflect the overall industrial development level, so the entropy method is used to determine the weight of indicators. By referring to relevant ecological efficiency literature [24], and combining with the industrial development characteristics of Huaihe River Economic Belt and considering the availability of data, the evaluation index of industrial ecological efficiency includes two levels of input and output. Among them, input includes capital, labor and natural resources. Output includes desirable output and undesirable output.

On the whole, this study constructed an evaluation system consisting of 2 major objective layers, 8 criteria layers and 18 basic indicators, as shown in Table 1. Based on the subjectivity of the research object, this study covers the period from 2014 to 2018. Among them, 2014 is the period of the 12th Five-Year Plan, 2016 is the first year of the 13th Five-Year Plan, and 2018 is the middle stage of the 13th Five-Year Plan. The following paper focuses on the analysis and evaluation of 2014, 2016 and 2018, which are also the landmark years with stage characteristics of China's economic and social development and have great indicative significance.

Data Processing

The research object of this paper is eight cities in Anhui section of Huaihe River Economic Belt, and the time span is from 2014 to 2018. The initial data of the indicators involved in this study are derived from the China Industrial Statistical Yearbook, China Environmental Status Bulletin, Anhui Province Statistical Yearbook and the statistical bulletin of national economy and social development of cities, etc. Occasionally the data are incomplete, and the interpolation method is used to calculate and supplement the index data in similar years [25].

In the multi-index system, in view of the different nature and statistical caliber of each evaluation index, this paper chooses the maximum deviation method for dimensionless data processing [26]. Where, x_i represents the sample value of the i^{th} indicator

Table 1. Index system of coupling coordination between industrial development and ecological efficiency.

Target layer	Rule layer	Index layer	Index sign	Index attribute
Comprehensive level of industrial development	Development scale	Per capita GDP (ten thousand yuan)	x_1	+
		Main business income of industrial enterprises above designated size (100 million yuan)	x_2	+
		Industrial added value (100 million yuan)	x_3	+
		Number of Industrial Enterprises above Designated size (units)	x_4	+
	Development structure	Investment in industrial projects (100 million yuan)	x_5	+
		The proportion of primary industry employment in total employment (%)	x_6	-
		Proportion of secondary industry (%)	x_7	+
	Development potential	R&D expenditure (ten thousand yuan)	x_8	+
		Sales revenue of new products of industrial enterprises above designated size (100 million yuan)	x_9	+
		Number of valid patents (pieces)	x_{10}	+
Industrial ecological efficiency level	Capital investment	Total value of industrial fixed assets (100 million yuan)	y_1	+
	Labor input	Number of people employed in the secondary industry (ten thousand)	y_2	+
	Natural resource input	Total Industrial Resource Demand (ten thousand tons of standard coal)	y_3	+
	desirable output	Industrial added value above designated size (100 million Yuan)	y_4	+
	Undesirable output	Industrial wastewater discharge (ten thousand tons)	y_5	-
		Industrial SO ₂ emissions (t)	y_6	-
		Industrial smoke and dust emissions (t)	y_7	-
		Production of industrial solid waste(ten thousand tons)	y_8	-

in the evaluation of industrial development comprehensive level, y_j represents the sample value of the j^{th} indicator in the evaluation of industrial ecological efficiency.

The dimensionless processing of industrial development level is carried out, and the positive indicator is expressed as:

$$X_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (1)$$

Negative indicator is expressed as:

$$X_i = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)} \quad (2)$$

In the formula, X_i is the standardized value of the i^{th} index in the index system of the comprehensive level of industrial development, x_i is the initial data, $\max(x_i)$ is the maximum value and $\min(x_i)$ is the minimum value of the evaluation index. Similarly, the standard value Y_j of industrial ecological efficiency level evaluation index can be obtained, and $X_i \in [0,1]$, $Y_j \in [0,1]$.

Weight is a measure standard to evaluate the importance of objects, and the entropy method is used to determine the weight of indicators in this study. Single parameter cannot fully reflect the industrial development status of Huaihe River Economic Belt. After standardizing the index data and determining the index weight, the comprehensive evaluation index model is needed to solve the industrial development index, and the formula is as follows:

$$f(x) = \sum_{i=1}^k (X_i \cdot w_i) \quad (3)$$

In formula (3), $f(x)$ is the value number of industrial development level, X_i is the standardized value of each index, W_i is the weight of the i^{th} index in the comprehensive evaluation index system of industrial development, and k is the index number of the comprehensive evaluation index system of industrial development, $f(x) \in [0,1]$.

Research Method

SBM-Undesirable Model

The SBM-Undesirable model can not only effectively solve the problem of input variable crowding or relaxation [27-28], but also measure the ecological efficiency with “undesirable output” and “negative output” indicators, which makes up for the radial and angular deviation of the DEA model. Therefore, this paper uses SBM-Undesirable model to measure the industrial ecological efficiency of Anhui section of Huaihe River Economic Belt, in order to ensure that the estimated value of industrial ecological efficiency is more scientific and effective. For n DMUs, each DMU has m inputs of x , S_1 kinds of desirable outputs of y^g and S_2 kinds of undesirable outputs of y^b , and the vector is expressed as $x \in R^m, y^g \in R^{S_1}, y^b \in R^{S_2}$.

$$\rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_{i=1}^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2} \left(\sum_{i=1}^{s_1} \frac{s_i^g}{y_{i0}^g} + \sum_{i=1}^{s_2} \frac{s_i^b}{y_{i0}^b} \right)}$$

$$s.t. \begin{cases} x_0 = X\lambda + S^- \\ y_0^g = Y^g\lambda - S^g \\ y_0^b = Y^b\lambda + S^b \\ S^- \geq 0, S^g \geq 0, S^b \geq 0, \lambda \geq 0 \end{cases} \quad (4)$$

In formula (4), S^-, S^g, S^b are slack variables of input, desirable output and undesirable output respectively; λ represents the weight vector; The target function $\rho^* (0 \leq \rho^* \leq 1)$ is strictly decreasing with respect to S^-, S^g, S^b . When $S^- = S^g = S^b = 0$, that is, $\rho^* = 1$, DMU is effective and input-output is the optimal combination. When one of S^-, S^g, S^b is not equal to 0, that is, $0 \leq \rho^* < 1$, DMU is invalid, and the input-output ratio needs to be further optimized.

