Temporal-spatial differences in and influencing factors of agricultural eco-efficiency in Shandong Province, China

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ABSTRACT: *Based on the panel data of 134 counties (cities and districts) from 1998 to 2017, the temporal-spatial variation characteristics and influencing factors of agricultural eco-efficiency in Shandong Province were analyzed by using various methods, such as the super-efficiency SBM (slacks-based measure) model considering undesired output and the STIRPAT (stochastic impacts by regression on population, affluence, and technology) model, which helps clarify the improvements needed for agricultural eco-efficiency and provides a basis for the development of ecological agriculture in Shandong Province. Results showed the following: (1) During 1998-2017, the agricultural eco-efficiency of Shandong Province showed a fluctuating increasing tendency, but the overall efficiency value wasrelatively low. (2) The agricultural eco-efficiency of Shandong Province had a significant regional disparity, and its spatial agglomeration gradually weakened. The spatial distribution had a sporadic distribution of high value areas at first and then gradually formed the "low-high-low-high" zonal distribution from west to east. (3) The net income per capita of farmers and the added value of the primary industry had a significantly positive correlation with the agricultural eco-efficiency of Shandong Province, while the mechanization level, the planting area per capita, the level of financial support to agriculture and the planting structure exhibited a mainly negative correlation with the agricultural eco-efficiency of Shandong Province. Moreover, the added value of the primary industry and the financial support to agriculture in the 0.75 quantile had no significant influence on the agricultural eco-efficiency of Shandong Province, and the planting structure in the 0.25 and 0.75 quantiles also had no significant influence.*
Key words: *agricultural eco-efficiency, superefficient SBM model, STIRPAT model, temporal and spatial difference.*

Diferenças temporal-espacial e fatores de influência da ecoeficiência agrícola na Província de Shandong, China

RESUMO: *Com base nos dados do painel de 134 municípios (cidades, distritos) na província de Shandong de 1998 a 2017, as características de variação espacial e temporal da ecoeficiência agrícola na província de Shandong foram analisadas usando vários métodos, como o modelo SBM (Medida baseada EM estacas) supereficiente. Considerando indesejados produção e modelo STIRPAT (Impactos estocásticos da regressão da população, da afluência e da tecnologia), ajudará a esclarecer a direção da melhoria da eco eficiência agrícola na província de Shandong e fornecerá uma base para o desenvolvimento da agricultura ecológica. Os resultados mostraram que (1) em 1998-2017, a ecoeficiência agrícola da província de Shandong mostrou uma tendência ascendente na flutuação, mas o valor geral da eficiência foi baixo. (2) A distribuição espacial da distribuição esporádica inicial da área de alto valor se formou gradualmente de oeste para leste, distribuição zonal " "baixo-alto-baixo-alto"" (3) O lucro líquido per capita dos agricultores e o valor acrescentado da indústria primária foram significativamente correlacionados positivamente com a ecoeficiência agrícola da província de Shandong. O nível de mecanização, a área de plantio per capita, o apoio financeiro ao nível agrícola e a estrutura de plantio, entre eles, o valor acrescentado da indústria primária e o apoio financeiro à agricultura em 0,75 quantil, a estrutura de plantio em 0,25 e 0,75 quantil na ecoeficiência agrícola da província de Shandong não é significativa.*
Palavras-chave: *ecoeficiência agrícola, modelo SBM supereficiente, modelo STIRPAT, diferenciação temporal e espacial.*

INTRODUCTION

Agriculture is the foundation of the national economy and guarantees social development in China. With the rapid development of the agricultural economy, a series of problems, such as ecological deterioration, environmental pollution, and resource waste, occurs (HOU et al., 2018a).

Agricultural pollution tends to replace industrial pollution as the first pollution source (ZHENG et al., 2017). According to the data in the "Construction Planning of Demonstration Project of Comprehensive Control for Agricultural Nonpoint Source Pollution in Key Watersheds (2016 ~ 2020)", the chemical fertilizer consumption in China was 60.22 million tons in 2015, and the utilization rate was only 35.2%.

In recent years, pesticide consumption (effective components) has stabilized at approximately 0.3 million tons, while the utilization rate has been 36.6%. Agricultural plastic film consumption has reached 1.45 million tons, but the recovery rate has been less than two-thirds. Regardless, the situation with agricultural nonpoint source pollution is severe. At the same time, agricultural pollution continues to be serious due to the imperfect supervision system, minimal public awareness about prevention and inadequate pollution treatment technologies, which influence food security, ecological security and even social and economic development. Therefore, reducing environmental pollution under the premise of maintaining the rapid growth of the agricultural economy; coordinating among resource savings, ecological soundness and agricultural development; and improving the ecological efficiency of agriculture are necessary trends to attain the sustainable development of resources, the environment and the social economy.

