



# Research on the ecological efficiency of the Yangtze River Delta region in China from the perspective of sustainable development of the economy-energy-environment (3E) system

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## Abstract

Balancing the relationship between economic development, energy utilization, and environmental protection has become an important task in China's Strip Planning and Construction. This article takes the annual panel data from 2005 to 2015 as the research object firmly grasps the research basis of the Economy-Energy-Environment (3E) System, and focuses on building a new research framework from both internal and external perspectives of the eco-efficiency index to achieve the exploratory research on regional ecological efficiency changes and influencing factors. First of all, it uses super-efficient slacks-based measure (SBM) model which introduces undesired outputs to measure eco-efficiency at different levels. Then, it applies Malmquist index to calculate total factor productivity and structural efficiencies. Finally, it selects six indicators and uses the STIRPAT regression model to analyze external factors. The results indicate that (1) the overall ecological efficiency is effective and maintaining a good momentum of development. Among all the cities and provinces, Shanghai and Zhejiang provinces play the role of "stabilizers," while Jiangsu and Anhui provinces act as "accelerators." (2) All 41 prefecture-level cities can be divided into four different types, i.e., "high-high", "low-high", "low-low," and "high-low" cities, and there is an obvious phenomenon of spatial clustering; (3) pure technical efficiency and scale efficiency is the core driving force for the improvement of ecological efficiency. (4) Anhui and Jiangsu provinces show a U-shaped relationship, while Zhejiang province shows an inverted U-shaped relationship.

**Keywords** Ecological efficiency · Economy-Energy-Environment (3E) System · Super-efficient SBM model · Malmquist index · STIRPAT model · Panel data regression

## Introduction

Yangtze River Delta region is made up of several closely connected cities in three provinces, i.e., Zhejiang, Jiangsu,

and Anhui, with Shanghai as the core. It traverses east and west, radiates north and south, and crosses the river and reaches the sea. It is one of the regions with the densest population and industries in the country, with the most developed economy, science, and technology. It is also one of China's "two vertical and three horizontal" urbanization pattern of optimal development and key development areas. In 2016, the total economic volume of "one city and three provinces" in the Yangtze River Delta region is as high as US\$2.67 trillion, accounting for approximately 22.72% of the total national economic volume. However, through the "excellent achievements" resulted in economic construction, we must recognize the increasingly severe ecological problems—the massive consumption of scarce resources, the destruction of beautiful environments, and the extensive economic growth model of "high input, high consumption, high pollution, and low efficiency." Water pollution, soil pollution, and haze frequency are the most direct true portrayal. Therefore, on the

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basis of the general principle of “equilibrium of population and resource environment and unity of economic, social and ecological benefits,” the research framework of the economy-energy-environment (3E) system should be established. And through the 3E System, the study of the dynamic and causes of the ecological pattern of the Yangtze River Delta region during the “11th Five-Year” (2006–2010) and “12th Five-Year” (2011–2015) planning has great theoretical and practical significance on the restoration and control of the ecological environment in the Yangtze River Basin and the promotion and coordination of regional economic development. It also has clear guidance and leadership significance to carry out ecological protection and compensation work and develop the green environmental protection industry throughout China in the “13th Five-Year” (2016–2020) and its later planning.

If there was more room for maneuver in the past period of rapid growth, then in the new era, the continuous expansion of the economic scale and increase in resources and environmental consumption could have led to an increasingly hard constraint and firm pressure on the ecosystem. To promote the transformation of the economy into a green and low-carbon sustainable growth mode, research on ecological efficiency is indispensable and emergent (2001). As early as 1972, the “Roman Club” first proposed the growth limit theory (2013) which led to discussions on the relationship between resources, environment, and economic development. Schaltegger and Synnestvedt (2002) then proposed the concept of “eco-efficiency” in 1990 to measure the impact of economic activity on resources and environment. Therefore, the World Business Council for Sustainable Development (Stigson 2001; Schaltegger and Sturm 1990; Kicherer et al. 2007; González et al. 2014) presented a widely recognized definition of eco-efficiency in 1992, that is, to provide competitive pricing goods and services that can meet human needs and improve the quality of life, and at the same time to reduce the ecological impact and resource intensity of the whole life cycle to at least a level consistent with the estimated carrying capacity of the earth. At present, domestic and foreign scholars have achieved outstanding results in the research on the binary systems of “energy-economy” and “environment-economy.” However, as the research deepens, the importance of integrating energy, environment, and economy into one system as a whole, namely the 3E ternary system framework that was jointly constructed by international energy research and related environmental protection agencies, has been discovered.

(1) The study of “Energy-Economy” Binary System: The system efficiency study mainly focuses on the measurement of energy efficiency, namely the single-factor energy efficiency (SFEE) and total-factor energy efficiency (TFEE) which play an important role in the green economy. In 1996, Patterson (1996) was the first to measure efficiency using energy intensity, which only takes energy as a single input to

calculate the gross domestic product (GDP) while neglecting other key inputs, such as capital and labor. Then, Rao and Kumar (2006) proposed a total-factor framework and initially put forward the TFEE index, which is constructed using data envelopment analysis (DEA) to derive Malmquist-Luenberger productivity indexes from overcoming the reliability of input-output measurement and the lack of carbon emission data. Besides, the research framework was gradually extended from single-factor energy efficiency to multi-input and multi-output all-factor energy efficiency (TFEE). After first attempt using TFEE index method of Rao and Kumar, Fan (2013) explored the factors that affect the environmental efficiency of different provinces, and applied various forecasting models to predict the further energy efficiency from 2011 to 2012, after examining the energy regulation efficiency after China’s accession to the World Trade Organization. Wu et al. (2017) used the DEA model with constant input-oriented scale returns to test the energy efficiency of Yangtze River Delta urban agglomeration; Tang et al. (2017) measured the total-factor energy efficiency of cities in the Yangtze River Delta region and found that it showed stage fluctuation. (2) The study of “Environment-Economy” Binary System: Focusing on the measurement of environmental efficiency at different levels and the analysis of influencing factors, such as Woo et al. (2015), followed closely by Yang et al. (2015), universally combined ecological energy in industry and the region. It is called ecological efficiency. Fan and Wang (2013) used the SBM directional distance function and the Lunenberg productivity index; Li et al. (2013) used the DEA method and Tobit model to measure the environmental efficiency of 30 provinces in China and analyzed the effects of the influencing factors. It is easy to see that the DEA method is still one of the most commonly used ways in efficiency measurement. Therefore, the selection of input-output indicators becomes very important, and whether the indicators can accurately cover and reflect the main aspects of economic development becomes the key.

However, as research progresses, the importance of integrating energy, environment, and economy into one system as a whole has become increasingly prominent. Therefore, international energy research and related environmental protection agencies jointly constructed the 3E system framework, in order to analyze the development rules and internal links between the three. In terms of research mechanism, Zuo et al. (2017) and Zhao et al. (2018) both studied the Beijing-Tianjin-Hebei region, as the research object, and constructed models of sustainable development of a 3E system and a 3E system simulation model under the CT mechanism based on system dynamics theory. The former not only clearly shows the complex logical relationship between the factors but also reveals the process of the 3E system. The latter studies the internal operation mechanism of the carbon emissions trading system and its impact on 3E by combing the related mechanisms of

the CT market, CO<sub>2</sub> emissions, energy consumption, and GDP. While from the angle of research, based on the research on energy efficiency and economic efficiency in the binary system theory, researchers gradually shift the perspective to eco-efficiency index. Yang et al. (2013) incorporated “three industrial wastes” into the input index, and Cheng et al. (2014) added the panel data for the total areal energy consumption to the indexes. Then Bowden and Payne (2009) added the panel data for the total areal energy consumption to the indexes. Therefore, the study of ecological efficiency needs to introduce DEA method with the unexpected output. Scholars Zhang and Choi (2013), followed by Song and Wang (2013), took investment expenditure such as labor force and investment in fixed assets as input index and took GDP as the output index of ecological efficiency research. Based on the “three industrial wastes” index, they included the total energy consumption in production as a function of production, and examined the changes in technical efficiency or total factor productivity (2017), and did not estimate the resource or environmental efficiency separately. There is no in-depth exploration of the extent and mechanisms of environmental regulation’s specific impact on these changes in efficiency (2012). It should be noted that most studies regard resource and environment as input cost or “bad” (unexpected) output factor in the setting of input-output index of efficiency measurement, that is, the real ecological indexes such as electric power, water, and energy indexes are regarded as the result of poor or low efficiency, and they are mixed with the most pollutant discharge indexes (such as “industrial three wastes”) to reflect the indexes of pollution output, making significant error on the accuracy of ecological efficiency measurement.

