



Research on the spatiotemporal evolution and influencing factors of green economic efficiency in the Yangtze River Economic Belt

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Received: 25 January 2022 / Accepted: 26 April 2022 / Published online: 10 May 2022
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Abstract

In the Yangtze River Economic Belt (YREB), the green economy is an essential to sustainable economic development. In this study, we calculated a comprehensive index of environmental pollution based on the global entropy weight method and used the super slacks-based measure (SBM) model to estimate the green economic efficiency (GEE) of provinces and cities in the YREB from 2005 to 2018. Subsequently, we explored temporal and spatial evolution characteristics combined with the Theil and Moran indexes, and adopted the spatial Dubin model to analyze its influencing factors. We divided the YREB into three watersheds to facilitate the analysis. The results show that the GEE in the YREB initially decreased and then increased, and the difference among the three major watersheds was higher than that within the watershed. We found a positive spatial autocorrelation in the development level of the green economy in the YREB. While industrial structure had a negative effect, economic development, scientific and technological level, and environmental regulation all had a positive effect on GEE. Finally, we offered policy recommendations to improve the level of green development in the YREB.

Keywords Yangtze River Economic Belt · Green economy · ESDA-SBM model · Spatial Dubin model · Green economic efficiency · Green development

Introduction

In important speech at the 75th United Nations General Assembly in 2020, Chinese President Xi Jinping stated that China would increase its nationally determined contribution, adopt more powerful policies and measures, and strive

to achieve peak carbon dioxide emissions by 2030 and carbon neutrality by 2060. The Yangtze River Economic Belt (YREB) spans over three major regions in the East, Middle, and West of China and comprises 11 provinces and cities along the Yangtze River. In 2019, its total population and economy accounted for 42.8 and 46.2%, respectively. Hence, it is an essential strategic support belt for economic development in the new era. However, with a rapid increase in economic development and the intensified impact of human activities, the ecological environment of the YREB is facing numerous problems, such as wetland degradation, severe water pollution, and depletion of fishery resources, which directly restrict the establishment of a sustainable civilization. The Politburo meeting of the CPC Central Committee in 2016 emphasized that the Yangtze River contributes to the development of the Chinese government. To develop the YREB, we must promote ecological priority, green growth, and joint efforts to reduce the negative impacts of large-scale development. In November 2020, President Jinping Xi, in a symposium on comprehensively promoting the development of the YREB, stated that it is necessary to unswervingly implement the new concept for the high-quality development of the YREB, create a new model for regional

Responsible Editor: Eyup Dogan

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synergetic development, and make the YREB the focal point of ecological priority and green development in China. It can be seen that the development of the green economy has become an effective way for the YREB to save resources, reduce pollution, and promote economic growth.

How can this feature of the green economy be accurately described? Measuring green economy efficiency is an appropriate method generally accepted by scholars (Zhuo and Deng 2020; Lin and Tan 2019; Wang 2020; Zhao et al. 2022), and strategies to improve green economy efficiency have become an important issue. In this study, GEE is the integration of the concept of green development into traditional economic efficiency, which is an indicator used to measure the ability of unit input cost to obtain desired output. Although current research on GEE has achieved positive results (Li et al. 2020; Li and Ji 2021), there are not many studies from the perspective of the YREB. Therefore, measuring the GEE of the YREB, exploring its temporal and spatial evolution characteristics, and evaluating its influencing factors have important theoretical and practical significance for promoting ecological development and regional economic transformation, improving the green economy level of the YREB.

Literature review

Since the term was coined (Costanza 1989), green economy has attracted extensive attention of scholars from both China and abroad. The research scope mainly includes measurement methods, the analysis of spatiotemporal evolution characteristics, and influencing factors. There are two main aspects of measurement methods: first, a combination of the pet model and L-V model is used to discuss the effect of population size and population structure on the development of green economy (Song et al. 2022), to establish a multi-dimensional indicator system for evaluation. Puppim de Oliveira et al. (2013) constructed an evaluation index of urban green development from four aspects: decision-making process, executive ability, urban economy, and social ecosystem. Maxime et al. (2006) and Nahman et al. (2016) developed a comprehensive index to measure green economic performance from the economic, social, and environmental aspects. Li et al. (2019) proposed a novel two-stage analytical framework including four methods. Additionally, Bilgaev et al. (2020) established a multiple regression equation to analyze ecological capacity. Second, to calculate efficiency for evaluation, Charnes et al. (1979) used the data envelopment analysis (DEA) method to calculate the economic efficiency of 28 cities in China. Tone (2004) put forward the slacks-based measure (SBM) model, which comprehensively considers the impact of unexpected outputs on efficiency evaluation.

In recent years, scholars have used green total factor productivity (GTFP), ecological efficiency, and GEE to calculate the development level of the green economy. Since Zhang et al. (2014) calculated the environmental total factor productivity (ETFP) using the Malmquist index. Ren (2020) used the Malmquist index to study the regional green total factor productivity (GTFP) in China and Xia and Xu (2020) adopted the DDF method to calculate GTFP. Li and Chen (2021) analyzed the GTFP in the Pearl River Delta. Tang et al. (2020) and Zhou et al. (2020) utilized an improved DEA model to measure the eco-efficiency of China. Many scholars have also calculated the GEE in China, for example, Su and Zhang (2020), Li and Ouyang (2020), and Wu et al. (2020) employed the super-efficient DEA model to measure China's regional GEE. Zhuo and Deng (2020) and Li et al. (2020) used the SBM model to evaluate China's provincial GEE. Lin and Tan (2019) and Li and Ji (2021) adopted the non-radial directional distance function to measure China's Urban GEE. Most existing studies used the SBM model and the traditional DEA model, but they were limited by the efficiency value of multiple decision-making units that could not be compared when the efficiency value was 1. However, the super-SBM model could effectively overcome this defect, and the calculated GEE value could be greater than 1, which could effectively improve the comparability between effective decision-making units. Therefore, this paper used the super-SBM model to measure the GEE of the YREB.