The Coupling Coordination Degree Model

In order to evaluate the coordination degree of coupling and interactive development between industrial development level and ecological efficiency, it is necessary to establish a coordination degree model. Referring to the capacity coupling system model, the coupling degree model of the interaction between industrial development and ecological efficiency system in Huaihe River Economic Belt is obtained [29]:

$$C = \left\{ \frac{f(x) \times g(y)}{\left| \frac{f(x) + g(y)}{2} \right|^2} \right\}^{1/2} \quad (5)$$

In Formula (5), $f(x)$ and $g(y)$ represent the comprehensive evaluation index of industrial

development level and ecological efficiency level index of Huaihe River Economic Belt respectively. C represents the coupling degree between industrial development level and ecological efficiency. The smaller the C value is, the lower the coupling degree is; the larger the C value is, the better the coupling degree is. Although coupling degree can measure the degree of influence between systems, it cannot measure the coordination level between the two systems, so the coupling coordination degree model is used to analyze the relationship between industrial development system and ecological efficiency system. In order to further identify the coordination degree between industrial development level and ecological efficiency, the comprehensive coordination index T is introduced to build a coupling coordination model of the two on this basis. The specific formula is as follows:

$$T = \alpha f(x) + \beta g(y)$$

$$D = \sqrt{C \times T} \quad (6)$$

In formula (6), D indicates the coupling coordination degree, $D \in [0, 1]$. The higher the D value is, the higher the coupling coordination degree of the two systems is. C represents the coupling degree; T represents the comprehensive development evaluation index, which reflects the comprehensive development level between industrial development level and ecological efficiency in Huaihe River Economic Belt. α and β are the undetermined coefficients of industrial development level and ecological efficiency. Among them, $\alpha + \beta = 1$. This paper argues that industrial development level and ecological efficiency subsystems play the same role in the overall coordinated development of the Huaihe River Economic Belt, with an average value of 1/2.

Exploratory Spatial Data Analysis

Exploratory spatial data analysis methods are applied in many fields, such as regional economy, spatial data mining and so on. Among them, the global Moran index is used to measure the similarity of spatial adjacency and adjacent area unit attributes [30]. The expression is as follows:

Global Moran's

$$I = n \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i \sum_j w_{ij} \sum_i (x_i - \bar{x})^2} \quad (7)$$

In formula (7): x_i is the measure value of regional i . $(x_i - \bar{x})(x_j - \bar{x})$ describes the similarity of measure values. w_{ij} represents the degree of interaction between space units i and j .

Local spatial autocorrelation is used to describe the similarity between a spatial unit and its neighborhood, which reflects the degree to which each local unit

obeys the global general trend (covering direction and magnitude), and explains spatial heterogeneity, showing how spatial dependency varies with location. Local spatial autocorrelation index is usually used to measure each spatial element in the selected area by means of local Moran index. The corresponding expression is as follows:

$$\text{Local Moran's } I_i = \left[(x_i - \bar{x}) / S_i^2 \right] \sum_{j=1, j \neq i}^n w_{ij} (x_j - \bar{x}) \quad (8)$$

In formula (8): x_i represents the attribute value of space unit i . S_i^2 represents the variance of x_i . w_{ij} represents the spatial weight matrix.

Usually, the Moran index is used to measure the Z value to verify the significant degree of conversion results. With the help of exploratory spatial data analysis method, the global autocorrelation and local autocorrelation can be used to analyze the spatial correlation and distribution characteristics of coupling coordination between industrial development and ecological efficiency in Huaihe River Economic Belt.

Results and Discussion

Temporal Characteristics of Coupling Coordination Degree between Industrial Development and Ecological Efficiency

According to the formula (3), the comprehensive index of industrial development level of the eight cities in Anhui section of Huaihe River Economic Belt was calculated. Afterward, referring to Formula (4) the industrial ecological efficiency was computed. Then, according to the coupling degree model, the coupling coordination degree model and the standardized index data, the coupling coordination degree of industrial development and ecological efficiency of eight cities in Anhui section of Huaihe River Economic Belt from

2014 to 2018 was calculated. The results were shown in Table 2.

The following characteristics could be summarized from Table 2. Firstly, the overall foundation of coupling coordination degree was good. The calculation results showed that the synergistic effect between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt from 2014 to 2018 was significant, showing a steady strengthening trend. The endogenous power of industrial development continued to increase, and the scale effect continued to spread. The mean value of the overall coupling coordination degree was generally between 0.6 and 0.7 (Fig. 1). The mean value of coupling coordination degree between industrial development level and ecological efficiency in Anhui section was 0.656. Referring to literature [31], the coupling coordination degree of the two was at the primary level of coupling coordination development. It showed that there was still room for improvement in the coordination of industrial development and ecological efficiency in Huaihe River Economic Belt, which required the coordination and interaction of industrial development and ecological efficiency to promote the high-quality industrial development in Huaihe River Economic Belt. In 2014, Bengbu achieved good coupling coordinated development type, Huaibei and Chuzhou belonged to intermediate coupling coordinated development type, Lu'an and Bozhou belonged to primary coupling coordinated development type, Huainan, Fuyang and Suzhou belonged to barely coupled and coordinated development type. On the whole, these eight prefecture-level cities had a higher starting point of coupling coordination degree between industrial development level and ecological efficiency, and a better overall development foundation of coupling coordination.

Secondly, the overall development trend was positive. According to the regional division standard of Anhui Province, among the eight cities in Anhui section of Huaihe River Economic Belt, Huaibei, Bozhou,

Table 2. Time evolution of coupling coordination degree between industrial development level and ecological efficiency from 2014 to 2018 (D).

City	2014	2015	2016	2017	2018	Mean value
Bengbu	0.845	0.919	0.906	0.857	0.896	0.885
Huainan	0.565	0.532	0.517	0.503	0.479	0.519
Fuyang	0.565	0.595	0.617	0.651	0.713	0.629
Lu'an	0.644	0.671	0.695	0.548	0.580	0.628
Bozhou	0.656	0.383	0.523	0.522	0.467	0.510
Suzhou	0.528	0.601	0.628	0.597	0.589	0.589
Huaibei	0.759	0.648	0.633	0.686	0.759	0.697
Chuzhou	0.732	0.761	0.782	0.789	0.895	0.792
Anhui section	0.662	0.639	0.663	0.644	0.672	0.656

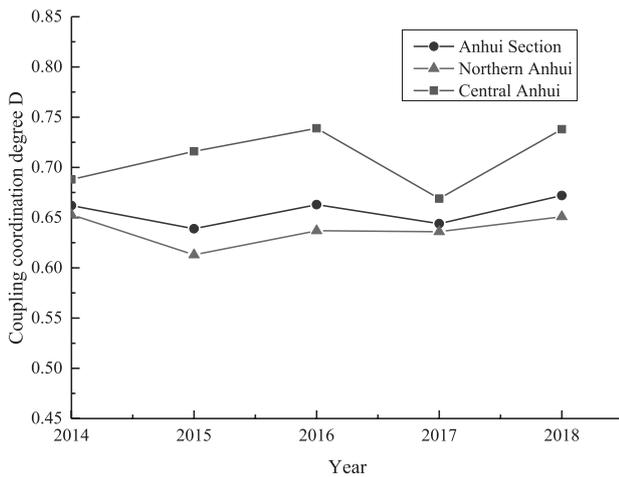


Fig. 1. *D* value of coupling coordination degree between industrial development level and ecological efficiency in 2014-2018.