In addition, in the analysis and discussion of the influencing factors, only a few studies have combined the DEA model and the measurement analysis method, and discussed the relationship between environmental regulation and the efficiency of ecological resources on the regional (Cheng et al. 2016; Li et al. 2013; You and Gao 2013). Although the relationship between the two has not yet formed a unified conclusion, some research conclude that the two are in line with the “U” type relationship, some scholars have proposed an inverted U-shaped relationship, and more scholars even believed that the current environmental regulation is not conducive to improve energy efficiency.

After combining and summarizing the outstanding achievements of domestic and foreign scholars, this article has the following innovations: (1) research basis—the transition is from the binary theory of “Energy-Economy” or “Environment-Economy” to 3E system theory, that is, to the “eco-economy” system, the theories and methods of resource efficiency and environmental efficiency are integrated and innovated from the angle of system theory and cybernetics. (2) Research direction—it focuses on the Yangtze River Delta region and researches the regional, provincial, and prefectural

level and demonstrates the level of ecological efficiency in all aspects and evaluates the quality of economic development from the macro level to the micro level. (3) Eco-efficiency calculation model—this paper selects the improved super-efficiency SBM model that introduces non-expected outputs and includes pollutant emissions as non-expected outputs in the model to avoid ecological efficiency deviation caused by improper treatment of non-expected productions. At the same time, it solves the problem that there is no ranking between active decision-making units, which makes the research conclusion more comprehensive and scientific. (4) In this paper, the Malmquist index is used to calculate the total factor productivity and its structural efficiency (technology progress index, pure technical efficiency index, and scale efficiency index). The decomposition index is used as an endogenous factor to promote the improvement of ecological efficiency, and then panel data regression is used to explore and test the impact direction and impact degree. (5) In this paper, six factors, such as the level of economic development, industrial structure, and utilization of foreign capital, are taken as external factors. The STIRPAT model is used to clarify the ecological efficiency structure of the Yangtze River Delta area and different provinces and examine whether there is a U-type relationship between the level of economic development and ecological efficiency.

In summary, from the three levels of regions, provinces, and prefecture-level cities, this paper uses the annual panel data from 2005 to 2015 to study the changes in ecological efficiency and its influencing factors in the Yangtze River Delta region based on 3E System, both horizontally and vertically. First, the eco-efficiency of different levels is measured by using the model of super-efficient SBM that introduces undesired outputs. Then, this paper uses the Malmquist index to calculate total factor productivity and other structural efficiencies, as well as the panel data regression to judge the impact of endogenous factors on ecological efficiency. Then we select the economic development level, the industrial structure, and the level of utilizing foreign capital, as the external influencing factors, and explain the changes from the regional and provincial levels respectively. Finally, according to the results of the empirical analysis, this paper excavates the essential characteristics of ecological efficiency among different regions, explores the sustainable development process of the 3E System, and puts forward the ecological protection measures to be taken in the future economic development.

## Material and methods

### Materials

This paper introduces the research methods from three modules of ecological efficiency measurement, endogenous

influence factors, and external influence factors, and the overall process is shown in the Fig. 1.

**Methods**

**Undesirable output model: based on SBM**

Since the innovative research on efficiency of Banker et al. (1988), the research of DEA method has been extensive and thorough. DEA method has been proved to be an effective tool in measuring efficiency and productivity between similar decision units. Tone (2002) put forward a non-radial DEA model in 2002: a method to evaluate efficiency based on slacks-based measure. What is different from the traditional BCC and CCR models is that the SBM model directly integrates the slack variables into the objective function, which makes the economic interpretation of the SBM model maximize the actual profit, not just the benefit ratio. And in the same year, Tone (2001) announced another super-efficiency SBM model to evaluate the efficient and hereby remedy a defect that fails to calculate all efficiency values. Through this method, the evaluation is first from the  $DMU_s$  and then to the  $DMU_s$  tests based on the super-efficiency method. In order to better address the relationship between inputs, outputs, and

pollution, Tone (2004) proposed the SBM model for adding unexpected outputs. Similarly, this paper supposes the decision unit  $DMU_s$  has  $m$  kinds of factor inputs and  $S$  types of outputs. But among the  $S$  types of outputs,  $S_1$  outputs are expected outputs, and  $S_2$  non-expected outputs.

$$\min \rho = \frac{1 - (1/m) \sum_{i=1}^m (w_i^- / x_{ik})}{1 / (r_1 + r_2) \left( \sum_{s=1}^{r_1} w_s^d / y_{sk}^d + \sum_{q=1}^{r_2} w_q^u / y_{qk}^u \right)}$$

$$s.t. \quad x_{ik} = \sum_{j=1}^n x_{ij} \lambda_j + w_i^- \quad i = 1, \dots, m$$

$$y_{sk}^d = \sum_{j=1}^n y_{sj}^d \lambda_j - w_s^d \quad s = 1, \dots, r_1$$

$$y_{qk}^u = \sum_{j=1}^n y_{qj}^u \lambda_j + w_q^u \quad q = 1, \dots, r_2$$

$$\lambda_j > 0 \quad j = 1, \dots, n$$

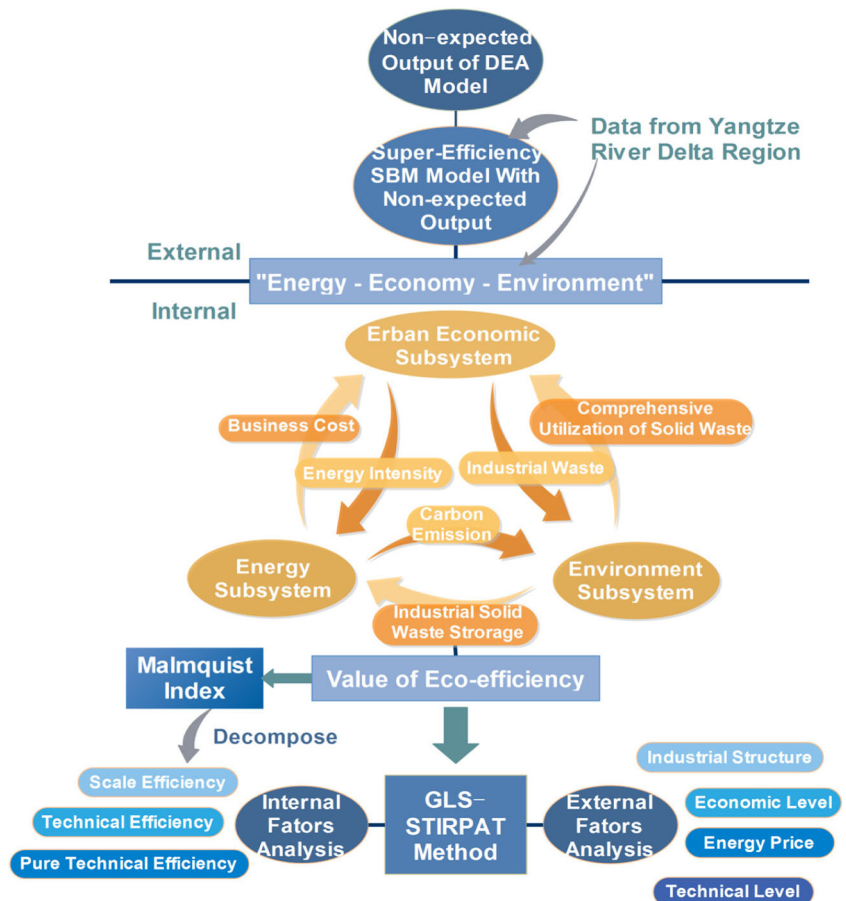
$$w_i^- \geq 0 \quad i = 1, \dots, m$$

$$w_s^d \geq 0 \quad s = 1, \dots, r_1$$

$$w_q^u \geq 0 \quad q = 1, \dots, r_2$$
(1)

Among them,  $\rho^*$  is the efficiency evaluation index;  $x_0B$  is the input vector of the decision unit;  $y_0^e$  is the expected output vector of the decision unit;  $y_0^b$  is the unexpected output vector

Fig. 1 Research methods for the whole paper



of the decision unit;  $X$ ,  $y^g$ , and  $y^b$  are the input matrix, expected output matrix, and undesired output matrix of the decision unit respectively; each input-output slack and  $\lambda$  represent a column vector. When  $1 < \rho$ , the decision unit was valid, equivalent to  $s^- = 0$ , namely there was no input-output slack under the best condition; when  $0 < \rho < 1$ , the decision-making unit was ineffective, and it could also be improved to achieve the best efficiency, namely:

$$\min \rho = \frac{1/m \sum_{i=1}^m (\bar{x}/x_{ik})}{1/(r_1 + r_2) \left( \sum_{s=1}^{r_1} \bar{y}^d/y_{sk}^d + \sum_{q=1}^{r_2} \bar{y}^u/y_{qk}^u \right)}$$

$$s.t. \quad \bar{x} \geq \sum_{j=1, \neq k}^n x_{ij} \lambda_j \quad i = 1, \dots, m$$

$$\bar{y}^d \leq \sum_{j=1, \neq k}^n y_{sj}^d \lambda_j \quad s = 1, \dots, r_1$$

$$\bar{y}^u \geq \sum_{j=1}^n y_{qj}^u \lambda_j \quad q = 1, \dots, r_2$$

$$\lambda_j > 0 \quad j = 1, \dots, n$$

$$\bar{x} \geq x_k \quad i = 1, \dots, m$$

$$\bar{y}^d \leq y_k^d \quad s = 1, \dots, r_1$$

$$\bar{y}^u \geq y_k^u \quad q = 1, \dots, r_2$$
(2)

**The Malmquist productivity index**

The index was first proposed by Malmquist (1953), and now the Malmquist index is based on the theory of Shephard (1970), Caves and Diewert (1982), Nishimizu and Page (1982), and Färe et al. (1994). They calculated the Malmquist exponent by introducing the DEA method to investigate the dynamic production efficiency between multi-input and multi-output variables in different periods, so as to measure the change of total factor productivity and analyze the influencing factors that drive the change of productivity.