From the analysis of temporal and spatial evolution characteristics, Yang et al. (2012) studied the temporal and spatial pattern changes of industrial eco-efficiency in 30 provinces in China based on the method of exploratory spatial data analysis (ESDA). Qiu et al. (2020) took the Xuzhou metropolitan area as examples to study the spatiotemporal heterogeneity of their green development efficiency; Zhou et al. (2020) analyzed the spatiotemporal evolution of urban green development efficiency (UGDE) in China based on spatial Markov chains. Li and Ji (2021) analyzed spatiotemporal characteristics of GEE in China based on static and dynamic spatial models. Peng et al. (2021) used ArcGIS software to illustrate the spatial-temporal evolution of urban environmental governance efficiency in China. Research on the YREB mainly focused on urbanization efficiency (Jin et al. 2018; Han and Chen 2021), industrial green total factor productivity (Li and Liu 2017), and green innovation efficiency (Xu et al. 2020), and there are few studies on green economy efficiency.

From the perspective of influencing factors and in terms of technological innovation, Grimaud and Rouge (2008) studied the effect and intensity of technological progress on GEE and analyzed the spillover of technology. Walz et al. (2017) found that technological innovation played an essential role in realizing green development. In terms of industrial structure, Shironitta (2016) argued that changing

the industrial structure had a critical impact on the carbon dioxide emissions of each country. Li et al. (2019) and Ren and Wang (2017) concluded that the rationalization and advancement of the industrial structure had a significant positive role in promoting the development of the green economy. In terms of openness, Kardos (2014) and Zhou et al. (2020) pointed out that FDI is an essential source of development, and particularly, sustainable development. Ren (2020) pointed out that FDI has a positive impact on GTFP. In terms of quantitative research, Tu et al. (2019) used the Tobit model; Qiu et al. (2020) used the geographically weighted regression (GWR) model; Wu et al. (2020) and Yang et al. (2020) used a spatial econometric model to explore the role and degree of influencing factors of GEE.

The research on the YREB mainly focused on industrial development, regional differences and coordinated development, key urban development, ecological environment, and sustainable development. Zhang and Chen (2021), and Sun et al. (2022) calculated the carbon emission efficiency of industry, agriculture, and tourism in the YREB, respectively; Zou and Ma (2021) analyzed the resource and environmental carrying capacity of the YREB from the perspective of spatial differences and sustainable development; Jin et al. (2018) and Han and Chen (2021) studied cities above the prefecture level in the YREB and explored the spatiotemporal pattern of urbanization efficiency and green development level and evaluated the ecological efficiency of the YREB. Xu et al. (2020) analyzed the research trend of green innovation efficiency in the YREB.

In general, current research on GEE mainly focuses on the national, provincial, and city level, and there are few studies on the YREB. Although quantitative analyses have been widely used to study the YREB, research on its temporal and spatial evolution characteristics remains understudied. Therefore, the exploration of the spatial evolution characteristics of green development in this study will make a valuable contribution to the literature on spatial heterogeneity,

especially as most studies do not capture the influencing factors that cause changes in GEE in the YREB.

Compared with the existing research results, the contributions of this study are mainly reflected in the following aspects: first, for the six industrial pollutants that reflect the undesired output, the global entropy weight method is used to calculate the comprehensive index of environmental pollution; second, the super-SBM model is used to calculate the GEE, which can effectively improve the comparability between effective decision-making units; third, the Theil index method is used to explore the distribution differences of GEE; ESDA is used to study the agglomeration phenomenon of green development level in the spatial distribution of the YREB; fourth, select the influencing factors of GEE from six aspects, and use the spatial Durbin model of fixed effects for spatial econometric analysis. According to the analysis results, we found the reasons that affect GEE and put forward relevant suggestions.

Data sources and research methods

Indicator selection and data sources

Based on the economic growth model, from the stochastic frontier production function, we know that labor and capital are necessary input factors, while energy consumption is the main source of undesired output. Therefore, this study selected labor, capital, and energy as input indicators. The expected output indicator is generally measured by the total economic output; this paper selected GDP as the expected output. To avoid using a single indicator of unexpected output and improve the measurement accuracy, this study selected industrial pollution emissions as the unexpected output. We used the data of 11 provinces and cities in the YREB from 2005 to 2018 for analysis; the details are listed in Table 1.

Table 1 The evaluation index system of GEE

Project	Category	Specific indicator composition	Unit
Input indicators	Labor	Number of employees at the end of the year	10 ⁴ people
	Capital	Capital stock	100 million
	Energy	Total energy consumption	10 ⁴ t of standard coal
Output indicators	Unexpected output	Industrial wastewater emission	10 ⁴ t
		Industrial COD emission	t
		Industrial solid waste emission	10 ⁴ t
		Industrial sulfur dioxide emission	10 ⁴ t
		Industrial NO _x emission	10 ⁴ t
		Industrial smoke (powder) dust emission	10 ⁴ t
	Expected output	GDP	100 million

In the above table, price-related indicators are deflated based on 2000. Among them, data on the number of employees at the end of the year and the GDP came from the “China Statistical Yearbook,” the data of total energy consumption was obtained from the “China Energy Statistical Yearbook,” and the capital stock data are not directly published. This study used the perpetual inventory method for analysis according to Zhang et al. (2004) and Shan (2008), and the relevant indicators of unexpected output came from the “China Environmental Statistics Yearbook” because of the large number of indicators, which are expressed in a comprehensive index of environmental pollution calculated by the global entropy weight method. The calculation results are presented in Table 2.

