Rev. Int. Contam. Ambie. 38 (Sustainable Architecture and Urban Environment) 173-183, 2022
https://doi.org/10.20937/RICA.54465

SPATIAL DISTRIBUTION AND INFLUENCING FACTORS OF ECOLOGICAL EFFICIENCY IN YANGTZE RIVER DELTA

Distribución espacial y factores de influencia en la eficiencia ecológica en el delta del río Yangtze

Penghui XU[1,2], Xicang ZHAO[1]* and Haili LI[2]

[1]School of Management, Jiangsu University, Zhenjiang, Jiangsu 212013, China.
[2]School of Humanities and Management, Wannan Medical College, Wuhu 241002, China.

*Author for correspondence: 549612136@qq.com

(Received: June 2021; accepted: December 2021)

Key words: Yangtze River Delta, ecological efficiency, spatial distribution, EBM model, Spatial Durbin Model (SDM)

ABSTRACT

This paper employs the EBM model and the Spatial Durbin Model(SDM) to describe the spatial characteristics and influencing factors of the 27 cities' eco-efficiency in China's Yangtze River Delta from 2003 to 2018. We find that the overall 27 cities' eco-efficiency in China's Yangtze River Delta fluctuates slowly, and the spatial difference of the ecological efficiency of the 27 cities in this area is obvious, showing the distribution characteristics of "East is better than west". The findings show that PGDP, FDI, industrial structure (IND), and population density (POP) have a significant positive correlation with the eco-efficiency of this area. On the contrary, there is a significant negative correlation between greening level (GRE) and ecological efficiency, but the level of technological innovation is not significant.

Palabras clave: delta del río Yangtze, eficiencia ecológica, distribución espacial, modelo EBM, modelo espacial de Durbin (SDM)

RESUMEN

Este trabajo emplea el modelo EBM y el modelo espacial Durbin (SDM) para describir las características espaciales y los factores de influencia de la ecoeficiencia de las 27 ciudades en el delta del río Yangtsé de China de 2003 a 2018. Encontramos que la ecoeficiencia general de las 27 ciudades en el delta del río Yangtsé en China fluctúa lentamente, y la diferencia espacial de la eficiencia ecológica de las 27 ciudades en esta área es obvia, mostrando las características de distribución de "el Este es mejor que el Oeste". Los resultados muestran que el PGDP, la IED, la estructura industrial (IND) y la densidad de población (POP) tienen una correlación positiva significativa con la ecoeficiencia de esta área. Por el contrario, existe una correlación negativa significativa entre el nivel de ecologización (GRE) y la eficiencia ecológica, pero el nivel de innovación tecnológica no es significativo.

INTRODUCTION

The Yangtze River Delta region, which accounts for one-fourth of China's total economy, is one of the most dynamic, open, and innovative regions (**Fig. 1**). But, the long-term economic development of the region has also brought about high resource consumption and high pollution emissions, resulting in its ecological environment system in a state of overload (**Figs. 2** to **4**). In recent years, this area has vigorously promoted the construction of ecological civilization, and the environmental quality has been significantly improved. However, the endless environmental problems are still an important factor restricting their high-quality development. Therefore, in 2019, the government officially announced the "Yangtze River Delta regional integration development planning outline", which emphasizes that this area should carry out cooperation around the "ecological environment" and other key areas, and the development of ecological environment integration will be an important dimension in the future process of Yangtze River Delta regional integration. Therefore, ecological efficiency is one of the important indicators to measure the coordinated relationship between the economy and environmental resources, and it is also an important basis to seek the path of green development. It has become an inevitable choice in the process of regional integration in this Delta.

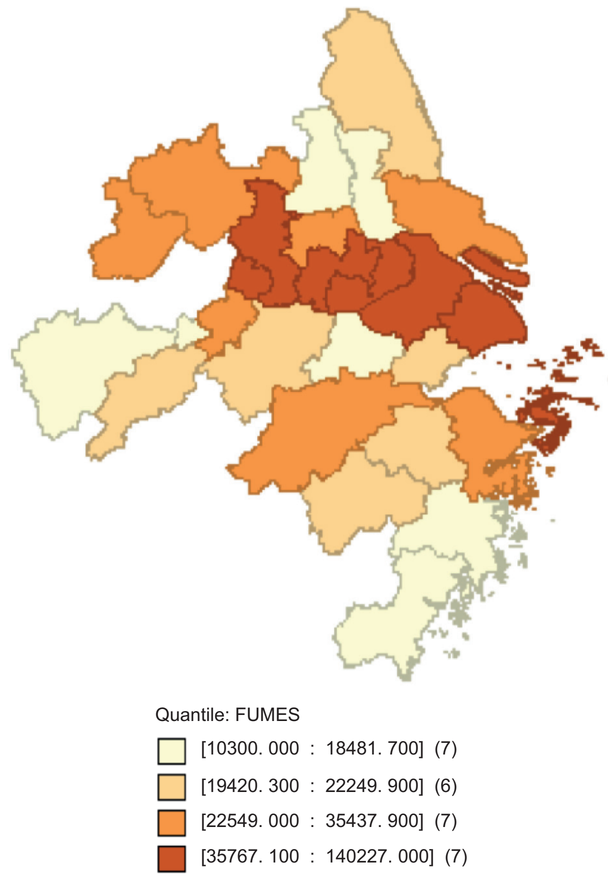

Fig. 2. Distribution of industrial dust emission in China's Yangtze River Delta from 2003 to 2018.