Suzhou, Bengbu, Fuyang and Huainan belonged to the northern Anhui region. Chuzhou and Lu 'an belonged to central Anhui region. By region (Fig. 1), the coupling coordination degree between industrial development and ecological efficiency in central Anhui was relatively high, which had been rising from primary coupling coordinated development type to intermediate coupling coordinated development type from 2014 to 2016. The coupling coordination level decreased slightly in 2017 and began to rise in 2018, with relatively stable curve changes. The coupling coordination degree of industrial development and ecological efficiency in northern Anhui was lower than that in Anhui and middle Anhui. The value of coupling coordination degree in the study period was between [0.6, 0.65], and the fluctuation was not obvious. On the whole, it showed a steady and rising development trend, but it had not exceeded the coupling coordination development level of Anhui. This indicated that the contribution of industrial development level and ecological efficiency in northern Anhui to the mean value of Anhui section of Huaihe River Economic Belt was negative. On the whole, the coupling coordination degree of industrial development level and ecological efficiency in this region from high to low was central Anhui, Anhui section, and northern Anhui.

Thirdly, the situation of eight cities along the Anhui section fluctuated slightly. The intercity absolute gap between industrial development and ecological efficiency synergistic effect was small, but the relative gap was large. The coupling coordination stage of Bengbu industrial development level and ecological efficiency was good coordination, the coupling coordination degree value increased from 0.845 in 2014 to 0.896 in 2018, and the coupling coordination level continued to improve in 2015 and 2016, realizing the leap to high-quality coupling coordination development type. From 2014 to 2017,

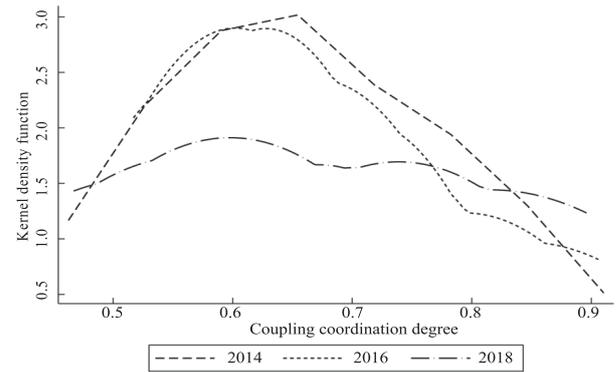


Fig. 2. Kernel density curve of coupling coordination degree between industrial development level and ecological efficiency in main years.

Chuzhou was in the intermediate stage of coupled and coordinated development. In 2018, Chuzhou moved to a good coupled and coordinated development type, with a good momentum of development and continuous improvement. During the study period, Fuyang, Lu 'an and Huaipei were in the initial stage of coupling coordinated development. Huainan, Bozhou and Suzhou belonged to the type of coupling coordinated development. Among them, Bozhou experienced a decline from the primary coupling coordinated development in 2014 to a slightly dysfunctional recession in 2015, and then to a barely coupled coordinated development in 2016 and 2017. In 2018, it fluctuated to a near-dysfunctional recession, which might be due to the distortion of factor distribution caused by weak economic foundation and excessive concentration of superior resources, and hindered the full release of synergistic effect between industrial development and ecological efficiency.

The kernel density function estimation method was used to draw the dynamic evolution trend chart of coupling coordination degree between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt in 2014, 2016 and 2018 (Fig. 2) [31]. It could be seen from Fig. 2 that the center of the kernel density curve of the coupling coordination degree showed a left-biased trend in 2014 and 2016, and a left-biased trend at first and then a right-biased trend in 2018, indicating that the concentration range of the coupling coordination degree between industrial development and ecological efficiency in the study area showed an unstable change trend. The "peak" of the curve in 2018 was much slower than that in 2016, and the peak value decreased greatly. The "peak" of the curve in 2016 was slightly slower than that in 2014, and the peak value dropped slightly, indicating that the gap of coupling coordination degree between prefecture-level cities in the study area had a narrowing trend. In 2018, the right end of the curve increased slightly, and the overall change was stable, indicating that the number of prefecture-level cities

with coupling coordination degree above 0.7 increased slightly compared with the previous period, and the overall development momentum was good. Therefore, all cities should strengthen cooperation, promote the transformation and upgrading of regional industrial structure of low-coupling coordinated development, and further narrow the gap between regions.

Spatial Characteristics of Coupling Coordination Degree between Industrial Development and Ecological Efficiency

Spatial Distribution Pattern of Coupling Coordination Degree

The coupling and coordinated development of industrial development and ecological efficiency not only had the characteristics of time series evolution, but also showed regional differences in spatial pattern. In order to more intuitively analyze the change of coupling coordination degree between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt from 2014 to 2018, this paper used ArcGIS10.2 software and natural discontinuity point

method to carry out visual analysis on spatial pattern of coupling coordination degree between the two in 2014, 2016 and 2018 (Fig. 3). The trend analysis tool was used to draw the spatial trend curve of the coupling coordination degree between industrial development and ecological efficiency (Fig. 4). The X axis points to due east, and the Y axis points to due north.