Research methods

Super-SBM model

In 2001, Tone proposed a non-radial and non-angular SBM model to solve the limitations of efficiency measurement, including unexpected output. However, with the change in input and output relaxation, multiple decision-making units can still be effective simultaneously. To this end, Tone et al. (2004) proposed a super-SBM model considering relaxation variables, which is calculated using the following equation:

$$\begin{aligned}
 \min \delta &= \frac{1 + \frac{1}{m} \sum_{m=1}^M \frac{s_{r_m}^x}{x_{r_0}}}{1 - \frac{1}{n_1 + n_2} \left(\sum_{n_1=1}^{N_1} \frac{s_{r_{m_1}}^g}{y_{r_{m_1}}^g} + \sum_{n_2=1}^{N_2} \frac{s_{r_{m_2}}^b}{y_{r_{m_2}}^b} \right)} \\
 s.t. \quad x_0 &= X\lambda + s^x \\
 y_0^g &= Y^g\lambda - s^g \\
 y_0^b &= Y^b\lambda + s^b \\
 s^t, s^g, s^b, \lambda &\geq 0
 \end{aligned}
 \tag{1}$$

$$m = 1, 2, \dots, M; n_1 = 1, 2, \dots, N_1; n_2 = 1, 2, \dots, N_2$$

where x_r^t is the input element; y_r^{gt} and y_r^{bt} are the expected and unexpected output, respectively; s_r^x is the input slack redundancy; s_r^g and s_r^b are the output slack redundancies; m, n_1, n_2 represent the number of factors of input and output indicators, respectively; δ is the efficiency value, with respect to s^t, s^g, s^b strictly decreasing monotonically.

Theil index method

The Theil index can be used to analyze the differences in GEE, and the overall differences can be decomposed into intra and inter-group differences to further determine the main reasons for these differences. This study used the Theil index to analyze the degree of difference in the development level of the green economy in the YREB. The following equation was used:

$$\begin{aligned}
 Theil &= Theil_B + Theil_W \\
 Theil_B &= \sum_{k=1}^K y_k \ln \left(\frac{y_k}{n_k/n} \right) \\
 Theil_W &= \sum_{k=1}^K y_k \left(\sum_{i \in G_K} \frac{y_i}{y_k} \ln \left(\frac{y_i/y_k}{1/n_k} \right) \right)
 \end{aligned}
 \tag{2}$$

where $Theil_B$ and $Theil_W$ represent the differences between and within groups, respectively; n is the number of regions in the YREB that are divided into K groups; and n_K is the number of regions in the K th group; y_i is the ratio of GEE in the i th region of the YREB; and y_K is the ratio of the GEE of the K th group of the YREB.

Exploratory spatial data analysis

1. Global spatial autocorrelation

Moran’s I index was used to measure the agglomeration degree and distribution of the green economic development level in the YREB. The equation is as follows:

Table 2 The comprehensive index of environmental pollution in the YREB from 2005 to 2018

	Shanghai	Jiangsu	Zhejiang	AnHui	Jiangxi	Hubei	Hunan	Chongqing	Sichuan	Guizhou	Yunnan
2005	82.37	6.83	11.87	13.39	14.4	11.91	8.58	18.49	7.42	41.22	20.9
2006	79.32	6.83	11.14	12.27	12.96	11.29	8.87	18.24	7.52	42.85	19.28
2007	79.53	6.73	10.56	11.34	12.08	11.21	8.37	18.03	8	41.91	17.74
2008	76.74	7.06	10.59	10.89	12.21	11.26	8.84	17.97	9.21	47.21	17.64
2009	76.63	7.66	10.75	11.06	12.92	12.04	9.17	18.97	10.27	48.53	19.4
2010	83.66	9.11	13.26	13.87	14.84	14.45	11.63	25.7	10.74	52.93	24.18
2011	88.42	15.16	26.31	26.94	27.42	26.23	24.29	55.16	23.98	47.8	27.47
2012	90.76	15.96	27.82	27.72	29.21	27.59	26.1	59.32	26.09	44.7	28.5
2013	91.36	15.59	27.42	26.75	28.06	26.98	25.8	55	25.97	42.49	27.41
2014	96.64	16.72	30.05	29.1	32.59	29.43	29.6	60.06	27.52	41.67	32.54
2015	95.61	14.78	26.33	24.7	25.72	26.19	26.07	54.5	24.12	39.33	28.27
2016	94.43	15.68	35.01	25.03	25.6	27.79	28.97	58.79	21.29	36.71	26.21
2017	97.76	10.06	22.18	15.45	16.91	18.19	21.08	39.61	12.76	19.69	17.48
2018	96.79	6.31	16.84	9.37	8.34	13.93	14.08	30.61	8.52	17.14	11.25

$$Moran's I = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \tag{3}$$

where n is the number of regions; Y_i and \bar{Y} are the value and mean value of GEE, respectively; S^2 is the variance of efficiency value; W_{ij} is the spatial relationship weight matrix constructed according to the “rook principle” (i.e., 1 is considered for adjacent regions); and 0 is considered for non-adjacent regions. The range of global Moran's I is $[-1, 1]$; the larger the absolute value, the more obvious the spatial agglomeration state. A significant positive value shows that there is a positive correlation in space, and a significant negative value shows that there is a negative correlation in space; 0 shows no correlation (i.e., it is randomly distributed in space).