According to the definition of the Malmquist index by Färe equal to 1992 years, its expression is as follows:

$$M(x_{t+1}, y_{t+1}, x_t, y_t) = \sqrt{\frac{D^t(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^{t+1}(x^t, y^t)}} \quad (3)$$

In Eq. (3),  $D^t(x^t, y^t)$  and  $D^{t+1}(x^t, y^t)$  are input distance functions compared with frontier technology according to the production point in the same time period, that is,  $t$  and  $t + 1$ , respectively.  $D^t(x^{t+1}, y^{t+1})$  and  $D^{t+1}(x^{t+1}, y^{t+1})$  are input distance functions obtained by comparing the production point with the frontier technique during the mixing period, respectively.

According to Färe et al.’s research, the total factor productivity (TFP) is decomposed into two parts: technological progress change and technical efficiency change. The technological efficiency change can be further decomposed into pure technical efficiency change and scale efficiency change.

Formula (3) can be transformed into:

$$M(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D^{t+1}(x^{t+1}, y^{t+1}|VRS)}{D^t(x^t, y^t|VRS)} \cdot \frac{D^{t+1}(x^{t+1}, y^{t+1}|CRS)}{D^{t+1}(x^{t+1}, y^{t+1}|VRS)} \cdot \frac{D^t(x^t, y^t|VRS)}{D^t(x^t, y^t|CRS)} \cdot \sqrt{\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \cdot \frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)}} = \text{pech} \times \text{sech} \times \text{techch} \quad (4)$$

Among them, the first term represents pure technological efficiency changes (Pech), the second term represents scale efficiency changes (Sech), and the third one represents technological progress (Tech). When  $\text{Pech} > 1$ , it means that the improvement of management level or system does increase the production efficiency; when  $\text{Sech} > 1$ , it means that there is scale efficiency in production activities; when  $\text{Tech} > 1$ , it means that due to the use of new technologies or the emergence of new inventions, the production frontier is facing forward and technological progress has been achieved; when  $\text{Tfpch} > 1$ , it means that production efficiency has improved. On the contrary, when the above index is less than 1, it indicates that the corresponding efficiency is degraded. Through the decomposition of TFP, we can measure the changes in efficiency and technology, and we can also study the intrinsic factors that are beneficial to the promotion of TFP growth.

**The STIRPAT model**

Ehrlich and Holden proposed the classic impact, population, affluence, and technology (IPAT) identity in 1971. In order to analyze the influence of population on the nonlinear change of environment, York et al. proposed a stochastic model of environmental pressure based on the IPAT identity. The stochastic model of environmental stress is widely used to analyze the determinants of environmental change, that is, the impact of human activities on environmental stress. In the same way, this paper improves the STIRPAT model and uses environmental efficiency as a measure of environmental pressure. Based on panel data, it analyzes the impact of force on environmental stress, of which are the economic development level, industrial structure, utilization of foreign capital, government environmental regulation, urbanization level, and technological progress. Obviously, the improved STIRPAT model is applicable to the related research on the factors affecting eco-efficiency and has strong scientific newness and coherence.

The classic IPAT identity equation is:

$$\text{Impact}(I) = \text{Population}(P) \times \text{Affluence}(A) \times \text{Technology}(T) \quad (5)$$

which considers all factors, such as environmental pressure, energy consumption, and environmental impact. In this equation,  $P$  stands for the population, it reflects the change of population scale;  $A$  is the level of affluence, it is usually

expressed in terms of GDP per capita; and  $T$  represents the technical level, which is usually expressed in terms of energy consumption or pollutant emissions per unit GDP. The main function of IPAT identity is to explore the driving factors that influence energy consumption or pollutant emission.

In order to analyze the nonlinear effect of population on the environment, York et al. (2003), based on the IPAT identity, estimates the environmental pressure by regression of population, wealth, and technology and proposed an environmental pressure stochastic model (Stochastic Impacts by Regression on PAT), referred to as STIRPAT model. The expressions are as follows:

$$I = aP^b \times A_c \times T^d \varepsilon \quad (6)$$

If it is assumed that  $a = b = c = d = e = 1$ , the STIRPAT model is reduced to the IPAT identities. In practical applications, Formula (6) is usually subjected to logarithmic processing:

$$\ln I = \ln a + b(\ln P) + c(\ln A) + d(\ln T) + \ln \varepsilon \quad (7)$$

In the formula,  $\varepsilon$  represents the model random error;  $b$ ,  $c$ ,  $d$  represent the model elasticity coefficient, which means that for each 1% change in  $P$ ,  $A$ ,  $T$ ,  $I$  changes  $b\%$ ,  $c\%$ , and  $d\%$  respectively. Based on this, the paper improves the model and selects the economic development level, industrial structure, foreign capital utilization level, government environmental regulation, urbanization level, and technological progress level as the external influence factors of ecological efficiency in order to achieve better results.

## Indicator selection and data sources

### Eco-efficiency measurement indicators

#### Input indicators

According to the nature of the factors required for production activities, input indicators include three categories of resource input, capital investment, and labor input.

**Resource input:** Select the total energy consumption and total water consumption in different provinces and cities. Due to the different types and dimensions of energy charges in different regions, the consumption of one-time primary energy (coal, oil, and natural gas) is unified and converted into a unit of “10,000 tons of standard coal.” The total consumption of water resources is expressed in terms of the total amount of water used in various regions.

**Capital investment:** The fixed asset investment of different provinces and cities is chosen, and the price of fixed assets is reduced in the base period of 2000.

**Labor input:** The total number of urban employees, private enterprises, and individual employees in different provinces

and cities is selected. Due to the lack of educational level data, it is assumed that there is no difference in the quality of the labor force.

#### Output indicators

Each individual person has different expectations and demands for products and services created in economic activities and their appendages, so output indicators are strictly divided into two categories: expected output and non-expected output.

**Expected output:** The regional GDP of different provinces and cities is selected to reflect the added value of products and services created by humans in economic activities, and the constant price reduction is based on the base period of 2000.

The GDP of different provinces and cities is chosen to reflect the added value of products and services created by human beings in economic activities, and reduction in constant prices for the 2000 base period.

**Unexpected output:** The industrial dust emission and sewage discharge from different provinces and cities are selected to demonstrate the waste of resources and environmental damage caused by human beings in the process of creating economic value.

### Data sources

The object of this study is the Yangtze River Delta region, including the city Shanghai and another three provinces Zhejiang, Jiangsu, and Anhui, and has jurisdiction over 41 cities. Given the completeness and availability of data, this paper decides to use the annual panel data of the four provinces and 41 cities for the period from 2005 to 2015. Its time span coincides with the time of the “11th Five-Year Plan” (2006–2010) and the “12th Five-Year Plan” (2011–2015) of China, so it is more realistic to measure and evaluate the changes in the environmental efficiency of different provinces and cities in the two five-year plans and their impacts.

The data used in this paper are sourced from the Jiangsu Statistical Yearbook, Zhejiang Statistical Yearbook, Anhui Statistical Yearbook and Shanghai Statistical Yearbook, China Statistical Yearbook, and China Environmental Yearbook from 2005 to 2016.

## Results of empirical analysis and discussion

### Calculation of ecological efficiency in Yangtze River Delta

The economic foundations of different provinces and cities are not the same. It is generally believed that the scale of compensation is a variable that seeks to maximize the desired output and minimize the input and undesired output to achieve higher

efficiency. Therefore, this paper uses the super-efficient SBM model under the condition of variable returns to scale (VRS), from the regional level to the provincial level, and then to the prefecture-level city level, to measure and comprehensively analyze the ecological efficiency. The results obtained from MaxDea 6.3 Professional Edition software are as follows.