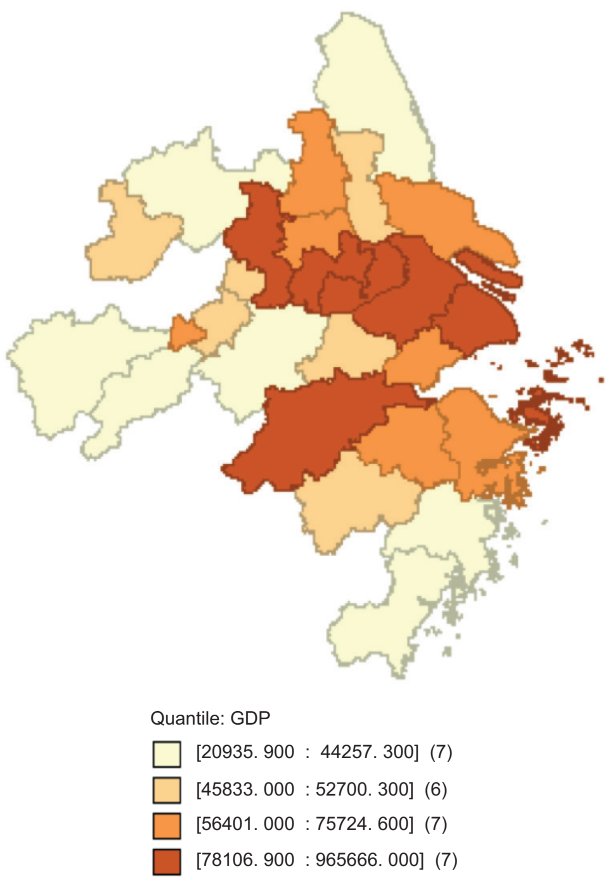

Fig. 1. GDP's Spatial distribution in China's Yangtze River Delta from 2003 to 2018.

In 1990, "ecological efficiency" was first put forward by Schaltegger and Sturm (1990). In 1992, eco-efficiency which is realized by satisfying the goods and services of human production and life and reducing the ecological impact and resource consumption within the carrying capacity of the earth was put forward by the World Business Council for Sustainable Development (WBCSD). In 1993, WBCSD further proposed seven elements to achieve the ultimate goal of ecological efficiency, which can be summarized as three goals, namely: 1) reduce the consumption of land, water, energy, etc.; 2) reduce the impact on nature, and 3) increase the value of services

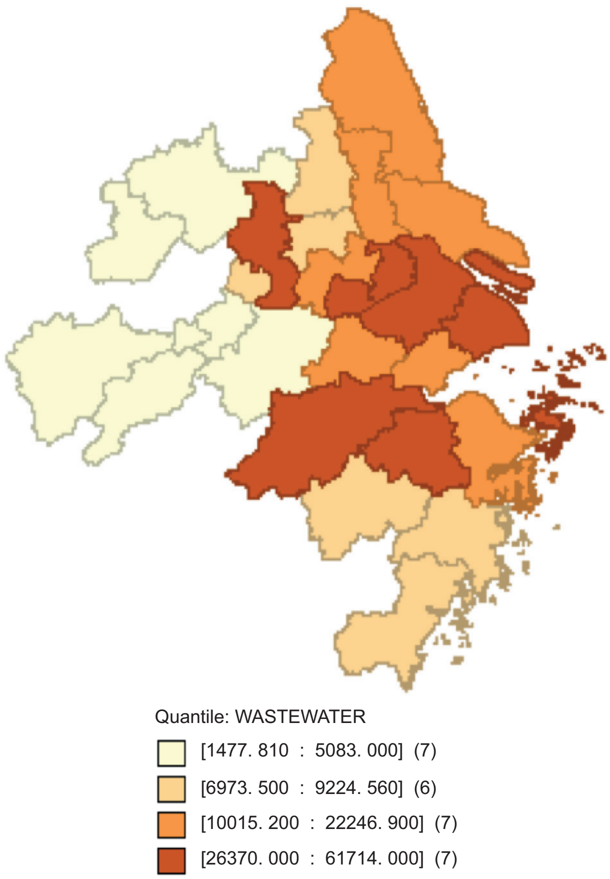

Fig. 3. Industrial wastewater discharge's Distribution in China's Yangtze River Delta from 2003 to 2018.

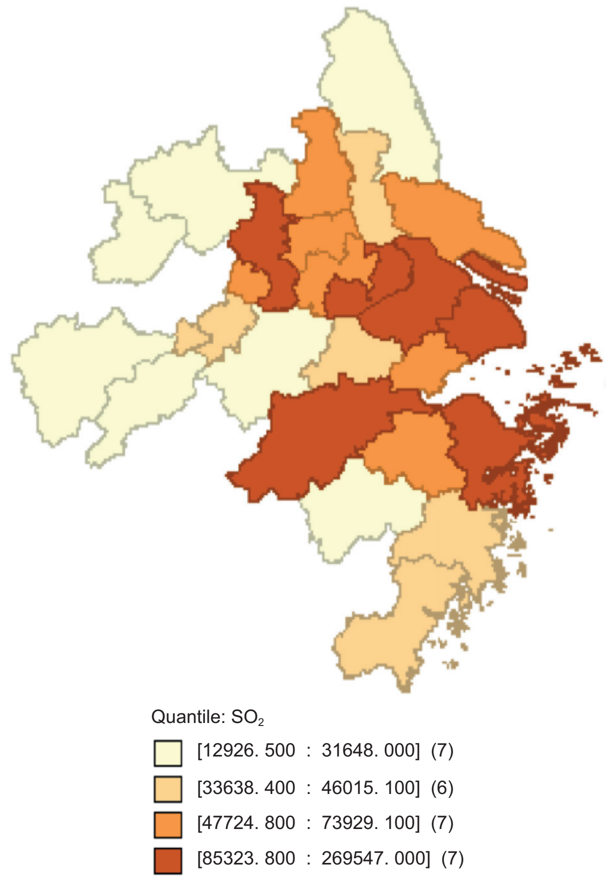

Fig. 4. Distribution of industrial SO_2 discharge in China's Yangtze River Delta from 2003 to 2018.