Since the concept of "ecological efficiency" was proposed in 1990 (SCHALTEGGER & STURM, 1990), it has been widely used in enterprise eco-efficiency, land-use eco-efficiency and regional eco-efficiency research. Agricultural eco-efficiency is the extended meaning of eco-efficiency in agricultural fields, specifically referring to obtain as much agricultural output as possible and ensuring the quality of agricultural products by minimizing resource consumption and environmental pollution. In the context of resource-saving and environmentally friendly agriculture, some researchers have carried out studies on agricultural eco-efficiency and obtained substantial results (WANG et al., 2016, LI et al., 2017, WU et al., 2012). Most of these studies used data envelopment analysis (DEA) and its extended model to evaluate and analyze the spatial and temporal differences in agricultural eco-efficiency in study areas, which provided a reference and basis for effectively formulating policies and measures consistent with the local agricultural ecological environment and maintaining sustainable development and ecological balance of agriculture (GAO et al., 2014). In terms of the spatial scale of research, agricultural eco-efficiency at the national scale is a research hotspot, but some researchers have studied agricultural eco-efficiency at the regional scale and watershed scale (ZANG et al., 2014, HU et al., 2018, HUANG, et al., 2018). However, research on factors affecting agricultural eco-efficiency is still deficient, and research methods are also comparatively simple. Considering that the traditional DEA has a censored value of 1, the existing studies mostly use the Tobit model for regression analysis (HONG et al., 2016, QU et al., 2014). Overall, the research on agricultural eco-efficiency still has the following deficiencies: (1) in terms of research indices, different studies lack comparability due to the subjectivity of the selection of evaluation index systems and regional disparity; (2) for the research methods, the measured values of the traditional DEA model are between 0 and 1; thus, this model is unable to make further distinctions of the decision making units (DMUs) that achieve full efficiency; and (3) in terms of the spatial scale of research, studies are overwhelmingly focused at the national scale, while studies based on provincial dimensions have gained less attention due to data availability.

Shandong Province is an important grain production base in China that plays a key role in ensuring regional and national food security (YU et al., 2017). Simultaneously, Shandong Province is also a major contributor to agricultural pollution. In the past five years, the amount of pesticide application has ranked first in the country, and chemical fertilizer consumption has ranked second in the country. Moreover, the recycling system of agricultural plastic film is inadequate, and its recovery rate is low. Thus, agricultural pollution intensity remains high. To date, Shandong Province is in the transitional stage from a traditional pattern to modern agriculture, and agricultural production activities are still achieving economic benefits at the expense of the ecological environment to meet the social and economic needs of the province with a large population, which results in severe resource waste and environmental pollution. Therefore, it is of great significance to evaluate and analyze the agricultural eco-efficiency of Shandong Province. In this paper, Shandong Province is the study area, and its 134 counties (cities and districts) are as the research unit. The superefficient SBM model considering the unexpected output was adopted to study the spatial and temporal variation in agricultural eco-efficiency in Shandong Province, and the STIRPAT model was used to analyse the factors affecting the change in agricultural eco-efficiency. This research will provide a reference for the development of ecological agriculture as well as precise regulation of key agricultural pollution areas in Shandong Province and have significant value for the formation of green and sustainable agricultural production models.

MATERIALS AND METHODS

Study area

Shandong Province is located in the eastern coastal area of China (Figure 1) and

downstream of the Yellow River within the scope of 34°22.9'~38°24.0'N and 114°47.5'~122°42.3'E, which governs 16 prefecture level cities and covers an area of 157900 km². The middle part of the province is mountainous with hilly regions, the eastern part is a peninsula with gentle rolling hills, and the western and northern area is part of the North China Plain. The areas of mountains, hills and plains in Shandong Province account for 55%, 15.5% and 13.2% of the total area of the province, respectively. Shandong Province has a warm temperate continental monsoon climate with an annual average temperature of approximately 11 ~ 14 °C and an annual average precipitation of approximately 550 ~ 950 mm. The vegetation type is mainly coniferous and broad-leaved mixed forest, and brown soil and cinnamon soil are widely distributed in the province.

As a large agricultural province with a large population in China, Shandong Province is also one of the 13 main grain production areas. In 2017, the total population of Shandong Province reached 100.06 million, and the gross agricultural output value was 44.03 billion CNY, both values ranking second in China. The amount of sown crop area and the total grain yield in the last five years in Shandong Province have ranked in the top third for China.