From Fig. 2 and Table 1, we can see that the overall eco-efficiency shows a slight upward trend, and the average eco-efficiency during the “11th Five-Year Plan” and the “12th Five-Year Plan” periods is 0.956 and 1.111 respectively. The level of eco-efficiency during the “12th Five-Year Plan” period is about 16.210% higher than that during the “11th Five-Year Plan” period. This means that during the 10 years from the “11th Five-Year Plan” to the “12th Five-Year Plan,” the quality of economic development in the Yangtze River Delta has improved slightly, and the “ecological cost” for economic development has declined slightly. The main tasks for “building a resource-saving, environment-friendly society” in the annual plan have basically completed. At the same time, the Yangtze River Delta region has achieved good results in the development of regional integration, especially in the two areas of economic construction and ecological civilization

construction. The eco-efficiency changes in the four provinces of Shanghai, Zhejiang, Jiangsu, and Anhui show a high degree of consistency. Although differences in directions and frequencies occurred in individual years, they do not affect the overall results.

From the perspective of development among different provinces, the eco-efficiency of Shanghai and Zhejiang provinces has remained active, with Shanghai staying put and Zhejiang province experiencing a slight increase in volatility; the eco-efficiency of Anhui and Jiangsu provinces has evolved from ineffective to effective, and there is a significant increase in volatility. At the same time, the improvement of ecological efficiency of these two provinces plays a more substantial role in promoting the overall development of environmental capability in the Yangtze River Delta. The average eco-efficiency for Shanghai, Zhejiang, Jiangsu, and Anhui is 1.000, 1.063, 0.994, and 0.948 during the “11th Five-Year Plan” period, and 1.000, 1.143, 1.156, and 1.143 during the “12th Five-Year Plan” period respectively. It shows that the environmental effects of the Yangtze River Delta have been continuously improved, and the utilization efficiency of resources and environment in different provinces has been

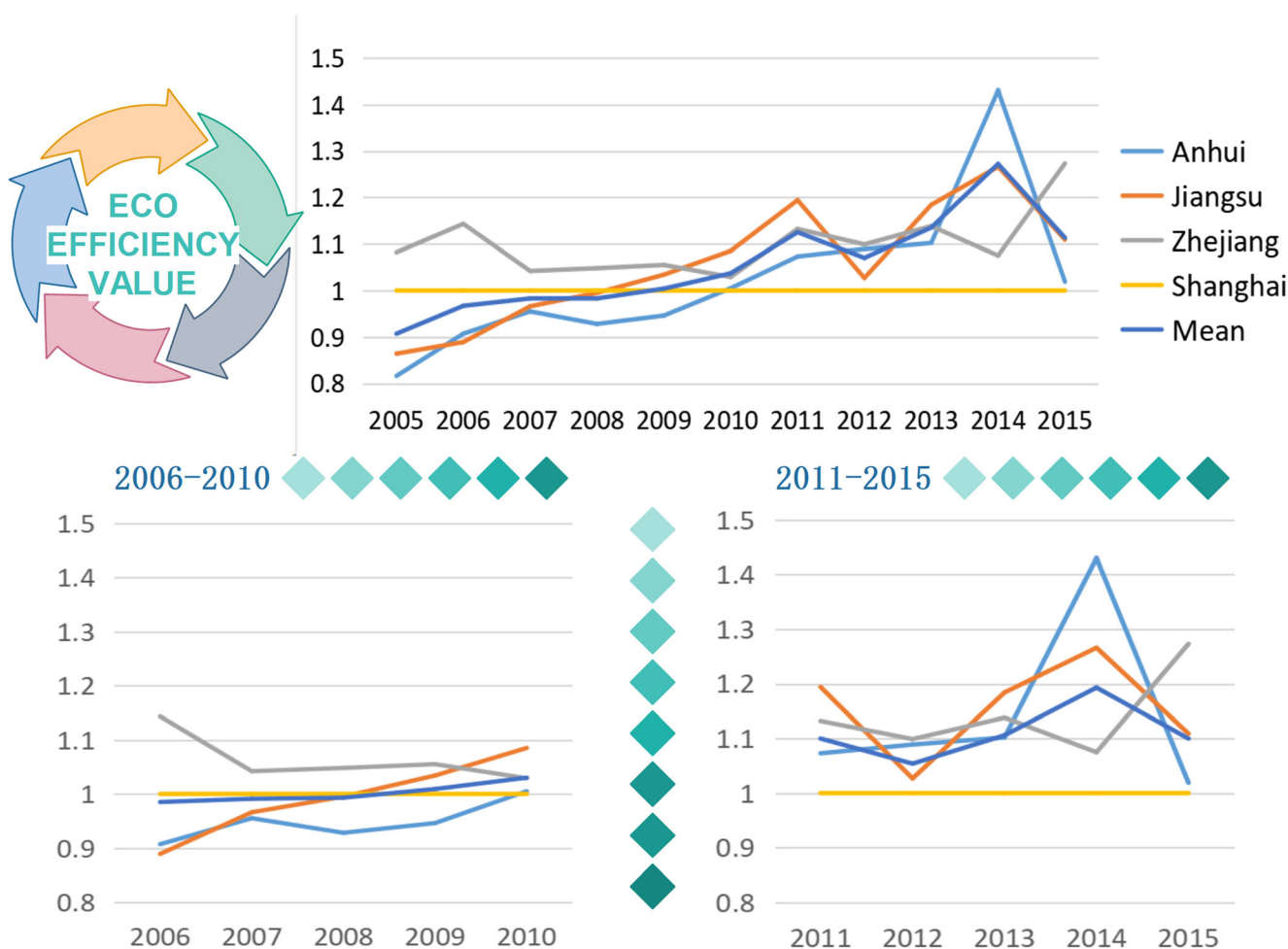


Fig. 2 The changing trends of three provinces and Shanghai in two different periods

**Table 1** The average results of the regional SBM efficiency in different provinces

Region	2006	2007	2008	2009	2010	Mean	Region	2011	2012	2013	2014	2015	Mean
The 11th Five-Year Plan							The 12th Five-Year Plan						
Anhui (4)	0.907	0.955	0.928	0.946	1.005	0.948	Anhui (3)	1.073	1.089	1.102	1.43	1.019	1.143
Jiangsu (3)	0.889	0.966	0.995	1.034	1.085	0.994	Jiangsu (1)	1.194	1.027	1.184	1.266	1.109	1.156
Zhejiang (1)	1.143	1.042	1.048	1.055	1.029	1.063	Zhejiang (2)	1.132	1.099	1.138	1.075	1.273	1.143
Shanghai (2)	1.000	1.000	1.000	1.000	1.000	1.000	Shanghai (4)	1.000	1.000	1.000	1.000	1.000	1.000
Mean	0.985	0.991	0.993	1.009	1.030	1.001	Mean	1.100	1.054	1.106	1.193	1.100	1.111

improved to various degrees. In the two five-year plans (2006–2010, 2011–2015), the two provinces of Shanghai and Zhejiang play the role of “stabilizers,” while Jiangsu and Anhui provinces act as “accelerators.”

As shown in Table 2 and Fig. 3, based on the ecological construction of cities in different provinces and changes in ecological efficiency of 41 prefectural cities (including Shanghai) during the 11th Five-Year Plan and the 12th Five-Year Plan, these cities can be divided into two categories and four subclasses. The first category is called “steady-state” cities, that is, cities whose eco-efficiency has been effective or ineffective during the two five-year plans include the continuously effective “high-high” types of cities and continuously ineffective “low-low” types of cities. The second category is called “non-steady-state” cities, that is, cities whose ecological efficiency is in a state of change and adjustment in the two five-year plans. These cities are divided into “high-low” types of cities, which are from effective to ineffective, and “low-high” type, which means from invalid to valid. Each type of city has different ecological problems. We can seek ways to replicate and promote ecological issues quickly through the analysis of their “commonalities.”

**“High-high” type of cities**

There are 22 cities in total, including Shanghai City, 7 cities in Zhejiang province (Hangzhou, Jiaxing, Jinhua, Ningbo, Shaoxing, Taizhou, and Wenzhou), 4 cities in Jiangsu province (Nantong, Suzhou, Wuxi and Yancheng), and 10 cities in Anhui province (Cangzhou, Chizhou, Fuyang, Hefei, Huangshan, Lu’an, Ma’anshan, Suzhou, Tongling, and Xuancheng). Regarding the average value during the “11th Five-Year” and “12th Five-Year Plan” periods, all the abovementioned prefecture-level cities remained active at a relatively high level. From the perspective of spatial pattern, the previously mentioned prefecture-level cities are mainly distributed in the eastern coastal areas of the Yangtze River Delta and the inland regions in the west. This shows that the abovementioned prefecture-level cities have good economic quality, apparent ecological and environmental protection effects, and more room for continuous development to higher levels. Even in the context of continuously strengthening

environmental governance and accelerating environmental governance processes, the abovementioned prefecture-level cities can continue to be effective, probably due to a sound green economy or the basis for the development of circular economy, or their strong ability to adjust the economic structure. All of these made the cities having the ability to respond to the challenges brought about by the changes in government regulations.