(Sinkin et al. 2008). In 1998, the OECD expanded the concept of eco-efficiency and applied it to more fields. It believed that eco-efficiency was to ensure social and economic development while considering the ecological environment and the rational use of resources, to achieve the state of sustained development of the economy.

The research on the application of ecological efficiency is mainly carried out from the enterprise level, industry level, and regional level. One is the enterprise level (Geissler 2015), the second is the industry level (Rebolledo 2019), and the third is the regional level (Halkos 2019). Among them, the existing literature on China's eco-efficiency mostly takes provinces as a unit to explore the overall evolution trend and regional differences (Han et al. 2019) or explore the influencing factors of eco-efficiency in China's western, central, and eastern regions based on regional heterogeneity (Yi and Liu 2020) or focus on the measurement and analysis of ecological efficiency in the Yangtze River economic belt and the Silk Road Economic Belt (Cao and Li 2018, Wang 2018). However, there are not only big differences among provinces in China but also unbalanced development among cities. Detailed analysis of ecological efficiency at the city level has more accurate decision-making value.

Although these research results can be used as a reference for the construction of regional eco-efficiency evaluation system and regional application research, the evaluation and analysis of spatial distribution characteristics and spatial spillover effect of the Yangtze River Delta's 27 cities are lacking. Therefore, this article selects this delta, 2003-2018 panel data, based on the expected output of the super-efficiency model (SBM) to measure the eco-efficiency of these data. As well, to evaluate the efficiency of ecological space distribution with the Spatial Durbin Model (SDM), that was used to explore the spatial spillover effect. This paper aims to reveal the existing problems and factors that need attention in the green development process, and to provide suggestions for improving the ecological efficiency of this region.

Theoretical hypothesis

We select six factors that may affect the 27 cities' eco-efficiency after comprehensively considering the actual situation of the region and the availability of data in the Yangtze River Delta region.

1) Economic development level

Due to a great increase in the level of national income per capita, people have higher demands for a survival environment. To take action to improve environmental quality, will need more attention to environmental quality in economically developed areas. People's environmental protection consciousness is stronger, that is, the region's economic development level will directly affect the productivity of the region and the environment, which influence the ecological efficiency.

H_1: There is a positive correlation between economic development level and ecological efficiency in the Yangtze River Delta. In other words, a high level of economic development is conducive to improving the ecological efficiency in this area.

2) Science and technology investment

The more science and technology input in local public financial expenditure indicates that the government attaches greater importance to science and technology. This provides good conditions for technological progress and can effectively stimulate the overall innovation power of the region and improve the feasibility and reduce the risk of solving resource and environmental problems with technological means. More and more enterprises are encouraged to apply new energy development, clean production, recycling, and other technologies to production activities, to reduce pollutant emissions while improving resource utilization, thus reducing the burden of the production process on the environment and promoting the improvement of eco-efficiency. In addition, the increase of scientific and technological input is conducive to the development of new and high-tech industries and emerging industries, promotes the optimization of industrial structure in this region, restrains the "environmental rebound effect" caused by the technological progress of industrial enterprises, and thus keeps the ecological efficiency at a stable and high level. Based on this, this paper puts forward the following hypothesis.

H_2: The increase of science and technology input in local fiscal expenditure can facilitate the improvement of 27 cities' eco-efficiency, and there is a positive correlation between science and technology input and ecological efficiency in the Yangtze River Delta.

3) Degree of opening to the outside world

According to the hypothesis of "pollution paradise", to relieve the environmental pressure faced by foreign enterprises in their home countries, they often choose to transfer the backward production capacity with high environmental costs to the investment destination by way of foreign investment, and the resulting pollution transfer effect will have a negative effect on the ecological environment of the destination. However, the "pollution halo" hypothesis holds that in the process of opening to the outside world, advanced foreign technology and management experience will be introduced, and the optimization and innovation of production mode will be promoted through the "spillover effect" of technology, the "demonstration effect" and the "competition effect" of foreign enterprises. With the increasingly strict environmental regulations in this Delta, the threshold of foreign capital introduction is also increasing continuously. The purpose of introducing foreign capital is not only to accelerate the speed of economic development but also to enhance international competitiveness and achieve high-quality economic development. In this case, the improvement of opening to the outside world can stimulate the vitality of the market, improve productivity, and provide opportunities and technological foundation for the "green transformation" of enterprises, to realize the improvement of environmental quality and the improvement of ecological efficiency. Based on this, this paper puts forward the following hypothesis.

H_3: Rational utilization of FDI can improve the 27 cities' eco-efficiency, and the degree of opening to the outside world is positively correlated with the eco-efficiency.