2. Local spatial autocorrelation

Global Moran's I index averages the differences among the regions, which makes it difficult to reflect the agglomeration in local space. Therefore, it is necessary to use the local Moran's I index for further analysis. The equation is as follows:

$$Moran's I = \frac{(Y_j - \bar{Y})}{S^2} \sum_i W_{ij} (Y_j - \bar{Y}) \tag{4}$$

where Y_j is the GEE value of the region j . The meaning of other variables is the same as in Eq. (2). The local Moran's I index can be presented using a scatter diagram (Lisa diagram), which can intuitively describe the local spatial differences and agglomeration characteristics of GEE in the YREB. There are four types of Lisa diagrams: H–H, H–L, L–H, and L–L.

Analysis of temporal and spatial evolution characteristics

Time series characteristic analysis

Evaluation of green economy development level

In order to comprehensively analyze the temporal and spatial differences and regional evolution of the GEE value in the YREB, we divided YREB into three major watersheds: the upper, middle, and lower reaches. The lower reaches included Zhejiang, Jiangsu, and Shanghai; the middle reaches included Hunan, Hubei, Jiangxi, and Anhui; and the upper reaches included Yunnan, Guizhou, Chongqing, and Sichuan.

The measured GEE of the YREB from 2005 to 2018 are shown in Table 3. Overall, the highest efficiency value was 1.61, while the lowest was 0.35. The efficiency level is not high, and regional differences are significant. Regarding temporal changes, the efficiency value first decreased from 2005 to 2015 and then increased from 2015 to 2018. Since 2015, with the proposal of a new development concept, various provinces and cities have increased investment in environmental governance strategies, and the development level of the green economy in the YREB has shown a steady upward trend. From the perspective of provinces and cities, Shanghai has the highest efficiency value, followed by Zhejiang and Jiangsu; and Guizhou and Yunnan have the lowest efficiency values. From 2005 to 2018, the GEE value range of each province and city was as high as 1.019, with obvious differences. Among them, the efficiency value of Shanghai has always been greater than 1 with an advanced green development level. The average efficiency

Table 3 GEE of different provinces in the YREB from 2005 to 2018

DMU	2005	2007	2009	2011	2013	2014	2015	2016	2017	2018	Average
Shanghai	1.58	1.61	1.44	1.41	1.28	1.30	1.28	1.27	1.27	1.27	1.395
Jiangsu	0.92	0.88	0.90	0.77	0.80	0.79	0.80	0.80	0.81	0.83	0.833
Zhejiang	1.02	1.02	1.02	1.01	0.78	0.77	0.77	0.77	0.77	0.75	0.891
Anhui	0.71	0.66	0.64	0.60	0.58	0.57	0.56	0.57	0.57	0.58	0.612
Jiangxi	0.72	0.63	0.63	0.61	0.61	0.59	0.59	0.59	0.60	0.59	0.630
Hubei	0.58	0.56	0.57	0.55	0.57	0.55	0.55	0.60	0.55	0.55	0.561
Hunan	0.65	0.64	0.63	0.70	0.63	0.56	0.54	0.59	0.62	0.63	0.621
Chongqing	0.54	0.52	0.54	0.54	0.60	0.59	0.60	0.64	0.64	0.67	0.571
Sichuan	0.84	0.79	0.80	1.01	0.62	0.60	0.61	0.65	0.67	0.69	0.764
Guizhou	0.40	0.40	0.40	0.38	0.37	0.36	0.35	0.35	0.35	0.35	0.376
Yunnan	0.53	0.50	0.51	0.45	0.44	0.41	0.41	0.40	0.40	0.39	0.454
Average	0.771	0.746	0.733	0.729	0.661	0.642	0.640	0.657	0.659	0.663	0.701

value of Jiangsu and Zhejiang is also higher than 0.8, but the efficiency value of most provinces and cities is lower than 0.8, and ranges between 0.4 and 0.7, especially in Guizhou Province, where the efficiency value has been lower than 0.4 since several years. This is in sharp contrast with leading provinces and cities.

The average efficiency of the lower reaches in the YREB is 1.04 (Fig. 1), which is higher than that of the entire watershed (0.7), and the middle (0.61) and upper reaches (0.54). From the perspective of development trends, as the “leader” of green economic development in the YREB, the efficiency value of the lower reaches has an apparent downward trend. As the “follower,” the efficiency value of the middle reaches has been in a stable state. As the “lagger,” the upper reaches have been struggling to improve. The upper reaches caught up with the middle reaches in 2011 and 2012, and became stable after declining in 2013. Overall, the coefficient of

variation of the efficiency value has fluctuated little since 2013, and the development level of the green economy in the whole watershed and individual watersheds has developed steadily.

Regional difference analysis

The Theil index method was used to analyze the source of the distribution difference of green economy development in each watershed of the YREB. The Theil index of efficiency values are shown in Table 4.