As can be seen from Fig. 3, during the study period, Bengbu, Chuzhou and Huaibei were always in the stage of coupling and coordinated development. In the planning and construction of Huaihe River Economic Belt, Bengbu was the “third pole” of economic growth, leading the urban development of Huaihe River Basin. Bengbu and Chuzhou adhered to the core strategy of “strong industrial city”, unswervingly adjust the structure, transfer mode and promote upgrading, and the industrial economy showed a good trend of taking the lead in growth, constantly optimizing the structure and gradually improving the strength. Compared with 2014, Lu ‘an had dropped from the primary coupling coordinated development type to the forced coupling coordinated development type. The coupling coordination degree of industrial development and ecological efficiency in Bozhou and Huainan had

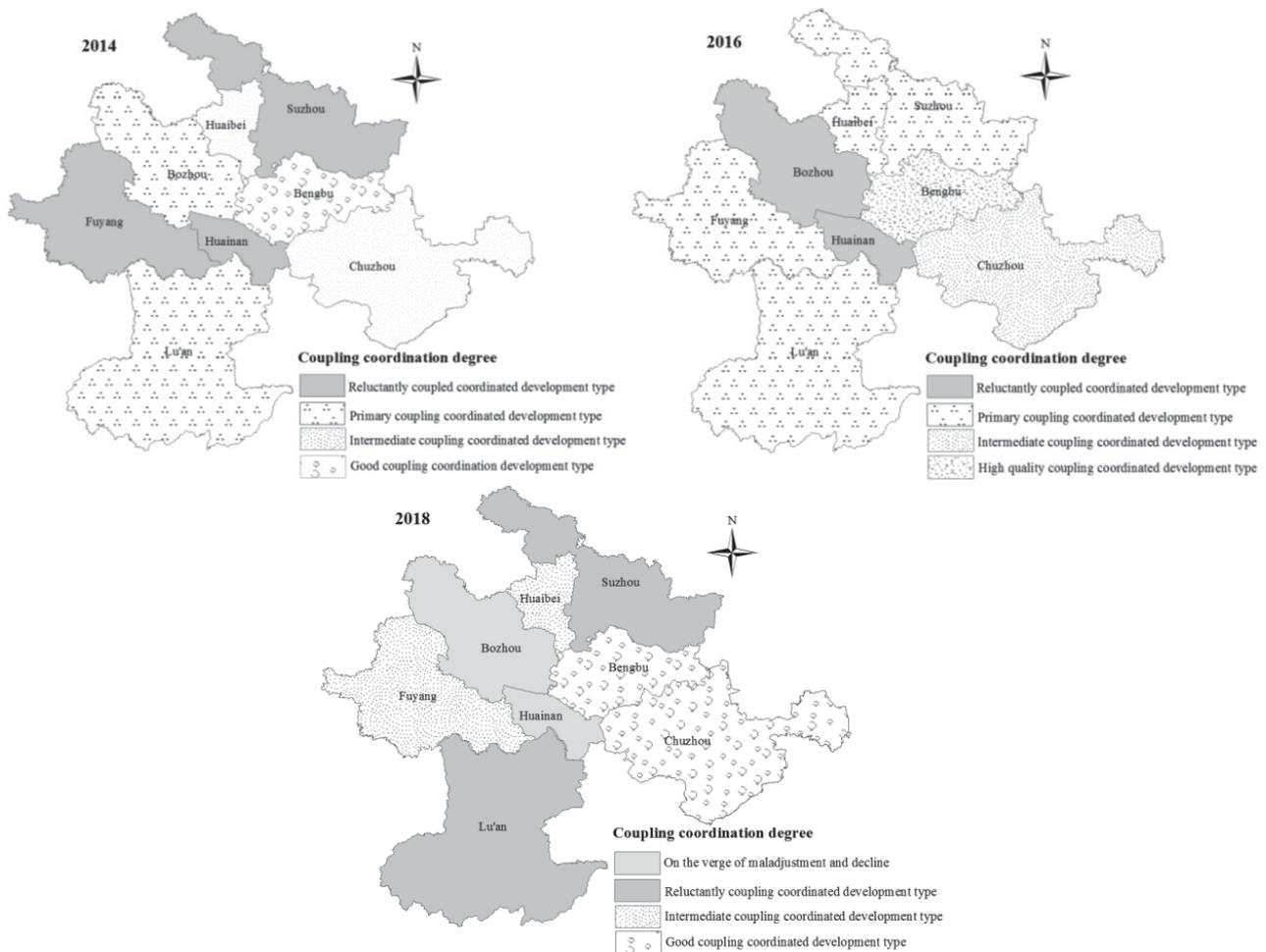


Fig. 3. Spatial distribution pattern of coupling coordination degree between industrial development and ecological efficiency in 2014, 2016 and 2018.

been reduced to near imbalance and decline. Fuyang improved year by year, experiencing a reluctant coupling coordinated development → primary coupling coordinated development → intermediate coupling coordinated development. This was to focus on the construction of the “four modernizations” coordinated development of the pilot area in 2014 and the goal of “competing for the first rank in northern Anhui, catching up with the province and realizing a well-off society”. Fuyang actively promoted reform and innovation, expanded effective input and transformed the development mode. As a whole, Suzhou was relatively stable without much change. On the whole, the proportion of cities was relatively stable, although there were some changes in the stage of coupled coordinated development. From the perspective of spatial distribution, the coupling coordination degree of industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt in 2014 presented a gradually improving spatial distribution pattern from northwest to southeast. In 2016 and 2018, the spatial distribution of coupling coordination degree further highlights the step characteristics, presenting a contiguous “block” distribution, suggesting that there may be spatial correlation between industrial development and ecological efficiency coupling coordination degree. Specifically, the regions with high coupling coordination degree were mainly distributed in the eastern part of Anhui Section (Bengbu and Chuzhou), the regions with low coupling coordination

degree were mainly distributed in the northern part of Anhui Section (Suzhou), and the regions with middle coupling coordination degree were widely distributed.

Combined with the global trend surface diagram in Fig. 4, the east-west direction of the coupling coordination degree between industrial development and ecological efficiency of eight cities in Anhui section of Huaihe River Economic Belt changed from a gradient spatial pattern of “low in the west, high in the east” in 2014 to a U-shaped structure of “high at both ends and low in the middle”, and the curve curvature increased. In the north-south direction, the coupling coordination degree always presented an inverted “U” structure of “low at both ends and high in the middle”, and the curvature of the curve increased slightly. This indicated that the coupling coordination degree of industrial development and ecological efficiency in the middle part of Anhui section of Huaihe River Economic Belt was obviously improved, while the coupling coordination degree of industrial development and ecological efficiency in the western part of Anhui Section was the weak area.