4) Industrial structure

The industrial structure is the "resource converter" of input of various economic activities, which changes the impact of economic activities on the ecological environment through different modes of allocation of production factors. On the one hand, industrial structure determines the type, quantity, and mode of resources consumed by economic activities, thus affecting the utilization efficiency of natural resources and the emission of pollutants. In three industry structures, the second industry mainly labor-intensive and capital-intensive industries, the production process involves the physical form a series of transformation, not only need to consume more natural resources, and has the characteristics of high energy consumption, high pollution, the third industry mainly provides intangible products, technology, information, management, and other intangible resources demand is more, The discharge of pollutants in the service process is less, so the improvement of the proportion of the tertiary industry has a promoting effect on the ecological efficiency. On the other hand, the development of the tertiary industry provides producers with better technical services and consumers with more choices, which is conducive to the transformation and upgrading of production modes and consumption concepts, and the improvement of ecological efficiency by promoting the formation of an ecological industrial system. Based on this, this paper puts forward the following hypothesis.

H_4: The upgrading of industrial structure is conducive to improving the 27 cities' ecological efficiency in China's Yangtze River Delta, and the proportion of the tertiary industry in the industrial structure is positively correlated with the ecological efficiency.

5) Population density

The "Push and Pull Theory" points out that the factor that is conducive to improving living conditions is the pull force of population flow, and the adverse conditions are the push force, and the force of population migration is composed of the push force of the place of migration and the pull force of the place of migration. Therefore, it can be inferred that cities with high-quality resources, complete infrastructure, bright employment prospects, and other advantages will attract population inflow and have a higher population density. This not only provides a sufficient labor force for economic development, but also attracts high-quality talents to gather, promotes the development of the knowledge economy in this region, and improves ecological efficiency by exerting knowledge efficiency. At the same time, the occurrence of environmental pollution accidents in densely populated cities will harm the lives and health of more people and make the local government become the focus of public opinion. To prevent such accidents, the government will often implement stricter policies to supervise environmental problems, so as to improve the local ecological efficiency. Based on this, this paper puts forward the following hypothesis.

H_5: The increase of population density in the carrying range will improve the 27 cities' ecological efficiency in China's Yangtze River Delta, and there is a positive correlation between population density and ecological efficiency.

6) Green level

Green construction is an important measure to optimize environmental quality and enhance city image. Many cities hope to attract investment and prosper the economy through environmental improvement, to achieve both, environmental and economic benefits. However, increasing the area of green coverage cannot solve the problem of environmental pollution from the source. The effect of landscaping brought by green space is stronger than that of ecological purification. In addition, due to the late maintenance of green space needs to invest more manpower and capital, so there is a widespread problem of "attaching importance to green and neglecting management" in urban construction, and it is difficult to achieve the economic goal of "attracting investment through the green". Based on this, this paper puts forward the following hypothesis.

H_6: Excessive pursuit of green coverage area is not conducive to the improvement of the 27 cities' eco-efficiency in China's Yangtze River Delta, and there is a negative correlation between the green level and ecological efficiency.

Ecological efficiency measurement and evaluation

Research object and data source

The 27 core cities in the Yangtze River Delta planned by the government mainly incluing Shanghai, Hangzhou, Ningbo, Wenzhou, Huzhou, Jiaxing, Shaoxing, Jinhua, Zhoushan, Taizhou, Nanjing, Taizhou, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Yancheng, Hefei, Wuhu, Maanshan, Tongling, Anqing, Chuzhou, Chizhou, and Xuancheng. The China's Yangtze River Delta 27 cities studied in this paper are taken as samples. The main input-output indicators of the research data are all from China Urban Statistical Yearbook and China Environmental Statistical Yearbook (2004-2020). Some missing data in the Yearbook are the data in the Statistical Bulletin of National Economic and Social Development published on the websites of municipal statistics bureaus or people's governments.

Construction of ecological efficiency evaluation index system

Based on the ecological efficiency emphasizes the concept of "resource consumption, environmental pollution minimization, and economic value maximization", we build the eco-efficiency evaluation index system of 27 cities in China's Yangtze River Delta while considering the availability of data (see **Table I**). The input index selects the input of capital and labor two kinds of production factors to

TABLE I. ECOLOGICAL EFFICIENCY EVALUATION INDEX SYSTEM.

Index	Specific index composition	Index description
Investment indicators	Capital investment	Fixed assets / 100 million yuan
	Labor input	Average number of employees / 10 000 people
	Energy input	Energy consumption / 10 000 tons of standard coal
Output indicators	Expected output	GDP / 100 million yuan
	Unexpected output	Industrial wastewater / 10 000 tons
		Industrial waste gas / 100 million cubic meters
		Industrial solid waste / 10 000 tons

measure. The expected output index selects a gross regional product to reflect the economic conditions of each city and transforms it into GDP at a constant price based on 2003 according to the GDP index. Unexpected output is represented by industrial three wastes, namely, the discharge of wastewater, gas, and solid waste (**Table I**).

The level of ecological efficiency depends not only on the difference of input-output factors but also on other external factors. According to the existing literature and the theoretical assumptions in the previous article, this paper selects the influencing factors of ecological efficiency from three aspects of the economy, society, and environment for exploration. The details are listed in **table II**.