Overall, the Theil index shows a fluctuating downward trend from 2005 to 2018, with successive increases and decreases. It reaches a maximum of 0.0815 in 2007 and a minimum of 0.0536 in 2013, and has fluctuated around 0.6 since 2013. The average contribution rate of the difference among the three major watersheds was 59.35%, which was

Fig. 1 The GEE of the whole watershed and each watershed in YREB from 2005 to 2018

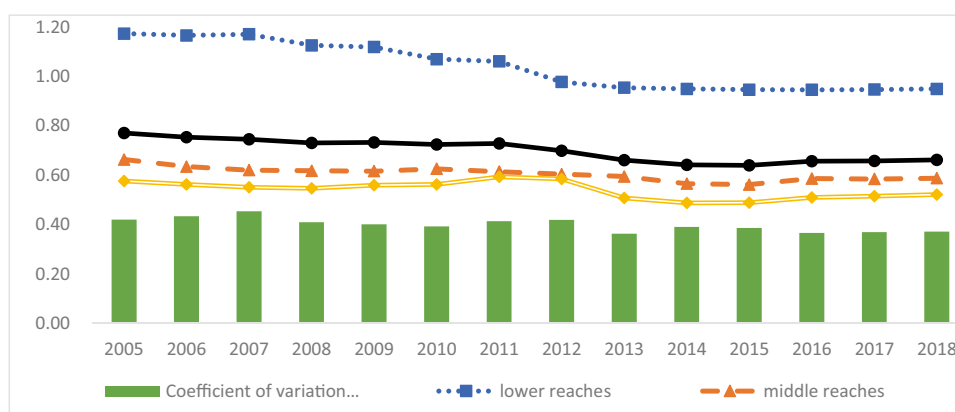


Table 4 Difference and decomposition of GEE in the YREB from 2005 to 2018

Year	Lower reaches TW	Ratio (%)	Middle reaches TW	Ratio (%)	Upper Reaches TW	Ratio (%)	Sum TW	TB	Ratio (%)	T
2005	0.0116	39.9	0.008	27.5	0.0095	32.6	0.029	0.042	58.9	0.071
2006	0.0119	38.6	0.0091	29.6	0.0098	31.8	0.031	0.044	59.0	0.075
2007	0.0143	42.9	0.0103	30.9	0.0087	26.2	0.033	0.048	59.1	0.082
2008	0.009	34.9	0.0101	38.9	0.0068	26.2	0.026	0.043	62.6	0.069
2009	0.008	30.3	0.0097	36.9	0.0087	32.8	0.026	0.041	60.6	0.067
2010	0.0107	33.4	0.0098	30.7	0.0115	36.0	0.032	0.035	52.0	0.067
2011	0.0117	29.6	0.0055	13.9	0.0223	56.4	0.040	0.032	44.9	0.072
2012	0.0174	39.9	0.0003	0.8	0.0259	59.3	0.044	0.030	40.9	0.074
2013	0.0112	63.7	0.0002	1.2	0.0062	35.1	0.018	0.036	67.1	0.054
2014	0.0126	64.0	0.0002	1.2	0.0069	34.8	0.020	0.040	67.1	0.060
2015	0.0117	60.0	0.0003	1.3	0.0075	38.6	0.019	0.040	67.1	0.059
2016	0.0107	51.4	0.0002	0.9	0.0099	47.7	0.021	0.039	62.5	0.055
2017	0.0105	54.3	0.0004	1.8	0.0085	43.8	0.019	0.038	66.2	0.057
2018	0.012	54.6	0.0005	2.2	0.0095	43.2	0.022	0.037	62.9	0.059

T is the overall gap, TB is the difference between watersheds, and TW is the difference within watersheds

significantly higher than the average contribution rate of the difference within the three major watersheds (40.65%). This indicates that the unbalanced development among the three major watersheds is a significant shortcoming that restricts the development of the green economy in the YREB.

From the analysis of differences among watersheds, the average Theil index among the three major watersheds was 0.03864, which decreased as a whole, and was consistent with the changing trend of the total Theil index. From 2005 to 2012, the Theil index among the regions showed an initial rising trend then followed by a declining one. The difference among the three major watersheds continued to expand from 2005 to 2007, and gradually narrowed from 2008 to 2012. It reached a peak of 0.0403 in 2014, and then decreased yearly (i.e., the difference among the upper, middle, and lower reaches reduced yearly), which is consistent with the conclusion in Fig. 1.

From the internal differences in the three major watersheds, the average Theil index in the watershed was 0.0271 from 2005 to 2018, and it was 0.0219 in 2018. From 2008 to 2012, the Theil index in the watershed gradually increased, the difference in the watersheds continued to expand and reached a peak of 0.437 in 2012. The average contribution rates of the differences in the upper, middle, and lower reaches were 38.9, 15.56, and 45.53%, respectively. Compared with the upper and lower reaches, the green development levels of regions in the middle reaches were more coordinated. After 2012, the net Theil index in the middle reaches decreased rapidly. This was also the main reason for the sudden decrease in the net Theil index in the three major watersheds. With the initiation of the “Several Opinions on Vigorously Implementing the Strategy of Promoting the Rise of the Central Region” by the State Council in 2012, the middle reaches saw continued acceleration in the development of emerging industries and strengthening of environmental governance. This has improved the development level of the green economy and significantly reduced differences within the watershed.

Exploratory spatial correlation analysis of GEE

To further explore whether differences in GEE among regions in the YREB are related to spatial distribution, we used the global and local *Moran's I* index for analysis. The global *Moran's I* index was calculated as shown in Table 5.