**“Low-low” type of cities**

There are 9 cities in total, including 2 cities in Zhejiang province (Huzhou and Zhangzhou), 4 cities in Jiangsu province (Huai’an, Lianyungang, Nanjing, and Zhenjiang), and 3 cities in Anhui province (Anqing, Huaibei, and Huainan). Generally speaking, during the “11th Five-Year” and “12th Five-Year Plan” periods, the above prefecture-level cities have remained ineffective and at a relatively low level. From a spatial perspective, these cities are mainly located in the central region of the Yangtze River Delta. This shows that these cities have poor economic quality and inadequate ecological and environmental protection. Although there are some positive trends, the speed of development is still slow. These cities remain ineffective, because they are not sensitive to the government’s ecological protection policies. They still continue their traditional methods of development and lack the ability to introduce and cultivate high-quality resources and high-quality industries. Nanjing is one of the most prominent cities in which problems occurred.

**“Low-high” type of cities**

There are 8 cities in total, including 2 cities in Zhejiang province (Lishui and Zhoushan), 3 cities in Jiangsu province (Changzhou, Taizhou, and Yangzhou), and 3 cities in Anhui province (Shao, Zhangzhou, and Wuhu). Regarding the average value, the abovementioned prefecture-level cities were ineffective during the “11th Five-Year Plan” and effective during the “12th Five-Year Plan” period. The increase was significant, which highly developed the ecological efficiency. From a spatial perspective, these cities are mainly located in the central and northern regions of the Yangtze River Delta.



**Table 2** The ecological efficiency values from the SBM results in the Yangtze River Delta from 2005 to 2015

Region	City	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean	
Anhui province	Anqing	0.382	0.448	0.480	0.485	0.412	0.569	0.707	0.758	0.692	0.684	0.661	0.559	
	Bengbu	0.412	0.539	0.461	0.476	0.522	0.561	0.685	0.707	1.298	1.699	1.641	0.791	
	Bozhou	1.000	1.000	1.000	1.000	1.000	1.000	1.180	1.173	1.137	1.334	1.478	1.108	
	Chizhou	1.000	1.337	1.557	1.000	1.000	1.000	1.653	1.666	1.676	1.499	1.370	1.342	
	Chuzhou	1.000	1.013	0.645	1.031	0.919	0.917	1.141	1.007	1.043	1.040	1.055	1.013	
	Fuyang	1.000	1.058	1.181	1.136	1.228	1.905	1.193	1.111	1.069	1.267	1.052	1.152	
	Hefei	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.948	
	Huaibei	0.437	0.495	0.514	0.531	0.535	0.675	0.715	0.637	0.707	0.712	0.508	0.577	
	Huainan	0.402	0.441	0.378	0.566	0.625	0.706	0.649	1.013	0.695	0.716	0.514	0.593	
	Huangshan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
	Luan	0.636	1.002	1.000	1.120	1.097	1.188	1.107	1.171	1.214	1.247	0.961	1.026	
	Maanshan	1.240	1.399	1.477	1.482	1.455	1.412	1.709	1.511	1.075	0.715	0.670	1.287	
	Suzhou	1.000	1.000	1.301	1.265	1.000	1.003	1.042	1.091	1.100	1.019	1.388	1.101	
	Tongling	1.005	1.042	1.014	1.013	1.316	1.105	1.162	1.093	2.038	2.770	1.172	1.311	
	Wuhu	0.356	0.449	1.005	0.455	0.542	0.544	1.000	1.020	0.645	5.021	0.822	1.019	
	Xuancheng	1.187	1.293	1.263	1.293	1.477	1.500	1.217	1.465	1.239	1.151	1.007	1.277	
	Mean	0.816	0.907	0.955	0.928	0.946	1.005	1.073	1.089	1.102	1.430	1.019	1.024	
	Jiangsu province	Changzhou	0.328	0.360	0.391	0.457	0.523	1.367	2.163	1.000	3.176	3.302	1.767	1.266
		Huaian	0.477	0.481	0.506	0.445	0.497	0.455	0.539	0.522	0.624	0.662	0.676	0.531
Lianyungang		0.526	0.521	0.513	1.066	1.155	1.147	1.020	0.801	1.033	0.881	0.751	0.839	
Nanjing		0.390	0.394	0.420	0.394	0.394	0.482	0.719	0.726	0.633	0.725	0.733	0.532	
Nantong		1.112	1.056	1.227	1.198	1.159	1.221	1.119	1.192	1.156	1.394	1.447	1.195	
Suzhou		1.477	1.490	1.433	1.600	1.571	1.771	1.899	1.683	1.459	1.558	1.475	1.577	
Suqian		1.215	1.056	1.066	1.002	1.126	1.059	1.026	0.760	0.818	1.022	1.072	1.033	
Taizhou		0.717	0.818	1.027	0.876	1.039	1.064	1.151	1.469	1.271	1.257	1.000	1.064	
Wuxi		2.119	1.956	1.920	1.168	1.029	1.278	1.169	1.380	1.382	1.233	1.115	1.411	
Xuzhou		0.720	0.806	1.055	1.042	1.223	1.176	1.074	0.784	0.796	1.010	1.011	0.976	
Yancheng		1.035	1.295	1.418	2.183	1.580	1.160	1.761	1.386	1.320	1.321	1.050	1.377	
Yangzhou		0.566	0.682	0.842	0.758	1.116	1.150	1.210	1.000	0.883	1.210	1.468	0.966	
Zhenjiang		0.550	0.639	0.741	0.746	1.024	0.771	0.674	0.655	0.842	0.881	0.857	0.782	
Mean		0.864	0.889	0.966	0.995	1.034	1.085	1.194	1.027	1.184	1.266	1.109	1.056	
Hangzhou		0.840	1.109	1.247	1.000	0.752	1.042	1.066	1.000	1.038	1.026	1.059	1.016	
Huzhou		0.556	0.618	0.715	0.734	0.757	0.755	0.725	0.679	1.155	1.128	1.103	0.811	
Jiaxing		0.622	1.050	1.051	1.104	1.091	1.051	1.043	1.056	1.063	1.047	1.059	1.022	
Jinhua		2.553	2.693	1.366	1.190	1.251	1.346	1.418	1.278	1.356	1.401	1.163	1.547	
Zhejiang province		Lishui	0.612	0.773	0.646	0.811	0.940	1.000	1.117	1.081	1.123	1.050	1.033	0.926
	Ningbo	1.194	1.082	1.086	1.064	1.071	1.045	1.066	1.051	1.153	1.000	1.000	1.074	
	Quzhou	0.412	0.535	0.591	0.672	0.707	0.663	0.728	0.809	1.032	1.008	0.695	0.714	
	Shaoxing	1.889	1.619	1.756	1.476	1.392	1.413	1.332	1.927	1.027	0.817	0.724	1.397	
	Taizhou	1.000	1.000	1.000	1.792	1.585	1.000	1.530	1.000	1.000	1.000	4.443	1.486	
	Wenzhou	1.221	1.000	1.000	1.000	1.000	1.000	1.267	1.000	1.287	1.000	0.719	1.045	
	Zhoushan	1.007	1.094	1.003	0.688	1.055	1.000	1.161	1.208	1.287	1.353	1.000	1.078	
	Mean	1.082	1.143	1.042	1.048	1.055	1.029	1.132	1.099	1.138	1.075	1.273	1.101	
	Shanghai	Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
The total average		0.907	0.967	0.983	0.983	1.004	1.037	1.125	1.070	1.135	1.272	1.113	1.055	

This shows that the quality of economic development in these prefecture-level cities has improved and the “ecological

deficit” problem has been effectively solved. The efficiency gains of the abovementioned prefecture-level cities have been