Research methods

Based on the EBM method

In the case of undesired output, resources, energy consumption, and pollution emissions are in an "inseparable" and "radial" relationship, while traditional input factors other than energy such as labor, capital, etc., and output are "inseparable" and "radial". Separable "non-radial" relationship, but neither the DEA model nor the SBM distance function can measure and process the input-output relationship with radial and non-radial relationships. Based on this, Tone and Tsutsui (2009) proposed a mixed-function model that includes both radial and non-radial distance functions. Since the parameter ε is used in the model, Tone calls it an EBM (Epsilon-based measure) function. The EBM model can make up for the shortcomings of the traditional DEA model and the SBM model to a certain extent. The EBM model is listed in equation (1).

$$\gamma^* = \min_{\theta,\lambda,s^-} \theta - \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{i0}}$$

$$\begin{cases} \theta x_{i0} - \sum_{j=1}^{n} \lambda_j x_{ij} - s_i^- = 0, i = 1,\cdots,m \\ \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{r0}, r = 1,\cdots,s \\ \lambda_j \geq 0 \\ s_i^- \geq 0 \end{cases} \quad (1)$$

Where, γ^* indicates the optimal efficiency value of DEA measured by EBM; θ represents the efficiency value under radial condition; s_i^- represents the slackness of the i-th input element under non-radial conditions; λ denotes the relative weight of input elements; (x_{i0}, y_{r0}) represents the input-output vector

TABLE II. VARIABLE DESCRIPTION OF INFLUENCING FACTORS.

Explanatory variable	Definition	Symbol
Economic level	GDP per capita / (10 000 yuan / person)	PGDP
Technological innovation level	Number of patent applications / (a)	EI
Openness to the outside world	Foreign direct investment / (100 million yuan)	FDI
Industrial structure	Tertiary/Secondary Industry (%)	IND
Human capital level	Population density / (people / square km)	POP
Greening level	Green area per capita / (square meters / person)	GRE

of the o-th DMU; w_i^- indicates the weight of the first input element which reflects the importance of the input element, and satisfies $\sum_{i=1}^{m} w_i^- = 1$; ε_x represents the core parameter that includes both radial variation ratio and non-radial relaxation vector, and satisfies $1 \leq \varepsilon_x \leq 1$. Parameter w_i^- and ε_x need to be determined before establishing the EBM model. In case $\gamma^* = 1$, which denotes that the decision-making unit technology is valid. Due to the complexity of the relationship between economy, resources, and environment, there are both expected output and unexpected output, and the radial and non-radial relationships exist in the meantime. Therefore, based on the EBM model, it is extended to the EBM model including unexpected output to measure the static ecological efficiency. Model (equation 2) is listed as follows:

$$\gamma^* = min \frac{\theta - \varepsilon_x \sum_{i=1}^{m} \frac{\omega_i^- s_i^-}{x_{io}}}{\varphi + \varepsilon_y \sum_{r=1}^{s} \frac{\omega_r^+ s_r^+}{y_{ro}} + \varepsilon_b \sum_{p=1}^{q} \frac{\omega_p^{b-} s_p^{b-}}{b_{po}}}$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- - \theta x_{io} = 0, i = 1,\cdots,m, \\ \sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ - \varphi y_{ro} = 0, r = 1,\cdots,s, \\ \sum_{j=1}^{n} b_{pj}\lambda_j + s_p^{b-} - \varphi b_{po} = 0, p = 1,\cdots,q, \\ \lambda_j \geq 0, s_i^- \geq 0, s_r^+ \geq 0, s_p^{b-} \geq 0 \end{cases} \quad (2)$$

The SDM Model

The Spatial Durbin Model considers both the spatial correlation of dependent variables and the spatial autocorrelation of independent variables, and its expression is shown in equation (3).

$$y = \rho W y + \beta X + W X \gamma + \varepsilon \quad (3)$$

In the formula, Y denotes the dependent variable; X denotes the independent variable; W denotes the spatial weight matrix; ρ and γ are spatial autoregressive coefficients. β denotes the regression coefficient; ε is the random disturbance term.

Ecological efficiency measurement results and analysis

In this paper, based on the EBM model, the MaxDEA software was used to calculate the 27 cities' ecological efficiency in China's Yangtze River Delta from 2003 to 2018. The average ecological efficiency of the 27 cities is listed in **figure 5**.

In this paper, the GeoDA software was used to divide the average ecological efficiency of 27 cities from 2003 to 2018 into three levels: low efficiency, medium efficiency, and high efficiency, so as to maximize the differences among different types. The corresponding distribution map was drawn (see **Fig. 6**), and according to the spatial distribution characteristics of ecological efficiency, The 27 cities in China's Yangtze River Delta were divided into three regions: high, medium, and low. The high-efficiency areas include Shanghai, Nanjing, Nantong, Suzhou, Wuxi, Hangzhou, Ningbo, Wenzhou, and Hefei, which are almost all economically developed regions. Medium efficiency areas include Zhenjiang, Yangzhou, Taaizhou, Changzhou, Jinhua, Shaoxing, Jiaxing, Taizhou, and Zhoushan. The low-efficiency areas include Chuzhou, Wuhu, Tongling, Chizhou, Anqing, Maanshan, Xuancheng, Yancheng, and Huzhou. In general, the spatial differences of the China's Yangtze River Delta 27 cities' eco-efficiency are relatively obvious, showing the feature of "East is better than West", except for Yancheng. The high-efficiency cities are mainly distributed in the eastern coastal areas. Under the radiation influence of the eastern cities, the medium-efficiency cities are concentrated in the middle of China's Yangtze River Delta 27 cities.