It can be seen that the global *Moran's I* indexes of GEE from 2005 to 2018 were positive and significant at the 5% level, which shows that there was a positive spatial autocorrelation in the green economic development level of the YREB (i.e., the GEE of adjacent regions in high-efficiency areas is higher, those in low-efficiency areas is lower). Overall, the global *Moran's I* index shows an increasing and decreasing trend. Its highest was in 2008 and lowest

Table 5 Global *Moran's I* index of GEE in the YREB from 2005 to 2018

Years	<i>Moran's I</i> index	Variance	Z value	p value
2005	0.34	0.153	2.879	0.002
2006	0.345	0.153	2.906	0.002
2007	0.321	0.147	2.861	0.002
2008	0.378	0.158	3.029	0.001
2009	0.366	0.162	2.874	0.002
2010	0.249	0.162	2.153	0.016
2011	0.234	0.172	2.064	0.021
2012	0.238	0.16	2.146	0.014
2013	0.295	0.142	2.789	0.003
2014	0.308	0.14	2.907	0.002
2015	0.318	0.144	2.902	0.002
2016	0.274	0.148	2.529	0.006
2017	0.297	0.149	2.665	0.004
2018	0.316	0.146	2.819	0.002

in 2011, which indicates that the development level of the green economy among regions was unstable because of the influence of adjacent provinces and cities. However, the global *Moran's I* index has been increasing since 2016, and the development level of the green economy in the YREB showed a promising trend.

Local spatial correlation analysis of GEE

To more accurately visualize the spatial agglomeration state of the GEE in the YREB, we conducted a local spatial correlation analysis. The calculation shows that the local *Moran's I* index is significant, and the efficiency value has a spatial agglomeration effect. Further, according to the *Moran's I* index scatter diagram of efficiency value in each year, the distribution table of spatial agglomeration types in the YREB in 2005, 2008, 2011, 2014, and 2018 is sorted (Table 6).

It is evident that from 2005 to 2018, most provinces and cities fall in the first and third quadrants, with the highest in the third quadrant, and relatively few in the second and fourth quadrants. Among them, Shanghai, Jiangsu, and Zhejiang have always been in the first quadrant; Anhui and Jiangxi are located in the second quadrant; Jiangxi transferred from the second quadrant to the third quadrant in 2014; and Sichuan was present in the fourth quadrant before 2011, and then moved to the third quadrant. In general, the GEE of the YREB in 2005–2018 is still at a low level, and the quadrant change of provinces and cities is insignificant, which indicates that the implementation of relevant departmental policies has not achieved the desired results. Therefore, the provinces and cities in the second, third, and fourth quadrants still need to make efforts to move towards the first quadrant.

Table 6 GEE agglomeration types in the YREB

	2005	2008	2011	2014	2018
H–H quadrant	Shanghai, Jiangsu, Zhejiang	Shanghai, Jiangsu, Zhejiang	Shanghai, Jiangsu, Zhejiang	Shanghai, Jiangsu, Zhejiang	Shanghai, Jiangsu, Zhejiang
L–H quadrant	Anhui, Jiangxi	Anhui, Jiangxi	Anhui, Jiangxi	Anhui	Anhui, Jiangxi
L–L quadrant	Hubei, Hunan, Chongqing, Guizhou, Yunnan	Hubei, Hunan, Chongqing, Guizhou, Yunnan	Hubei, Hunan, Chongqing, Guizhou, Yunnan	Hubei, Hunan, Chongqing, Guizhou, Yunnan, Sichuan, Jiangxi	Hubei, Hunan, Chongqing, Guizhou, Yunnan, Sichuan
H–L quadrant	Sichuan	Sichuan	Sichuan		

Analysis of influencing factors

Since GEE in the YREB has a significant spatial correlation, it is necessary to use the spatial econometric model to analyze its influencing factors.

Model setting and variable selection

Model setting

There are generally three spatial econometric models: the spatial error model (SEM), spatial autoregressive model (spatial lag model, SAR), and spatial Durbin model (SDM).

The general static space panel model equation is as follows:

$$\begin{cases} y_{it} = \rho\omega_i y_t + x_{it}\beta + d_i X_t \delta + u_i + y_t + \varepsilon_{it} \\ \varepsilon_{it} = \lambda m_i \varepsilon_t + v_{it} \end{cases} \quad (5)$$

where ω_i is the i th row of the spatial weight matrix of the dependent variable; ρ is the spatial autoregressive coefficient, which measures the influence of the spatial lag term $\omega_i y_t$ on y_t ; $\rho\omega_i y_t$ is the influence of the dependent variable in the adjacent area to the dependent variable in the area; $x_{it}\beta$ is the product of the parameter to be estimated and the independent variable; $d_i X_t \delta$ is the spatial lag term of the independent variable; u_i is the individual effect of region i ; and y_t is the time effect. When $\lambda = 0$, the equation is: $y_{it} = \rho\omega_i y_t + x_{it}\beta + d_i X_t \delta + u_i + y_t + v_{it}$.

This model is a spatial Durbin model, which can not only examine the influence of independent variables in adjacent areas on its own dependent variables but also examine the influence of dependent variables in adjacent areas on its own dependent variables.

When $\lambda = 0$ and $\delta = 0$, the equation is $y_{it} = \rho\omega_i y_t + x_{it}\beta + u_i + y_t + v_{it}$.

This approach is a spatial lag model, that is, only the influence of the spatial lag $\rho\omega_i y_t$ term is considered.

When $\rho = 0$ and $\delta = 0$, the equation is:

$$\begin{cases} y_{it} = x_{it}\beta + u_i + y_t + \varepsilon_{it} \\ \varepsilon_{it} = \lambda m_i \varepsilon_t + v_{it} \end{cases}$$

This model is a spatial error model, that is, only the spatial correlation of the disturbance term is considered.

We used Stata software to establish the SEM, SAR, and SDM models. After testing, the LR test values were 35.87 and 32.48, respectively, which were significant at the 1% confidence level, and the Wald test values were 71.46 and 53.81, respectively, which were also significant. The goodness of fit of the SDM model was the highest, which shows that the SDM model is the most reasonable. The Hausman test value was also significant at the 1% confidence level. Therefore, the SDM model with a fixed effect was finally used for the analysis (Lai et al. 2021).