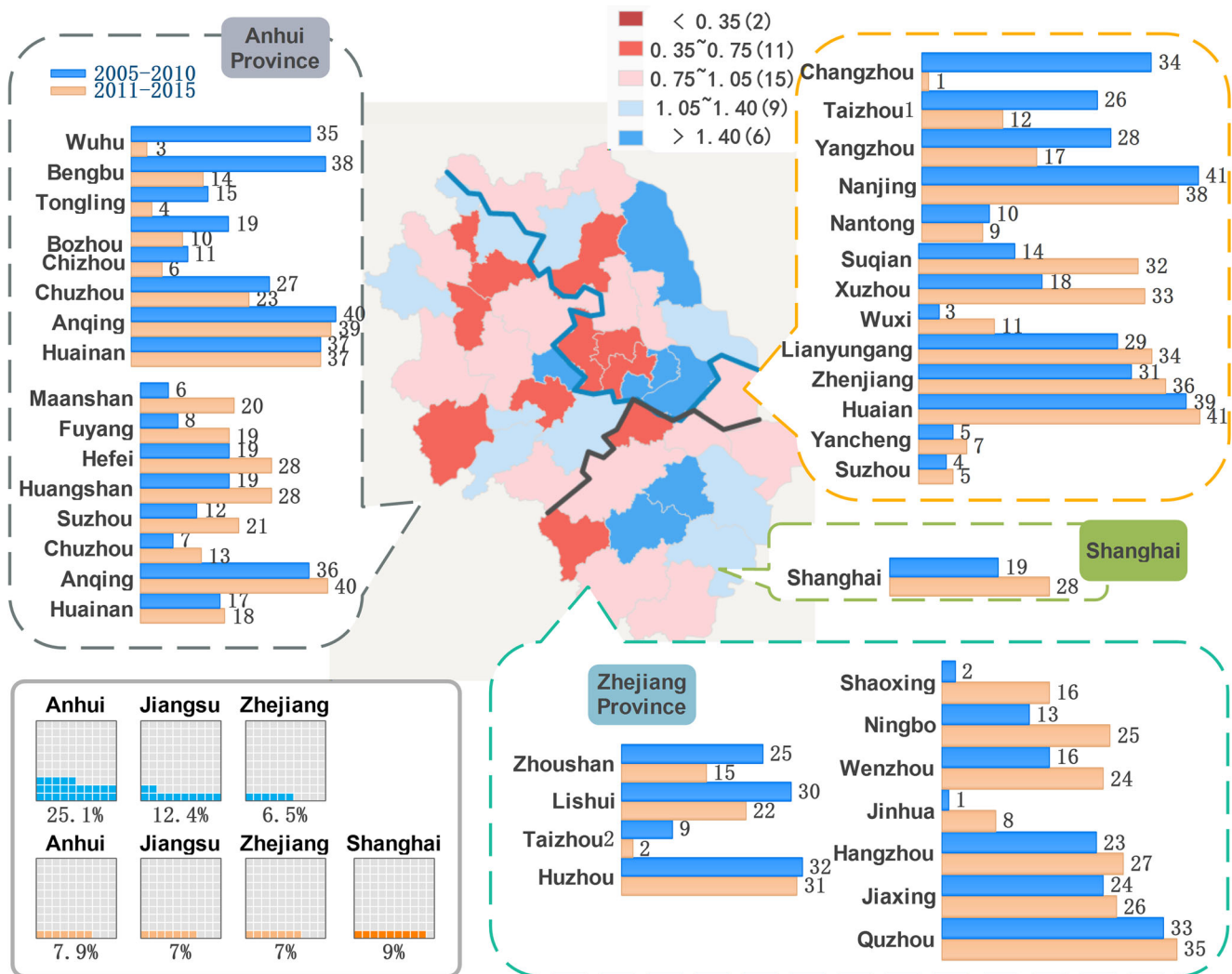


Fig. 3 The regional eco-efficiency values from the SBM showed in different shades of colors in the Yangtze River Delta of China from 2005 to 2015

rapid and obvious, showing a high degree of sensitivity to the government’s ecological protection policies and a strong ability to adjust the efficiency gains.

“High-low” types of cities

There are 2 cities in total, both in Jiangsu province (Xuzhou and Suqian). Judging from the average value, the abovementioned prefecture-level cities were effective during the “11th Five-Year Plan” period and were invalid during the “12th Five-Year Plan” period. The decline rate was relatively moderate, and the ecological efficiency was only slightly below the critical value. From a spatial perspective, the abovementioned prefecture-level cities are all located in the northwestern part of the Yangtze River Delta and in marginal areas. This shows that the quality of economic development in the abovementioned prefecture-level cities has deteriorated, and ecological problems have reappeared. However, according to development

experience, it can be judged that the decline in the above two prefecture-level cities is temporary. On one hand, it is due to the ongoing adjustment and upgrading of the industrial structure. On the other hand, there is a certain inefficiency adjustment in the economic development of the city and the implementation of the government’s environmental policy.

In the bottom left corner of Fig. 3, the first row shows the provinces in the list of cities that have risen in the 11th Five-Year Plan and the 12th Five-Year Plan periods. The indicators below in Anhui, Jiangsu, and Zhejiang indicate the average number of specific rises in these rising cities. The data of Anhui province is  $(32 + 24 + 11 + 9 + 5 + 4 + 1 + 0)/8 = 10.8$ , and the data of Jiangsu province is  $(33 + 14 + 11 + 3 + 1)/5 = 12.4$ . Zhejiang province’s data is  $(10 + 8 + 7 + 1)/4 = 6.5$ . Similarly, the second line shows the provinces in the list of cities that have risen in the 11th Five-Year Plan and the 12th Five-Year Plan periods. Shanghai has fallen in two periods, so it only appears in the second line.

The conclusions about the dynamic characteristics of ecological efficiency and related influencing factors in this paper belong to the general characteristics of long-term trend, because economic development, structural adjustment, and scientific and technological progress are a gradual process, and thus the improvement of eco-efficiency is also the same. Therefore, the dynamic characteristics of eco-efficiency are relatively stable, and the effects of relevant influencing factors appear to be small and orderly changes in a certain period, in which the direction of influence remains unchanged and the intensity of impact changes accordingly. Malmquist index examines the dynamic production efficiency of multiple input and multiple output variables across the period, measures total factor productivity (TFP) changes, and analyzes the factors that drive productivity changes. Combining eco-efficiency with three structural efficiencies (technology progress index, pure technical efficiency index, and scale efficiency index) can illustrate which kind of productivity promotes eco-efficiency and the quantitative relationship between eco-efficiency and the productivity more clearly.

**Analysis of endogenous impact factors of ecological efficiency**

This paper uses the Malmquist index method to calculate the TFP and its rate of change, including technology progress index, pure technical efficiency index, and scale efficiency index at the regional and provincial levels during the “11th Five-Year” and “12th Five-Year Plan” periods respectively. The result of using Deap2.1 software is as follows.

From Fig. 4 and Table 3, it can be seen that, not only at the regional level of the Yangtze River Delta but also at the provincial level of Anhui, Jiangsu, Zhejiang, and Shanghai that most of the numerical values of total factor productivity indicators, pure technical efficiency indicators, and scale efficiency indicators are greater than 1, while majority of the indicators of technological progress are less than 1. It is easy to see that the main driver of the increase in TFP and eco-efficiency in the Yangtze River Delta region is the highly effective pure-tech efficiency and scale efficiency. It should be noted that the indicator of technological progress in the Yangtze River Delta region has been relatively sluggish. This shows that in addition to Shanghai, there have been slight technical regressions in Anhui, Jiangsu, and Zhejiang provinces, which is also a major obstacle to the further improvement of eco-efficiency.

In order to thoroughly study the endogenous factors of eco-efficiency, this paper uses pure technical efficiency index, scale efficiency index, and technological progress index as explanatory variables, and uses ecological efficiency as an explanatory variable. This paper constructs regional and provincial-level measurement models. Because the Malmquist index represents changes from the previous year, the eco-efficiency of the explanatory variables will also be converted to the ratio of the previous year. The constructed panel data regression model expression is as follows:

$$EE_{i,t} = C + \beta_1 TECH_{i,t} + \beta_2 PECH_{i,t} + \beta_3 SECH_{i,t} + \varepsilon_{i,t} \quad (8)$$

In the formula,  $EE_{it}$ ,  $TECH_{it}$ ,  $PECH_{it}$ , and  $SECH_{it}$  represent the change in rate of eco-efficiency, change in technical