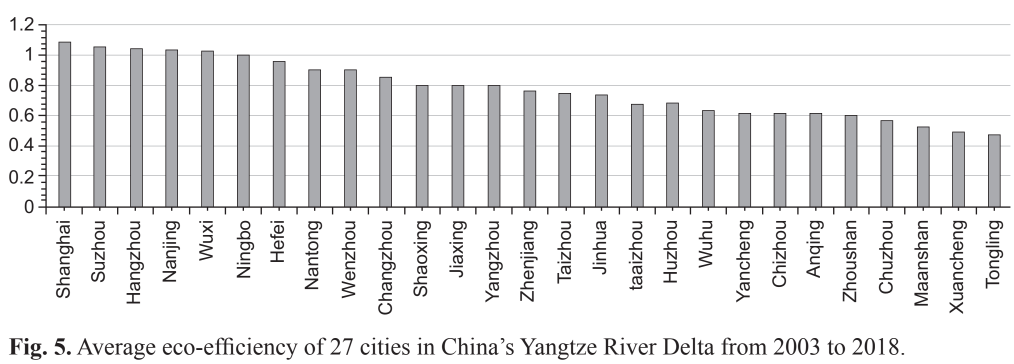

Fig. 5. Average eco-efficiency of 27 cities in China's Yangtze River Delta from 2003 to 2018.

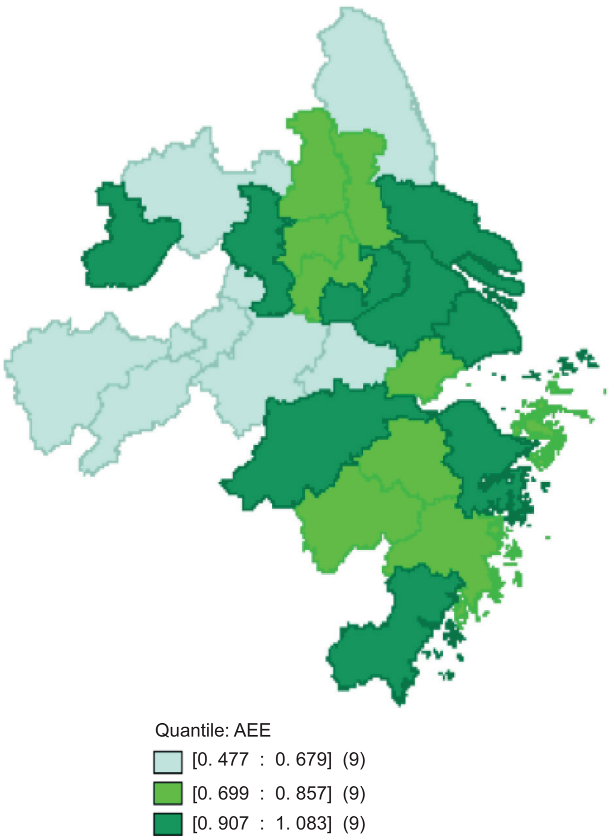

Fig. 6. Spatial distribution of mean eco-efficiency of 27 cities in China's Yangtze River Delta from 2003 to 2018.

However, this influence weakens with the increase of geographical distance, so all the western regions except Hefei are at a low-efficiency level.

Model construction and empirical analysis

Spatial Durbin Model (SDM)

We select the ecological efficiency (EE) of 27 cities from 2003 to 2018 as the dependent variable, and the level of economic development (PGDP), technology input (EI), degree of opening (FDI), industrial structure (IND), population density (POP) and greening level (GRE) as the independent variables. The specific variables are shown in **table IV**. To reduce the influence of heteroscedasticity, some variables are logarithmically treated, and the specific model is set as equation (4), where, *i* and *t* denote the region and time, respectively. ε_{it} denote the random disturbance term. υ_i denotes the regional effect, $\omega\varepsilon_i$ denotes the regional effect, The spatial autoregressive coefficient ρ indicates the spatial spillover effect of the explained variable, and indicates the extent of the impact of changes in the ecological efficiency of the region on other regions. The adjacency matrix and the economic distance matrix *W* are represented by a spatial weight matrix of order $n \times n$, *WLnEE* denotes the spatial lagging dependent variable; γ and β represents the unknown coefficient. The SDM panel model expression is listed as follows:

$$
\begin{aligned}
&LnEE_{it} = \rho WLnEE_{it} + \beta_1 LnPGDP_{it} + \\
&\beta_2 LnEI_{it} + \beta_3 LnFDI_{it} + \beta_4 LnIND_{it} + \beta_5 LnPOP_{it} + \\
&\beta_6 LnGRE_{it} + W(\beta_1 LnPGDP_{it} + \beta_2 LnEI_{it} + \\
&\beta_3 LnFDI_{it} + \beta_4 LnIND_{it} + \beta_5 LnPOP_{it} + \\
&\beta_6 LnGRE_{it})\ \gamma + \upsilon_i + \omega_t + \varepsilon_{it} \\
&\varepsilon_{it} : N(0, \sigma^2 I_n)
\end{aligned} \tag{4}
$$