Variable selection

Referring to relevant literature research results, the factors affecting GEE in the YREB mainly included the following:

1. Economic development. The improvement of the economic development level can promote the development of energy-saving and emission-reduction technologies, rationally optimize the energy structure, improve the efficiency of resource utilization, and promote the improvement of GEE. It is expected to have a positive impact.
2. Industrial structure. The secondary industry with high pollution and high emission, while promoting economic growth, will bring about rapid resource consumption and environmental pollution, making GEE lower than traditional economic efficiency. It is expected to have a negative impact.
3. Openness. Expanding the level of openness will help attract foreign investment and foreign advanced technologies to upgrade domestic industries, but it will also easily lead to the transfer of industries with high pollution and high energy consumption from developed countries to developing countries, which is the “pollution paradise hypothesis.” At present, the environmental supervision mechanism for foreign-investment enterprises in the YREB is relatively weak. It is expected to have a negative impact.
4. Education level. Education is not only the fundamental guarantee of technological progress, but also an important way to improve public awareness of environmental

protection, which may have an impact on the GEE. It is expected to have a positive impact.

5. Science and technology level. The development and utilization of new technologies can reduce environmental pollution emissions and improve energy utilization, thereby helping to improve GEE. It is expected to have a positive impact.
6. Environmental regulation. The higher the degree of investment in pollution control, the lower the pollution emissions associated with the expected output per unit in the production process, and the greater the promotion of GEE. It is expected to have a positive impact.

The specific indicators are listed in Table 7.

Empirical results and analysis

The above variables were empirically analyzed using Stata 14.0 software (original) in the fixed effect SDM model. The results are listed in Table 8.

The spatial lag coefficient of the explanatory variable cannot accurately explain its spillover effect owing to the existence of the spatial effect. Therefore, the spillover effect of SDM is decomposed using the partial differential method proposed by Lesage, which can be divided into direct (local effect), indirect, and total effect. According to the regression results, the spatial rho coefficient is significantly positive, which indicates an apparent positive spillover effect in the

GEE among regions (i.e., the regions with higher development levels of the green economy can promote the development of adjacent regions through technology transfer).

The specific influence of each factor is as follows:

- (1) Economic development can significantly promote GEE, and the coefficients of local effect, as well as spatial direct and indirect effect are significantly positive (Qiu et al 2020; Xu et al 2020). This shows that the higher the economic development level in the YREB, the more it can introduce and carry out new technologies, adjust and optimize the energy structure, as well as improve the resource utilization rate and the GEE.
- (2) The industrial structure can significantly hinder GEE, and the coefficients of local and spillover effects are significantly negative (Tu et al 2019). This shows that the higher the proportion of the secondary industry, the more it hinders green economic development. While promoting economic growth, secondary industries with high pollution will cause insufficient resource supply and severe environmental degradation, which limits the sustainable development of the economy, resources, and environment. The spatial direct and indirect effect coefficients are insignificant, which indicates that the industrial structure of adjacent regions has no evident spatial impact on GEE.
- (3) The degree of openness has no significant positive effect on GEE (Kardos 2014). The coefficient of the direct spatial effect is positive and not apparent, which

Table 7 Variable description and descriptive statistics of influencing factors

Influencing factors	Variable	Illustrate	Mean	Standard deviation
Economic development	LAGP	Per capita GDP takes the natural logarithm	10.35732	0.720629
Industrial structure	ISG	Proportion of secondary industry in GDP	0.456331	0.057465
Openness	FG	Proportion of foreign direct investment in GDP	0.025649	0.014682
Educational level	EG	Proportion of education expenditure in financial expenditure	0.164665	0.023003
Scientific and technological level	SG	Proportion of science and technology expenditure in financial expenditure	0.020289	0.015163
Environmental regulation	PG	Proportion of industrial pollution control investment in GDP	0.001104	0.000695

Table 8 SDM model regression results of influencing factors

Explanatory variable	Coefficient		Effect decomposition			Spatial rho
	Local effect	Spillover effect	Direct effect	Indirect effect	Total effect	
LAGP	0.392*** (11.46)	0.559*** (6.69)	0.340*** (8.33)	0.244*** (3.76)	0.584*** (11.64)	0.624*** (5.56)
ISG	-0.367** (-1.96)	-0.673* (-1.80)	-0.295 (-1.31)	-0.354 (-1.16)	-0.649*** (-3.10)	
FG	0.310 (0.36)	-3.963** (-2.56)	1.114 (1.14)	-3.229** (-2.54)	-2.116* (-1.86)	
EG	-0.005 (-0.01)	3.266** (2.57)	-0.552 (-1.07)	2.617*** (2.85)	2.065** (2.11)	
SG	2.182* (1.68)	-3.875* (-1.83)	3.097* (1.86)	-4.210** (-2.02)	-1.113 (-1.00)	
PG	1.396** (2.08)	140.8406*** (4.90)	-22.337 (-1.20)	112.568*** (4.55)	90.231*** (3.86)	

***, **, and * indicate significance at the 1, 5, and 10% confidence levels, respectively

indicates that the technology spillover effect brought about by the introduction of foreign capital in adjacent regions is not obvious (Ren 2020; Li 2020). However, the coefficient of the spatial indirect effect is significantly negative, which shows that foreign investment in the various areas of the YREB has resulted in a crowding out effect and aggravated environmental pollution in the adjacent regions, indirectly reducing GEE.