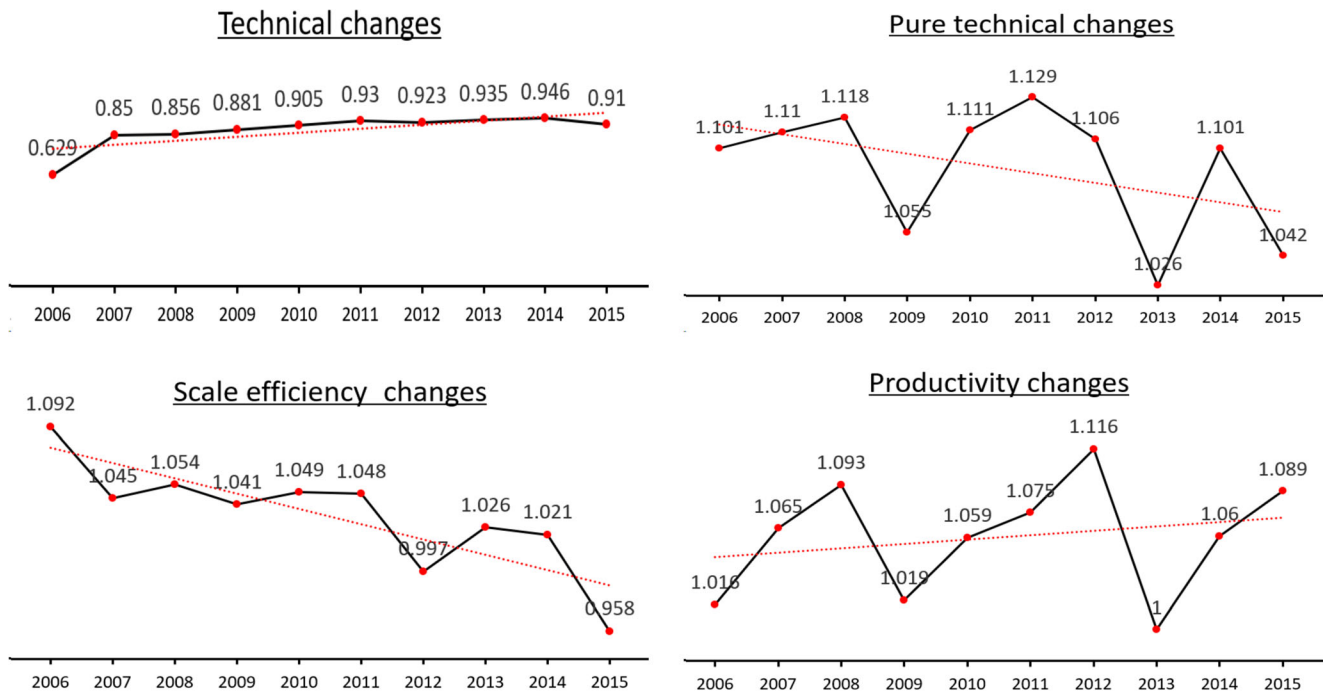


Fig. 4 Changes and decomposition of the region showed in smooth curves

**Table 3** Changes and decomposition of three provinces and Shanghai

Province	Year	Technical changes	Pure technical changes	Scale efficiency changes	Productivity changes
Anhui	2011–2012	0.932	1.139	1.057	1.076
	2012–2013	0.924	1.100	0.997	1.109
	2013–2014	0.935	1.022	1.024	0.998
	2014–2015	0.944	1.102	1.018	1.062
	2015–2016	0.904	1.045	0.954	1.096
	Mean	0.928	1.082	1.010	1.068
Jiangsu	2011–2012	0.939	1.135	1.041	1.087
	2012–2013	0.929	1.101	0.994	1.114
	2013–2014	0.936	1.013	1.020	0.997
	2014–2015	0.949	1.099	1.023	1.054
	2015–2016	0.909	1.042	0.954	1.092
	Mean	0.932	1.078	1.006	1.069
Zhejiang	2011–2012	0.934	1.132	1.042	1.084
	2012–2013	0.923	1.106	0.993	1.121
	2013–2014	0.931	1.019	1.022	1.001
	2014–2015	0.944	1.116	1.025	1.066
	2015–2016	0.901	1.027	0.950	1.082
	Mean	0.926	1.080	1.007	1.071
Shanghai	2011–2012	1.000	1.000	1.000	1.000
	2012–2013	1.000	1.000	1.000	1.000
	2013–2014	1.000	0.998	1.000	0.998
	2014–2015	1.000	1.000	1.000	1.000
	2015–2016	1.000	0.991	1.000	0.991
	Mean	1.000	0.998	1.000	0.998

progress, change in pure technical efficiency, and change in scale efficiency in period  $t$  of  $i$  area;  $C$  represents interception item and  $\varepsilon_{it}$  represents random disturbance item.

In this paper, we use Eviews8.0 software to estimate the model parameters and test the independent variables and dependent variables by unit root test. It shows that each variable is a stationary sequence, and then we used the Hausman test to determine the random effect model and the weighted GLS method to estimate the regression. The regression results are shown in Tables 4 and 5.

From Tables 4 and 5, we can see that whether at the regional level or at the provincial level, the three endogenous factors of changes in technological progress, changes in pure

technological efficiency, and changes in economies of scale have all passed the 5% level test of significance, which means they have significant impact on the change in ecological efficiency. At the regional and provincial levels, the influence of the three endogenous factors remains exactly the same, but the impact is slightly different. First, for each 1% increase in the technological progress index, the eco-efficiency in the Yangtze River Delta, Anhui, Jiangsu, and Zhejiang provinces dropped by an average of 0.184%, 0.806%, 1.099%, and 1.101%. Technological progress not only did not promote but also inhibited efficiency, so we can determine from the improvement that there is an “ecological rebound effect” in the whole, and the excessive costs of R&D and investment operations cover the benefits of technological progress and efficiency improvement. Second, for every 1% increase in the purely technical efficiency index, the ecological efficiency in the Yangtze River Delta, Anhui, Jiangsu, and Zhejiang provinces increased by an average of 0.951%, 0.916%, 0.943%, and 0.954%; the improvement of pure technical efficiency has more obvious promotion effect. Third, a 1% increase in the scale efficiency index causes an average reduction of 1.096%, 0.832%, 0.715%, and 0.706% in ecological

**Table 4** Regression results

Variables	Yangtze region	Std. error	$t$ statistic	Prob
$C$	1.318117	0.134208	9.821418	0.0001
$TC_{it}$	-0.183777	0.069130	-2.658441	0.0376
$PuTC_{it}$	0.950543	0.073687	12.89973	0.0000
$SaEC_{it}$	-1.096069	0.085191	-12.86602	0.0000

**Table 5** Regression results for provinces

Variables	Yangtze region	Anhui	Jiangsu	Zhejiang	Shanghai
$C$	1.318117	1.665249	1.796155	1.772037	***
$TC_{it}$	-0.183777	-0.806241	-1.098926	-1.101146	***
$PuTC_{it}$	0.950543	0.916373	0.943895	0.953513	***
$SaEC_{it}$	-1.096069	-0.831974	-0.715340	-0.706275	***

\*\*\* represents that the coefficients of variables may be perfectly collinear. In this part, Shanghai cannot achieve regression because its correlation coefficient will have serious multi-collinearity problems. In theory, there is no necessary relationship between the high correlation of explanatory variables and the high degree of observation. It is possible that the two explanatory variables are theoretically highly correlated, but the observations are not necessarily highly correlated, and vice versa. So multi-collinearity is essentially a data problem. (1) Explanatory variables all share a common time trend. (2) One explanatory variable is another lag, and both tend to follow a trend. (3) Because the basis of data collection is not broad enough, some explanatory variables may change together. (4) There is some approximate linear relationship between some explanatory variables. These may be the reasons for the multi-collinearity of the data. In the above internal decomposition of the SBM index, based on the data of Shanghai, the multi-year ecological measurement value of Shanghai is set to 1. In the process of decomposing technical indicators, pure technical indicators, scale efficiency change indicators, and productivity change indicators, Shanghai has always maintained its status as a benchmark city, and its city value has remained at 1 during the 11th and 12th Five-Year Plan periods, or slightly fluctuated around 1. The data is multi-collinear, so regression analysis of internal/external influencing factors is not possible

efficiency in the Yangtze River Delta, Anhui province, Jiangsu province, and Zhejiang province, and the improvement of scale efficiency has a more obvious inhibitory effect.

The improvement of pure technical efficiency and scale efficiency comes from the fact that enterprises introduce advanced management concepts, adopt advanced technology and equipment actively, expand production and operation scale continuously, and then improve economic production efficiency. The goal is to enhance its competitiveness and adapt to the internationalization of the market. The decline in the technological progress efficiency comes from the great adjustment of the economic development and ecological protection route by China's party and government to. In the field of economic production, enterprises with backward production, low efficiency, and serious pollution have gone bankrupt and eliminated, which has prompted enterprises to improve production technology and management level to a certain extent. However, comparing with traditional manufacturing enterprises or resource development enterprises, the energy conservation and environmental protection industry is backward

and mismatched. Therefore, social efficiency is regressed in a short period of time.

### Analysis of external influence factors of ecological efficiency

In order to further study the external factors of ecological efficiency, this paper uses the STIRPAT model to quantitatively analyze the impact of human factors on ecological efficiency. According to the definition of eco-efficiency influencing factors by domestic and foreign scholars and at the same time the actual conditions of socio-economic development in the Yangtze River Delta region, the economic development level, industrial structure, foreign capital utilization level, government environmental regulation, urbanization level, and technological progress are selected as ecological efficiency. Among them, the specific indicators selected in different influencing factors and their usages are shown in Table 6.