The construction of space weight matrix

The spatial weight matrix reflects the spatial relationship of environmental regulations between regions. On the one hand, this spatial relationship is related to spatial distance, and on the other hand, it is also related to factors such as the level of regional economic development. The closer the level of economic development, the more areas there will be. Based on this, this paper constructs a spatial weight matrix from two aspects: geographic adjacency and economic similarity. 1) Geographic adjacency weight matrix (W_{ij}^G). If two regions i and j have a common geographic boundary, they are considered adjacent, and the weight is 1, that is, $W_{ij} = 1$; if they are not adjacent, the weight is 0, that is, $W_{ij} = 0$. 2) Economic distance weight matrix (W_{ij}^E). That is, the smaller the gap between the economic development levels of the two regions, the greater the empowerment: otherwise, the smaller the empowerment. By referring to the relevant literature, the reciprocal of the economic development level gap between the two provinces is used as the spatial weight matrix, which is defined as: $W_{ij}^E = 1/|\bar{Q}_i - \bar{Q}_j|$, $i \neq j$; when $i = j$, $W_{ij}^E = 0$. Q_i and Q_j are the mean values of GDP per capita in regions *i* and *j* during the study period (the base period deflator in 2000), respectively.

RESEARCH RESULTS AND ANALYSIS

Firstly, the OLS estimation of the traditional panel model without spatial factors shows that there are significant regional effects and time effects. Secondly, we use the Hausman test to judge whether we should choose a fixed effect model or a random effect model. The statistical value of the Hausman test is 45.0641,

TABLE III. REGRESSION RESULTS OF THE SPATIAL DURBIN MODEL.

Variable	Spatial adjacency matrix			Spatial economic distance matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
LnPGDP	0.0314** (1.0418)	0.0138* (0.5783)	0.0452** (1.4443)	0.0032*** (0.0894)	0.0717** (0.9274)	0.0749** (1.0910)
LnEI	0.0217* (0.7025)	–0.1406*** (-3.0275)	–0.1189*** (-3.3593)	0.0627** (2.0179)	0.1133* (1.3390)	0.1759** (2.0269)
LnFDI	0.0459* (1.2040)	0.1317*** (3.0914)	0.1776*** (8.5686)	0.1501* (6.9242)	0.0724* (1.2469)	0.2225* (3.9725)
LnIND	0.4544*** (6.5618)	0.1387* (1.4920)	0.5931*** (9.9865)	0.4266*** (2.9792)	0.1280* (1.0105)	0.5546*** (8.7234)
LnPOP	0.3224*** (3.6008)	0.1816*** (1.3717)	0.5040*** (3.9884)	0.0301*** (2.7241)	0.8187*** (5.3950)	0.8488*** (5.5392)
LnGRE	–0.1064*** (-3.1185)	0.0181 (0.2911)	–0.0884** (–1.5243)	–0.1071*** (-3.0808)	–0.0756 *** (-1.0238)	–0.1828*** (-2.4474)
ρ		–0.0493**			–0.0409***	
Wald_spatial_lag		13.5478**			13.2191**	
Wald_spatial_error		13.7043**			13.3088**	
Time fixed effects		yes			yes	
Period fixed effects		yes			yes	
R^2		0.5456			0.6191	
N		432			432	

Note: t-values in parentheses, ***, **, and * indicate the significance levels of 1%, 5%, and 10% respectively; ( ) is the t-statistic value of the coefficient test.

the p value is 0.0000, which significantly rejects the original hypothesis that the estimation coefficient has non-systematic differences, indicating that we should choose the spatial fixed-effect model. Thirdly, the maximum likelihood method is used to estimate the spatial fixed effect Durbin model, and the Wald test is used to judge whether the model can be simplified as a spatial lag model or spatial error model. The adjoint probability p value of Wald test value rejects the original hypothesis that can be simplified at the 1% significance level. Under the two spatial weight matrices, the estimation results of the double fixed effect SDM are shown in **table III**.

From **table III**, we can see that economic development level (PGDP) and ecological efficiency have a positive correlation at the significance level of 10%, and H_1 is established. The improvement of the level of economic development will bring a lot of investment in technology and capital, upgrade the industrial structure, and inject vitality into improving the regional environmental level and promoting sustainable economic development. The influence coefficients of innovation input (EI) and ecological efficiency are positive and negative, indicating the spatial differences of factors affecting ecological efficiency, H_2 does not hold, indicating that increasing R&D investment cannot effectively improve the level of ecological efficiency. The reason may be that the "innovation compensation theory" of innovation input is less than the "cost effect", and the income brought by innovation does not offset the costs of environmental regulation and innovation input, it hinders output growth. FDI is positively correlated with the total effect and direct effect of ecological efficiency at a significant level of 10%, and H_3 is established. It shows that, overall, the technology spillover effect, human capital effect, and advanced management experience brought by international capital entry can play a positive role in improving the ecological efficiency of inflow areas. There has a positive correlation between industrial structure (IND) and ecological efficiency at the significance level of 10%, and H_4 is established. In recent years, China's Yangtze River Delta 27 cities continue to optimize and upgrade the tertiary industry structure, and constantly improve the efficiency of resource allocation and utilization, to further improve the ecological efficiency. There had a positive correlation between population density and ecological efficiency at the significance level of 1%, which indicated that the increase of population per unit area had a positive effect on ecological performance, and H_5 is established. Human resources of China's Yangtze River Delta 27 cities play an important role in promoting the development of the knowledge economy and enhancing the overall awareness of regional environmental protection. There was a negative correlation between the greening level and ecological efficiency at the significant level of 5%, and H_6 is established. The greening forms of 27 urban built-up areas in the Yangtze River Delta are mainly green belts and lawns, which are difficult to form a complete ecosystem. To a large extent, they only beautify the city, which is not conducive to the improvement of environmental quality but also reduces the ecological efficiency because of the high maintenance cost in the later stage.