Spatial Correlation Analysis of Coupling Coordination Degree

The coupling coordination degree between industrial development and ecological efficiency showed a centralized and contiguous “block” distribution in space, and the changes of coupling

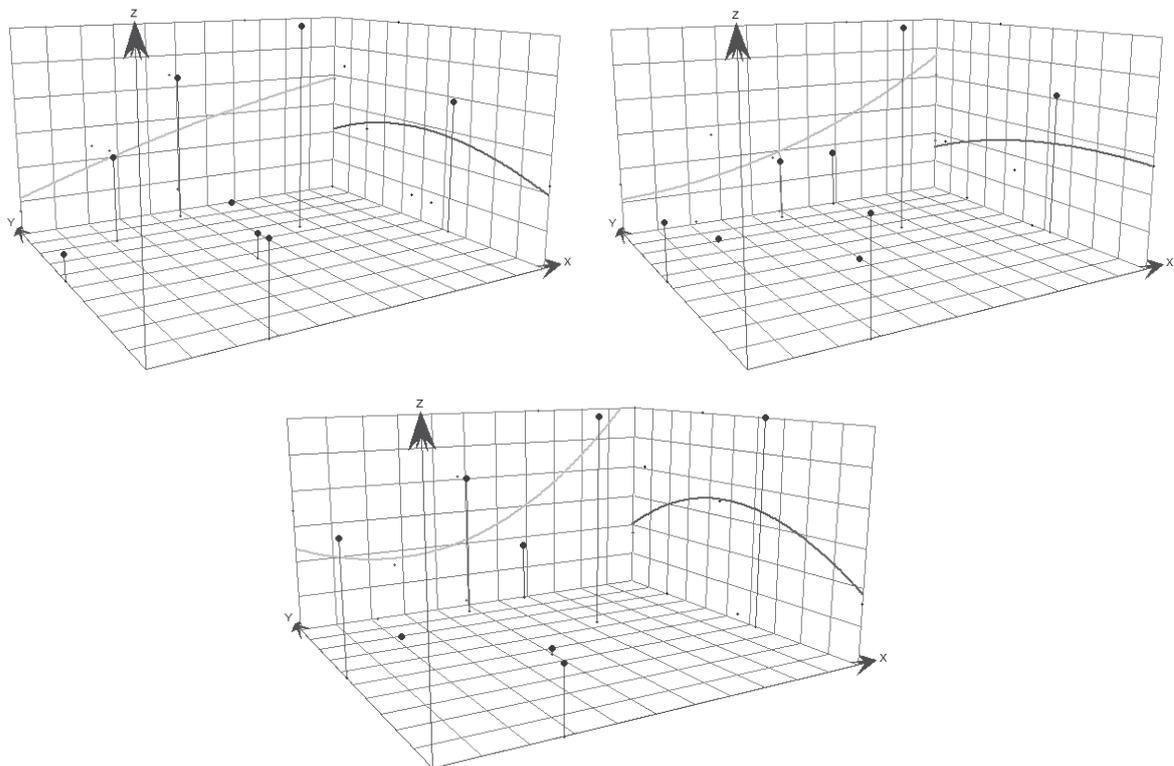


Fig. 4. Global trend surface diagram of coupling coordination degree between industrial development and ecological efficiency in 2014, 2016 and 2018.

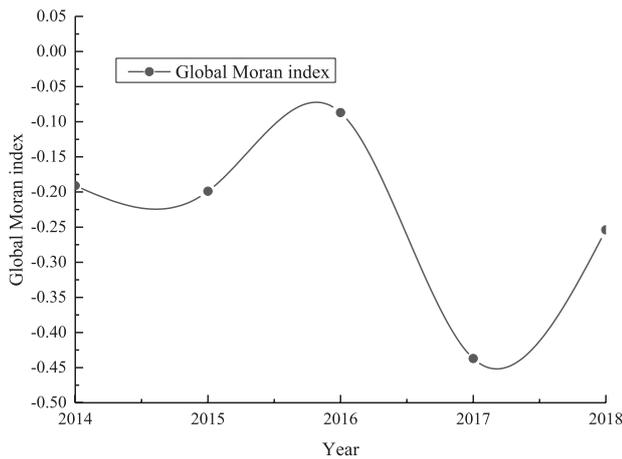


Fig. 5. Global Moran index of coupling coordination degree between industrial development and ecological efficiency from 2014 to 2018.

coordination degree between regions might also be spatially correlated. GeoDa software was used to solve the global Moran index of coupling coordination degree between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt from 2014 to 2018 (Fig. 5), and analyzed its spatial heterogeneity and dependence.

As can be seen from Fig. 5, the coupling coordination degree of industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt fluctuated within the range $[-0.45, -0.05]$, and was significant at the 10% level. This indicated that the spatial distribution of the coupling coordination degree between industrial development and ecological efficiency was not random, and there was a strong spatial dependence among cities. Where, Moran's $I < 0$ represents spatial negative correlation, and the smaller its value is, the greater the spatial difference is. From 2014 to 2018, the global Moran index of coupling coordination degree between industrial development and ecological efficiency fluctuated greatly, but it was less than 0 on the whole, presenting a "W" type evolution trend. Spatial agglomeration characteristics peaked in 2016, with the global Moran index of -0.087 , and then plummeted to -0.437 in 2017. From 2017 to 2018, the global Moran index increased sharply, indicating that the spatial impact of coupling coordination degree between industrial development and ecological efficiency persisted. According to the spatial pattern analysis, the coupling coordination degree between industrial development and ecological efficiency of eight cities in Anhui section of Huaihe River Economic Belt was quite different. Therefore, local cities should strengthen the division of labor and coordinated development, promote industrial integration, functional complementarity, and ecological co-construction, and accelerate the construction of open platform and so on to comprehensively improve the construction of ecological civilization and high-quality economic development of

Anhui section of Huaihe River Economic Belt.

According to Formula (8), the scatter diagram of local Moran index was calculated and drawn (Fig. 6). The coupling coordination degree of eight cities could be divided into four types according to the four quadrants of the scatter plot. The first quadrant is High-High (H-H) agglomeration area, indicating that the coupling coordination degree of industrial development and ecological efficiency is high between this area and its adjacent areas, and the spatial correlation is high level area. The second quadrant is the Low-High (L-H) aggregation area, indicating that the coupling coordination degree of the region is lower than that of the neighboring region, and the spatial correlation is in the development stage. The third quadrant is a Low-Low (L-L) agglomeration area, indicating that the coupling coordination degree of industrial development and ecological efficiency is low in this region and its adjacent regions, and the spatial performance is a low-coupling coordination area. The fourth quadrant is the High-Low (H-L) aggregation area, indicating that the coupling coordination degree of this area is higher than that of adjacent areas, and the spatial correlation is manifested as spillover effect.

Because Lu'an has no neighbor object in the spatial weight, Lu'an was deleted when the local Moran index scatter plot was output. As can be seen from Fig. 6, the coupling coordination degree of industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt mainly occurred in Low-High (L-H) and High-Low (H-L) agglomeration areas. L-H agglomeration areas were mainly distributed in the northern Anhui region, including Suzhou, Huainan and Bozhou. The industrial development in this region started relatively late, the industrial growth mode was extensive, the optimization of industrial structure and industrial transformation and upgrading effect was not ideal. The coupling coordination degree between industrial development and ecological efficiency was relatively low and was still in the development stage. H-L agglomeration area was mainly distributed in Bengbu. The main reason was that bengbu has been vigorously promoting the formation of green development mode and lifestyle in recent years, adhering to scientific and technological treatment of haze, precise control of gas and pollution control according to law, and rational and effective allocation of resources in time and space. The coupling coordination degree of industrial development and ecological efficiency presented obvious spatial spillover effect.