In addition, in order to test whether there is a "U" curve between economic development level and ecological

**Table 6** Influencing factors used in the method

Influencing factors	Specific indicators	Instructions
The level of economic development	GDP per capita	The natural logarithm of GDP per capita
Industrial structure	The proportions of secondary and tertiary industry	The proportion of tertiary industrial output value $\times$ 0.6 + second industry $\times$ 0.4
Utilization of foreign capital	Foreign direct investment	Foreign direct investment/GDP
Environmental Policy	Investment toward environmental pollution control	Environmental pollution control investment/GDP
Urbanization	Urbanization rate	Urban population/total population
Technological innovation	Market turnover of technology	R&D cost/GDP

**Table 7** Regression results of the STIRPAT model for different provinces in the region

Variables	Yangtze region	Anhui	Jiangsu	Zhejiang	Shanghai
<i>C</i>	− 1.843447	6.399099	− 8.482001	26.76763	***
(lnGDP <sub><i>it</i></sub> ) <sup>2</sup>	1.255914	0.029769	4.289440	− 13.43048	***
lnInstructure <sub><i>it</i></sub>	0.826048	− 3.883823	6.996324	− 6.553478	**
FDI <sub>GDP<sub><i>it</i></sub></sub>	0.647747	3.693964	1.269203	7.815981	***
Investment <sub>GDP<sub><i>it</i></sub></sub>	0.018952	− 0.462364	0.039112	0.358689	*
Urban <sub><i>it</i></sub>	− 0.966442	− 2.868386	− 1.887971	3.597801	***
Technology <sub>GDP<sub><i>it</i></sub></sub>	2.491175	0.471202	3.718827	3.242877	**

\*\*\*, \*\*, and \* represent significance of the variable coefficients at the levels of 1%, 5%, and 10%, respectively

efficiency, the economic development level indicators in the model are adjusted, and the model expressions constructed are:

$$\begin{aligned}
 EE_{it} = & \beta_0 + \beta_1(\ln GDP_{it})^2 + \beta_2 \ln Instructure_{it} \\
 & + \beta_3 Investment_{GDP_{it}} + \beta_4 Urban_{it} + \beta_5 FDI_{GDP_{it}} \\
 & + \beta_6 Technology_{GDP_{it}} + \varepsilon_{it} \tag{9}
 \end{aligned}$$

The relevant indicator data during the “11th Five-Year” and “12th Five-Year Plan” periods are selected, and the results obtained by using Eviews 8.0 software to estimate the model parameters are as follows.

From Table 7, we can see that at regional level or provincial level, most of the six external factors of economic development level, including industrial structure, foreign capital utilization level, government environmental regulation, urbanization level, and technological progress level, have passed the 10% level. These variables have significant impact on the change in ecological efficiency. At the regional level and the provincial level, the degree of influence is significantly different, reflecting the particularity and complexity of the driving factors of ecological efficiency in the Yangtze River Delta region.

From a regional perspective, the improvement of the level of economic development, industrial structure, utilization of foreign capital, government environmental regulations, and technological progress has a positive impact on the improvement of ecological efficiency. Once each of these five factors increases by 1%, the eco-efficiency increases by an average of respectively 1.256%, 0.826%, 0.019%, 0.648%, and 2.491%; the increase of urbanization level has a negative impact on the improvement of ecological efficiency; with an increment of 1%, the ecological efficiency decreased by 0.966% on average. Among them, there is a “U” relationship between economic development level and eco-efficiency. With the alternation of economic dominance between the secondary industry and the tertiary industry, the eco-efficiency drops first and then rises. According to the calculation, the urbanization level at 27.380% is a turning point in the “U” relationship. At present, the ecological and economic development in the Yangtze River Delta

region is in a “rebound” phase, and it gradually transits to a green, environmentally friendly, and sustainable direction.

In Anhui province, the improvement of the level of economic development, utilization of foreign capital, and technological advancement has a positive impact on the improvement of eco-efficiency. For every 1% increase in the three factors, the eco-efficiency increases by an average of 0.030%, 3.694%, and 0.471%. The improvement of industrial structure, government environmental regulations, and urbanization level has a negative impact on the improvement of eco-efficiency. When each of the three factors increases by 1%, the eco-efficiency respectively decreases by an average of 3.884%, 0.462%, and 2.868%. Among them, there is a “U”-type relationship between economic development level and ecological efficiency, and it is a turning point for the “U”-type relationship when the urbanization level is calculated to be 31.450%.

In Jiangsu province, the level of economic development, industrial structure, utilization of foreign capital, government environmental regulations, and technological progress have a positive impact on the improvement of eco-efficiency. When each of these five factors increase by 1%, the eco-efficiency will increase by an average of 4.289%, 6.996%, 1.269%, 0.039%, and 3.719%, respectively; the increase in the level of urbanization has a negative impact on the improvement of ecological efficiency; with a 1% increase, the eco-efficiency decreased by an average of 1.888%. Among them, there is a “U”-type relationship between the level of economic development and eco-efficiency. According to the calculation of urbanization level, 41.120% is the turning point for the “U”-type relationship.

In Zhejiang province, the increase in the level of foreign capital utilization, government environmental regulations, urbanization, and technological advancement has a positive impact on the improvement of eco-efficiency. For every 1% increase in these four factors, the eco-efficiency increases by an average of 7.816%, 0.359%, 3.598%, and 3.243%. The increase in economic development level and industrial structure has a negative impact on the improvement of eco-efficiency. With two factors increasing by 1%, ecological efficiency decreased by an average of 13.430% and 6.553%. It should be pointed out that there is an inverted “U” relationship between

the level of economic development and eco-efficiency, and a different approach should be adopted to deal with the ecological problems in Zhejiang province.

## Conclusions and policy recommendations

### Conclusions

1. According to the measurement results of the regional, provincial, and prefectural levels, the overall eco-efficiency in the Yangtze River Delta region of China during the “11th Five-Year” and “12th Five-Year” periods has been effective and has maintained a good momentum of development, and the regional economy-energy-environment (3E) system is generally in good coordination. However, different provinces have significant differences in the improvement of the utilization efficiency in resources and the environment. Among them, Shanghai and Zhejiang province play the role of “stabilizers” and Jiangsu and Anhui province play the role of “accelerators.”
2. According to the changes in ecological efficiency during the “11th Five-Year” and “12th Five-Year” periods and the implementation of ecological policies, 41 prefecture-level cities in the Yangtze River Delta were classified. The proportion of “high-high” cities and “low-high” cities is 73.17%. These cities concentrated in the east, west, and south areas. The government’s ecological policy within these cities has been effectively implemented, and ecological efficiency has achieved healthy development. The proportion of “low-low” cities and “high-low” cities is 26.83%. These cities concentrated in the central and northern regions. These areas lack the ability to use and cultivate high-quality resources and green industries, making the development of ecological efficiency into a vicious circle, and it is not conducive to the sustainable development of the 3E System.
3. The decomposition of structural efficiency through the Malmquist index shows that during the “11th Five-Year” and “12th Five-Year” planning periods, the increase in pure technical efficiency and scale efficiency was the main driver of improvement of ecological efficiency in the Yangtze River Delta region, while the scale of technological regression is a key factor in inhibiting the improvement of eco-efficiency. The purely technical efficiency coefficient of the whole region and Anhui province exceeds the coefficient of technological progress, indicating that there is indeed a “rebound effect” in technological progress, that is, technological progress will also increase productivity and increase ecological demand while increasing eco-efficiency and reducing eco-environmental consumption. The “rebound effect” of Jiangsu and Zhejiang province is not obvious.
4. The economic development level and eco-efficiency of the Yangtze River Delta region, Anhui province, and Jiangsu province all show a “U-type” relationship, while Zhejiang province shows an inverted “U-type” relationship. With the promotion of the six factors of economic development level, industrial structure, utilization of foreign investment, government environmental regulations, level of technological progress, and the level of urbanization, there are different directions and degrees of improvement in the ecological efficiency between the whole region and different provinces. The influences, such as industrial restructuring, have a negative impact on Anhui province and Zhejiang province, but have a positive impact on Jiangsu province.

### Policy recommendations

1. Continue to adhere to the regional coordinated development strategy and enhance the development integrity. Ensure that Shanghai City and Zhejiang province continue to play the role of stabilizers in eco-efficiency, give full play to comparative advantages, and promote the spatial balance of population and economy, resources, and environment. Meanwhile, ensure that Jiangsu and Anhui province continue to play the role of accelerators in eco-efficiency, promote the orderly and free flow of factors, and improve the spatial allocation efficiency of various resources, and then achieve higher quality, more efficient, fairer, and sustainable development in all regions.
2. Continue to adhere to the innovation-driven development strategy and accelerate the transformation of development momentum. On one hand, strengthen the leading role of innovation in the “high to high” and “low to high” types of cities and support the development of innovation alliance in energy conservation and environmental technology. On the other hand, guide core technologies tackling in the “low-low” and “high-low” types of cities, accelerate the elimination of “high-input, high-consumption, high-pollution” industries, and then promote the development of economic structure to low carbonization.
3. Promote the development of the Yangtze River Delta region with the aim of large-scale protection and no large-scale exploit, and implement the long-term mechanism of ecological protection and pollution prevention fully. Strengthen the ecological protection and restoration of various regions; enhance the protection of forests, wetlands, and biodiversity; and improve the comprehensive improvement of urban and rural environment. Make a good fight against pollution prevention and cure with high standards and strict requirements, carry forward institutional reform and innovation, and promote the optimization and upgrading of the spatial pattern, industrial structure, production methods, and lifestyles in the Yangtze River Delta.

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