The regression coefficient of the ecological efficiency spatial spillover coefficient (δ) is significantly negative, indicating that there is no positive effect between the improvement of the ecological efficiency level of the region and the surrounding areas. This may be due to the improvement of the ecological efficiency level in the region, In the meantime, the transfer of polluting industries to the surrounding areas makes the negative impact of the transfer of polluting industries greater than the positive impact of technology spillover, resulting in negative externalities to the surrounding areas.

The above show that, firstly, spatial factors play an important part in the study of ecological efficiency, ignoring spatial spillovers, which is not consistent with reality, but also may lead to partial conclusions. Secondly, there are spatial spillover effects in the 27 cities' ecological efficiency in China's Yangtze River Delta. The ecological efficiency between cities with close proximity and similar economic development level has a profound mutual influence on each other. Without considering the spatial spillover effect of eco-efficiency, the impact of other factors on ecological efficiency will be underestimated. The results of the two spatial weight estimations are verified mutually, and the robustness and reliability of the results are proved.

CONCLUSIONS AND SUGGESTIONS

The results indicate that the 27 cities' ecological efficiency in China's Yangtze River Delta rises slowly and shows the spatial distribution characteristics of "East is better than West". Economic development level, opening to the outside world, industrial structure, and population density are significantly positively correlated with the eco-efficiency of China's Yangtze River Delta 27 cities, but there has a significantly negative correlation between the greening level and the ecological efficiency. The impact of technological innovation level on ecological efficiency is not significant.

Therefore, in the process of ecological civilization construction of China's Yangtze River Delta 27 cities, first of all, we should pay attention to the optimization of the industrial structure and promote the upgrading process of the industrial structure of the cities by vigorously supporting high-tech industries and strategic emerging industries. However, the rush of various regions to develop emerging industries may lead to the convergence of industrial structure, resulting in relative overcapacity and vicious competition. Therefore, while pursuing the optimization and upgrading of industrial structure, we should also pay attention to industry segmentation, and optimize the allocation of resources through the heterogeneous adjustment of industrial internal structure. Secondly, the government should increase investment in science and technology and encourage enterprises to carry out R&D and innovation of low-carbon technology, clean production technology, recycling technology, and other green technologies by providing subsidies and financial support, to realize green, circular and low-carbon development. Then, cities with high ecological efficiency should actively play a leading role in promoting the improvement of the ecological efficiency of surrounding cities by sharing ecological environment management experience and development dividends. In addition, cities can introduce a series of preferential policies to attract high-level talents and appropriately increase the population density within the scope of resources and environment. Finally, local governments should reduce unnecessary investment in urban greening, reasonably plan urban greening areas, and avoid resource waste caused by formalism and "face projects".

ACKNOWLEDGMENTS

The authors thank all participants who contribute to this study. This work was funded by grants from the Ministry of Education of China "Research on statistical measurement and systematic evaluation of health resource allocation from the perspective of high-quality development" (No. 20YJCZH193).

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Cao J. and Li X. (2018). Measurement and analysis of ecological efficiency of Yangtze River economic belt. Ecological economy 34 (8), 174-179.

Geissler B., Mew M.C., Weber O. and Steiner G. (2015). Efficiency performance of the world's leading corporations in phosphate rock mining. Resources, Conservation and Recycling 105, 246-258. https://doi.org/10.1016/j.resconrec.2015.10.008

Halkos G. and Petrou K.N. (2019). Assessing 28 EU member states' environmental efficiency in national waste generation with DEA. Journal of Cleaner Production 208, 509-521. https://doi.org/10.1016/j.jclepro.2018.10.145

Han Z., Wang Q. and Liu T. (2019). Spatiotemporal dynamic distribution and evolution trend of ecological efficiency in China. Statistics and decision making 22, 85-88. https://doi.org/10.13546/j.cnki.tjyjc.2019.22.020

Rebolledo-Leiva R., Angulo-Meza L., Iriarte A., González-Araya M.C., and Vásquez-Ibarra L. (2019). Comparing two CF+DEA methods for assessing eco-efficiency from theoretical and practical points of view. Science of the Total Environment 659, 1266-1282. https://doi.org/10.1016/j.scitotenv.2018.12.296

Schaltegger S. and Sturm A. (1990). Ökologische rationalität: ansatzpunkte zur ausgestaltung von ökologieorientierten managementinstrumenten. die Unternehmung, 273-290.

Sinkin C., Wright C.J. and Burnett R.D. (2008). Eco-efficiency and firm value. Journal of Accounting and Public Policy 27 (2), 167-176. https://doi.org/10.1016/j.jaccpubpol.2008.01.003

Tone K. and Tsutsui M. (2009). Network DEA: A slacks-based measure approach. European Journal of Operational Research 197 (1), 243-252. https://doi.org/10.1016/j.ejor.2008.05.027

Wang Y. (2018). Ecological efficiency measurement and influencing factors of provinces along the

Silk Road Economic Belt: from the perspective of FDI and industrial structure optimization. East China Economic Management 32 (11), 44-51. https://doi.org/10.19629/j.cnki.34-1014/f. 180626002

Yi X. and Liu J. (2020). Ecological efficiency evaluation and its influencing factors in Western China. Statistics and Decision 36541 (1), 107-111. https://doi.org/10.13546/j.cnki.tjyjc.2020.01.023