The spatial-temporal transition of the coupling coordination degree between industrial development and ecological efficiency in Anhui section of Huaihe River Economic Belt was reflected by the changes of cities in different spatial agglomeration types in different periods [32]. It is mainly divided into three types: The first is the standard transition, which means that the range of the region has not changed. The

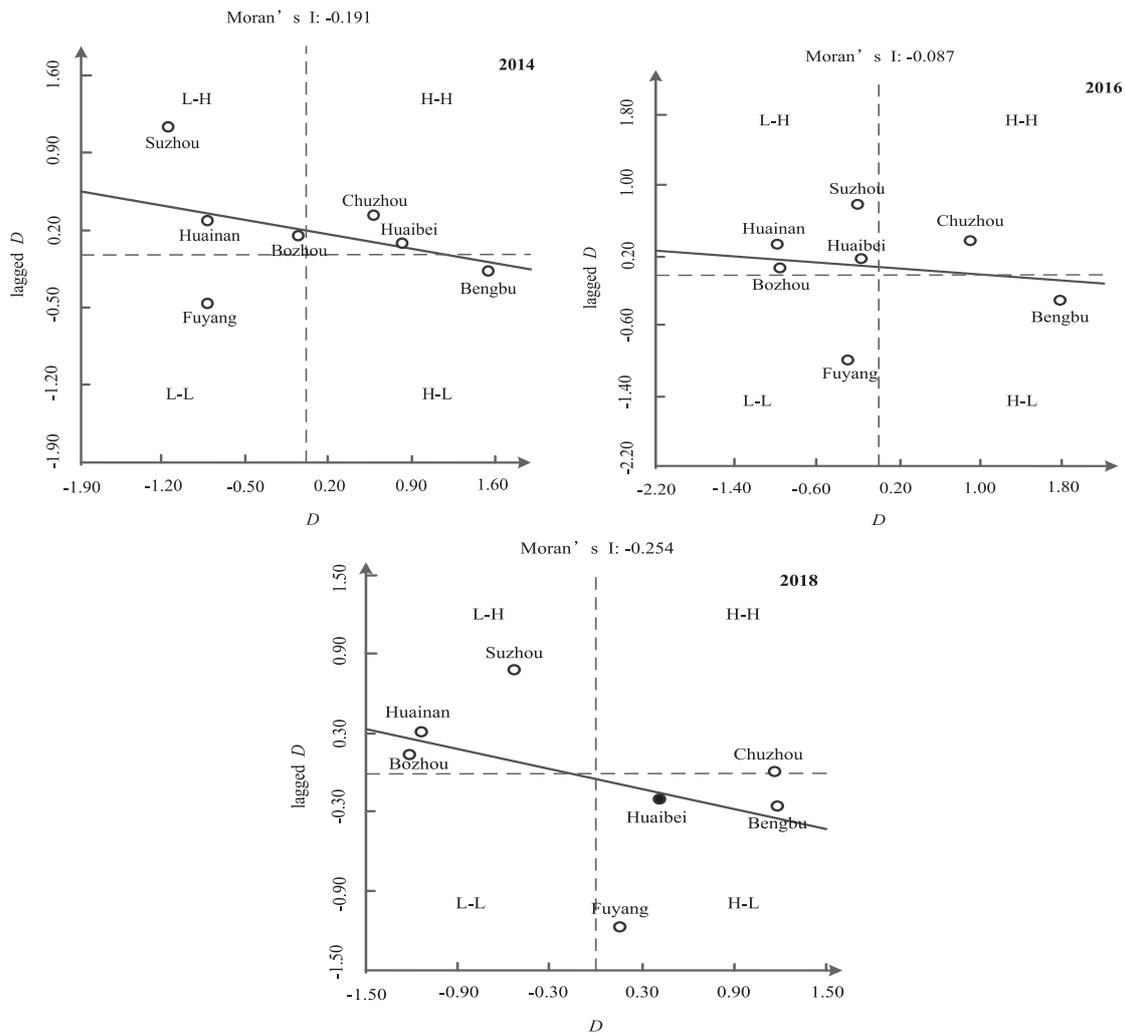


Fig. 6. Scatter diagram of local Moran index of coupling coordination degree between industrial development and ecological efficiency in 2014, 2016 and 2018.

second is the upstream transition, which refers to the transition of the region to a higher level interval, such as (L-L→H-L, L-H→H-H). The third is the downstream transition, which refers to the transition of the region to a lower horizontal interval, such as (H-L→L-H, H-H→L-H). In 2014, 2016 and 2018, Chuzhou, Bengbu, Suzhou, Huainan and Bozhou were mainly in the first, second and fourth quadrants, indicating that the coupling coordination degree of industrial development and ecological efficiency broke through the dilemma of “Matthew effect”. The upstream transition was mainly Fuyang, and the downstream transition was Huaibei. The proportion of cities with transition was 28.571%, indicating that the coupling coordination degree of industrial development and ecological efficiency had good local spatial stability. Therefore, the high-coupling coordination region should give full play to the spillover effect, avoid the dilemma of “Matthew effect”, and promote the transformation from low-coupling coordination region to high-coupling coordination region. Meanwhile, the low-coupling coordination region should constantly improve its own industrial

production system and actively accept the radiation driving effect from the high-coupling coordination region.

Study on Influencing Factors of Coupling Coordination Degree

Set Variable

Based on the above analysis of coupling coordination degree and relevant literature, four variables were selected as explanatory variables to study the coupling coordination degree factors of industrial development level and industrial ecological efficiency in eight cities in Anhui section of Huaihe River Ecological Economic Belt. Economic development level (X_1): per capita GDP is an important indicator to measure regional comprehensive strength. Its environmental externalities have dynamic evolution characteristics, and the direction of their influence on industrial ecological efficiency is the result of the game between

Table 3. Regression results of influencing factors of coupling coordination degree.

D	Coefficient	t	P
X_1	0.198	5.540	0.000
X_2	2.075	3.000	0.003
X_3	-0.026	-3.240	0.001
X_4	0.039	0.660	0.509
c	0.282	1.130	0.259

positive and negative externalities. R&D intensity (X_2): R&D investment of enterprises, along with the emergence of new technologies and products, promotes the sustainable development of ecological environment by changing the environment or human production and life style. Industrial structure (X_3): the proportion of the secondary industry, which is closely related to the types of resource consumption and pollution discharge, is an important factor affecting the sustainable development of ecological environment. Environmental regulation (X_4): investment in industrial pollution control. Effective environmental regulation tools play an important role in environmental pollution control, urging enterprises to save energy and reduce emissions, and can evaluate the intensity of regional industrial pollution control.