- (4) Education level has no significant negative effect on GEE, and the coefficient of local effect is very low (Wu and Zhou 2020). This shows that the impact of increasing education expenditure to improve the GEE is not apparent. However, the coefficient of the spatial indirect effect is significantly positive. Increasing investment in education can improve the regional human capital, and the adjacent areas can promote the development of the areas surrounding through spillover of the knowledge economy.
- (5) The level of science and technology has a significant positive impact on GEE (Walz et al. 2017), and the coefficients of the local and direct spatial effects are both significantly positive (Li and Ouyang 2020). This shows that increasing investment in technology will inevitably facilitate the development of the green technology innovation industry to promote technological progress and improve the green economic development. However, the indirect effect of space is significantly negative. An increase in technological investment forms a “siphon effect”; the elements of technological innovation in the surrounding areas must flow to adjacent high-level areas, which hinders surrounding environmental innovation.
- (6) Environmental regulation has a significant positive effect on GEE (Zhou et al. 2020). The results show that enterprises can purchase and introduce new technologies and equipment by increasing investment in industrial pollution treatment, which significantly reduces the emission of unexpected output. Further, the spatial indirect effect is significantly positive; therefore, the increase of environmental governance investment has an apparent externality to the surrounding area.

Conclusions and recommendations

Research conclusion

We used the super-SBM model to calculate the GEE in the YREB from 2005 to 2018, combined with the Theil and Moran indexes to explore its temporal and spatial evolution characteristics. Further, we selected the spatial Dubin model to analyze the factors influencing GEE. We drew the following conclusions:

1. From the time series development analysis, GEE in the YREB shows a declining trend followed by a subsequent rise. The average efficiency in the lower reaches is higher than that in the middle, upper reaches, and entire watershed. Compared with the upper and lower reaches, the green development levels of regions in the middle reaches were more coordinated. The unbalanced development among the three major watersheds is a significant shortcoming that restricts the development of the green economy in the YREB.
2. The spatial evolution analysis shows that the number of areas with high GEE in the YREB decreased. The global Moran's I index shows that there is a spatial positive autocorrelation in the green economy development level. The local Moran's I index scatter chart shows that most provinces and cities fall in the first and third quadrants, with more in the third quadrant, and fewer in the second and fourth quadrants.
3. From the analysis of influencing factors, the spatial rho coefficient was found to be significantly positive, and there was an apparent positive spillover effect among the GEE regions. Economic development, scientific and technological level, and environmental regulation have a significant positive effect on the GEE. The influence of industrial structure was significantly negative. In contrast, the effects of openness and education level were non-significant.

Policy recommendations

Based on these conclusions, we put forward the following suggestions to further improve GEE in the YREB:

1. Improve factor utilization. From the perspective of factor input, the YREB must improve capital utilization, encourage green technology innovation, and accelerate the realization of a new model of mutual promotion between domestic and international dual cycles; increase human capital accumulation, improve labor quality, and continuously optimize the level of labor supply; accelerate green technology innovation and promote green energy substitution to improve energy utilization. From the perspective of factory output, while promoting economic growth, the YREB must reduce undesired outputs and confront pollution, so as to improve the GEE of the YREB.
2. Collaborative industrial planning. The differences among the three major watersheds are an important shortcoming that restricts the development of the green economy in the YREB. Therefore, it is necessary to attach great importance to the synergy of policies between regions. It is necessary to strengthen the effective agglomeration of capital, human resources, innovative resources, give full play to the advan-

tages of scale effect, and promote the common development of green economic development among regions.

3. Adjustment, optimization, and upgrading of the industrial structure should be promoted. The industrial structure has a restraining effect on improving the development level of the green economy in the YREB, and the adjustment of industrial structure is imperative. Technological transformation in the fields of steel, textile, and non-ferrous metals must be accelerated. Enhancing cleaner production in key industries, and eliminating backward production capacity are also essential. Furthermore, new energy and materials to improve the level of technological research and development should be formulated (Shahzad et al. 2021). The industrial chain should be taken as a whole, and the interaction between upper and lower reaches industries must be strengthened. Finally, regional coordinated development should be promoted.
4. Investment in technological innovation must be increased. The technology level has a positive effect, while the impact at the educational level is non-significant. It is clear that we need to increase science and technology investment, promote technological innovation, and improve the green education system. All provinces and cities should adapt to their development strategies, tap into the potential of their scientific and technological innovation resources, build an independent, controllable, safe, and efficient industrial chain supply chain, and improve upon their original innovation level and ability (Xia et al. 2022). They should also expediate the establishment of critical scientific and technological infrastructure and acknowledge and support the crucial role of scientific research institutions, such as universities and research institutes.

Limitation and future recommendation

This study encountered several limitations. (1) Owing to the hysteresis of data, the latest efficiency value could not be measured. (2) The efficiency value calculated by the SUPER-SBM model may also have had shortcomings, and some better estimation methods require further study. (3) There may be some unconsidered influencing factors that also affect the efficiency value.

Author contribution Writing-original draft, methodology, resources, writing-review and editing: Y. Song; conceptualization, data curation, funding acquisition: X. Sun; formal analysis, investigation: P. Xia; project administration, software: Z. Cui; supervision, validation, visualization: X. Zhao.

Funding This work was supported by the Natural Science Research Project of Colleges and Universities in Anhui Province (Grant Nos.

KJ2019ZD45, KJ2020A0120), the Social Science Planning Project in Anhui Province (Grant No. AHSKF2021D29), the Innovation Development Research Project in Anhui Province (Grant No. 2021CX053), and the National Natural Science Foundation of China (Grant No. 71901088).

Data availability The datasets used or analyzed during the current study are available from the yearbooks or the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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