Result Analysis

According to Tobit model, Stata 12.0 software was used to conduct regression analysis on factors influencing the coupling coordination degree between eco-efficiency and industrial development, and the results were shown in Table 3.

It can be seen from Table 3 that the growth coefficient of economic development level X_1 is positive, and through the significance test, it shows that the better the economic development, the higher the coupling coordination degree between ecological efficiency and industrial development. For each unit of GDP, the coupling coordination degree will increase by 0.198 units, which has a significant impact. This is because the improvement of regional economic level will drive local industrial development, increase ecological efficiency and enhance the coupling and coordination effect between industrial development and ecological efficiency. The X_2 coefficient of R&D intensity is positive, and the significant effect is obvious. The increase of R&D capital investment can improve the comprehensive level of industrial development. Industrial development can enable enterprises to reduce environmental pollution, increase main business income, and enhance the coupling and coordination effect of industrial development and ecological efficiency. The X_3 growth coefficient of industrial structure is negative and passes the significance level. It shows that the current industrial structure allocation

of cities in the Huaihe River ecological economic belt is the restrictive factor for the coupling and coordinated growth of industrial ecological efficiency and industrial development. The X_4 coefficient of environmental regulation intensity is positive, and the impact effect is more significant through the significance level. The greater the environmental regulation intensity, the greater the coupling coordination degree between ecological efficiency and industrial development. For each additional unit of environmental regulation intensity, the coupling coordination degree between ecological efficiency and industrial development will increase by 0.039 units. In real life, if you want to increase the coupling coordination, you can increase the environmental regulation intensity. The government requires industry to reduce pollutant emissions. In order to maintain production, enterprises are forced to continuously carry out innovative development, optimize industrial structure and reduce enterprise pollution, so as to increase the coupling coordination between ecological efficiency and industrial development.

Conclusions

As an energy-intensive area with a high proportion of heavy and chemical industries, the Huaihe River Economic Belt must strive to improve ecological efficiency in order to achieve sustainable and high-quality development. This paper used the Comprehensive Development Index and the Undesirable output SBM model to measure the industrial development level and ecological efficiency of eight cities in Anhui section of Huaihe River Economic Belt from 2014 to 2018, using the coupling coordination degree model to measure the coupling coordination degree of industrial development level and ecological efficiency, using spatial analysis method to deeply analyze the spatial texture and spatial agglomeration characteristics of the coupling coordination degree, and drawing the following conclusion and enlightenment:

(1) The industrial development of Anhui section of Huaihe River Economic Belt had achieved remarkable results. From 2014 to 2018, the overall level of industrial development was not high but showed an annual growth trend. Resource demand, increasing consumption intensity and backward industrial structure were the main constraints, and the potential of science and technology innovation was the basic kinetic energy supporting industrial development. The overall ecological efficiency was at a medium level, the resource-saving and environment-friendly production methods had not been developed, and the industrial growth mode was relatively extensive.

(2) There were great differences in industrial ecological efficiency between the case cities. Compared with 2014, the gap of industrial ecological efficiency showed an expanding trend in 2018, and Bengbu

and Chuzhou ranked first and second. The industrial ecological efficiency of most cities showed a good development trend. The average value of industrial ecological efficiency in Bengbu, Bozhou and Lu'an was all above 0.7, but Huainan was at a relatively low level with relatively large resource consumption and unit output emissions under backward production technology.

(3) The coupling coordination effect of industrial development and ecological efficiency was remarkable. The mean value of the overall coupling coordination degree was between 0.6 and 0.7, which was above the average level, but the relative gap was still wide. Spatially, the east-west direction had evolved from a gradient spatial pattern with "low in the west and high in the east" in 2014 to a "U" type structure of "high at both ends and low in the middle". The coupling coordination degree in the north-south direction always presented an inverted "U" type structure of "low at both ends and high in the middle", and the curvature of the curve increased slightly, indicating that the coupling coordination degree between industrial development and ecological efficiency in the middle of the study area was obviously improved, while the coupling coordination degree between industrial development and ecological efficiency in the west became the weak area in Anhui section.

(4) Environmental regulation, economic development level and R&D intensity have a significant positive impact on the coupling coordination degree of industrial ecological efficiency and industrial development, and industrial structure has an inhibitory effect on the coupling coordination degree. Industrial structure is an important link between economy and environment. At present, China's economic development is in the critical period of strategic transformation, but the industrial structure model dominated by high energy consumption and high pollution still occupies the dominant position, and the negative impact on industrial ecological efficiency will continue to exist.

There are great differences in different regions of Anhui section of Huaihe ecological economic belt, and its industrial development and ecological efficiency pattern and influencing factors still need to be further studied at the finer county and township scales. At the same time, industrial development and ecological efficiency are the comprehensive embodiment of the technological level of resource utilization and pollution control of enterprises. It is urgent to bring the heterogeneity of enterprises into theory and model analysis, and make more accurate measurement and quantitative estimation of influencing factors based on the micro data of industrial enterprises.

Acknowledgments

This work was supported by the following programs:
1. Key Projects of Humanities and Social Sciences in

Anhui with the title "Research on the safety and early warning system of underground support deformation monitoring based on laser intrusion detector" (No. SK2020A0213). 2. Independent Project of State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines with the title "Research on underground dust monitoring and intelligent early warning system" (No. SKLMRDPC20ZZ12). 3. Science Research Fund for young teachers of Anhui University of Science and Technology with the title "Research on Speed Regulation System of Switched Reluctance Motor" (No. QN2019119).

Conflict of Interest

The authors declare no conflict of interest.

References

- Guangming Daily. Good ecology is the fairest public product. Available online: <http://cpc.people.com.cn/n/2015/0506/c78779-26957223.html> (accessed on 8-9-2021).
- LI X.H. Guiding high quality development of manufacturing industry with new development concept. Available online: <https://www.163.com/dy/article/GJ7RIKE70514AE01.html> (accessed on 8-9-2021).
- The Website of the Central People's Government of the PRC. The reply of the State Council on the Development plan of Huaihe Ecological Economic Belt. Available online: http://www.gov.cn/zhengce/content/2018-10/18/content_5332105.html (accessed on 4-9-2021).
- YANG L., YU Q.Q., ZHANG X.L. A study on the evaluation and the restructuring and upgrading path of green industrial Development in cities along the Yangtze River in Jiangsu province. *Jiangsu Social Sciences*. **6**, 249, **2019**.
- LOURENO E.J., BAPTISTA A.J., PEREIRA J.P., DIASFERREIRA C. Multi-layer stream mapping as a combined approach for industrial processes eco-efficiency assessment. Springer Singapore. **January, 2013**.
- DEMIRAL E.E., SAGLAM U. Eco-efficiency and Eco-productivity assessments of the states in the United States: A two-stage Non-parametric analysis. *Applied Energy*. **303** (117649), **2021**.
- CORTES A., CASILLAS-HERNANDEZ R., CAMBES-FRANCO C., BORQUEZ-LOPEZ R., MAGALLON-BARAJAS F., QUADROS-SEIFFERT W., FEIJOO G., MOREIRA M.T. Eco-efficiency assessment of shrimp aquaculture production in Mexico. *AQUACULTURE*. **544**(737145), **2021**.
- SHI D., LI P. Development quality evolution and current situation evaluation of Chinese industry in 70 years. *China Industrial Economics*. **9**, 5, **2019**.
- ZHANG L.P., MA Y.J. Level measurement and spatial pattern evolution of county industry development of Jilin province. *Journal of University of Chinese Academy of Sciences*. **32** (03), 325, **2015**.
- WANG Z.F., LIU Q.F. Spatio-temporal evolution and influencing factors of tourism eco-efficiency in the Yangtze River Economic Belt. *Resources and Environment in the Yangtze Basin*. **28** (10), 2289, **2019**.

11. SHI Y. Performance analysis of industrial green development in Inner Mongolia based on entropy weight TOPSIS and non-expected output SBM model. *Journal of Inner Mongolia University of Technology (Natural Science Edition)*. **37** (06), 473, **2018**.
12. WU C.Q., HUANG L. Research on the performance and the synergistic effect of green development of Yangtze River Economic Belt industry. *Journal of China University of Geosciences (Social Sciences Edition)*. **18** (03), 46, **2018**.
13. HUANG Y., LI L. Comprehensive measurement and spatial-temporal evolution of green development level of Urban agglomerations in China. *Geographical Research*. **36** (7), 1309, **2017**.
14. WU C.Q. Industrial development report of the Yangtze River Economic Belt (2017). Beijing: Social Sciences Academic Press. **November, 2017**.
15. WANG X.L., FANG X.C. Eco-efficiency evaluation and its influencing factors for the old northeast industrial base of china based on DEA-Malmquist-Tobit model. *Ecological Economy*. **33** (05), 95, **2017**.
16. ZHAO Z., BAI Y.P., HU Z.M., CHEN J.C., DENG X.Z. Evaluation of ecological efficiency and factors influencing grassland animal husbandry in the Hulunbuir region based on a super-efficiency DEA model. *Acta Ecologica Sinica*. **38** (22), 7968, **2018**.
17. MA M., TANG L. Evaluation of ecological efficiency of industrial chain in Jilin Province under production inducement – based on the combination of Input-output method and DEA method. *Taxation and Economy*. **1**, 103, **2018**.
18. HUANG M., DING R.J., XIN C.H. Impact of technological innovation and industrial – structure upgrades on ecological efficiency in China in terms of spatial spillover and the threshold effect. *Integrated Environmental Assessment and Management*. **17** (4), 852, **2021**.
19. SONG C.Z., YIN G.W., LU Z.L., CHEN Y.B. Industrial ecological efficiency of cities in the Yellow River Basin in the background of China's economic transformation: spatial-temporal characteristics and influencing factors. *Environmental science and pollution research international*. **August, 2021**.
20. ZHANG Y., ZHANG H., FU Y., WANG L., WANG T. Effects of industrial agglomeration and environmental regulation on urban ecological efficiency: evidence from 269 cities in China. *Environ Sci Pollut Res Int*. **July, 2021**.
21. ZHANG R.L., LIU X.H. Evaluating ecological efficiency of Chinese industrial enterprise. *Renewable Energy*, **178**, 679, **2021**.
22. WU M.R. Measurement of Regional Industrial Ecological Efficiency in China and an Analysis of Its Influencing Factors. *Journal of World Economic Research*, **9** (1), 43, **2020**.
23. LIU C.H., GAO M.D., ZHU G., ZHANG C.X., ZHANG P., CHEN J.Q., CAI W. Data driven eco-efficiency evaluation and optimization in industrial production. *Energy*. **224**, 120170, **2021**.
24. REN F., YU X. TFEE Measurement, Decomposition and Influencing Factors Analysis of Eight Economic Regions in China. *Polish Journal of Environmental Studies*. **29** (6), 4291, **2020**.
25. ASHKAN S., ARMAN K. An improved node-based smoothed point interpolation method for coupled hydro-mechanical problems in geomechanics. *Computers and Geotechnics*. **139**, 104415, **2021**.
26. LI X.C. Application of Maximum Deviations and Entropy to Effectiveness Evaluation of Missile Early Warning System. *Journal of CAEIT*. **15** (03), 284, **2020**.
27. CHEN W., NING S.Y., CHEN W.J., LIU E.N., WANG Y.N., ZHAO M.J. Spatial-temporal characteristics of industrial land green efficiency in China: Evidence from prefecture-level cities. *Ecological Indicators*. **113**, 106256, **2020**.
28. GUO L., NA S.Y., TAN X.H., GUI P.F., LIU C.C., POLAT K. Evolution of the Efficiency of Nationwide Commercial Banks in China Based on an SBM-Undesirable Model and DEA Window Analysis. *Mathematical Problems in Engineering*. **2020**, 4682790, **2020**.
29. LIU X.L., GUO P.B., YUE X.H., ZHONG S.C., CAO X.Y. Urban transition in China: Examining the coordination between urbanization and the eco-environment using a multi-model evaluation method. *Ecological Indicators*. **130**, 108056, **2021**.
30. CUI H.R., LIU Z.L. Spatial-Temporal Pattern and Influencing Factors of the Urban Green Development Efficiency in Jing-Jin-Ji Region of China. *Polish Journal of Environmental Studies*. **30** (2), 1079, **2020**.
31. WANG Q.Y., ZHAO C.Y. Dynamic evolution and influencing factors of industrial green total factor energy efficiency in China. *Alexandria Engineering Journal*. **60** (1), 1929, **2021**.
32. XIONG X., XIAO J. Evaluation of coupling coordination between urbanization and eco-environment in six central cities, Wuling Mountain region. *Acta Ecologica Sinica*. **41** (15), 1, **2021**.