Data

The data for the input and output index used in this article were mainly from the statistical yearbooks and statistical communiques of 17 cities in Shandong Province from 1998 to 2017, and part of the data came from the "National Population Statistics of Counties and Cities of the People's Republic of China" as well as the "China County Statistical Yearbook". Moreover, the missing data were calculated by interpolation. The "Handbook of Agricultural Pollution Sources Fertilizer Loss Coefficient", "Handbook of Pesticide Loss Coefficient" and "Handbook of Farmland Plastic Film Residue Coefficient" in the "Manual of National First Pollution Census" promulgated by the First National Pollution Sources Census Leading Group Office were the main references for the various pollution coefficients. In addition, considering the actual situation of Shandong Province, the coefficients of fertilizer loss, pesticide ineffective use and plastic film residual were determined to be 69%, 65% and 36%, respectively.

Methods
Super-efficient SBM model considering undesired output

The DEA model is widely used in eco-efficiency evaluations, and the SBM model proposed by Tone (TONE et al., 2001) in 2001 can measure agricultural eco-efficiency under the constraints of the ecological environment. Compared with the
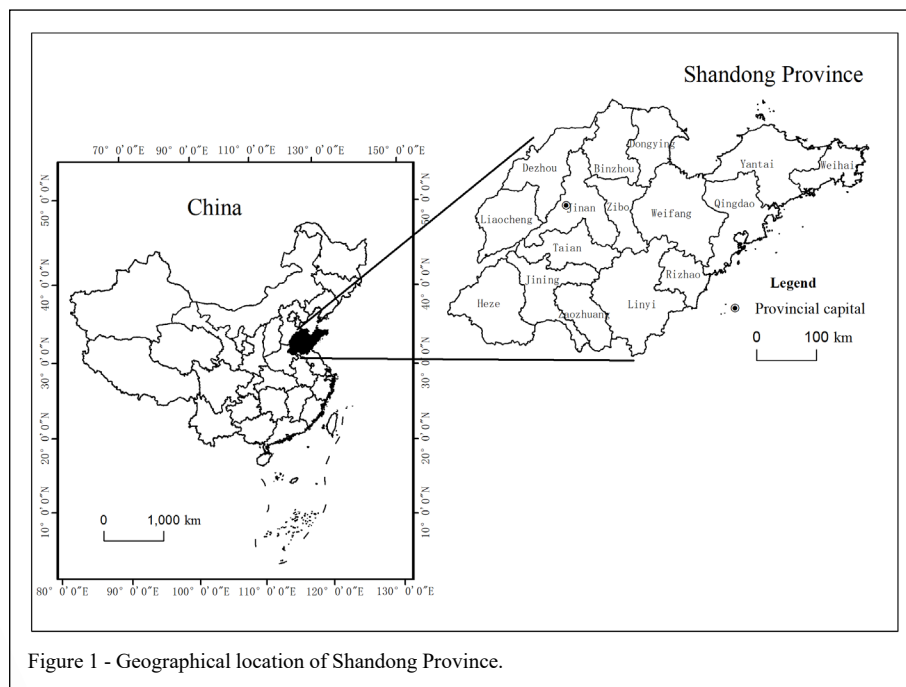

Figure 1 - Geographical location of Shandong Province.

traditional radial and angular DEA model, the non-radial and non-angular SBM model can resolve the issue that the radial model does not contain relaxation variables in the measurement of inefficiency. However, there is usually more than one DMU efficiency value that equals 1 in the actual measurement. Therefore, a super-efficiency model to further distinguish effective DMUs was proposed by Andersen and Petersen (Andersen & Petersen., 1999), was introduced into the SBM model in 2002 by Tone (TONE et al., 2002) and was defined as the SBM super efficiency model. The formula is given as follows:

$$\rho^* = \min \frac{\dfrac{1}{m}\sum_{i=1}^{m} \overline{x_i}/x_{i_0}}{\dfrac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\overline{y_r^d}/\substack{g\\r_0} + \sum_{t=1}^{s_2}\overline{y_t^b}/y_{t_0}^g\right)}$$

$$\begin{cases} \overline{x} \geq \sum_{j=1,\neq 0}^{n}\lambda_j y_j^b, \overline{y^g} \leq \sum_{j=1,\neq 0}^{n}\lambda_j y_j^g, \overline{y^b} \leq \sum_{j=1,\neq 0}^{n}\lambda_j y_j^b, \\ \overline{x} \geq x_0, \overline{y^g} \leq y_0^g, \overline{y^b} \geq y_0^b; \sum_{j=1,j\neq 0}^{n}\lambda_j = 1, \overline{y^g} \geq 0, \lambda \geq 0 \end{cases}$$

where it is assumed that there are n decision-making units, each of which is composed of input m, desired output s_1 and undesired output s_2; x, y^b and y^g represent the elements in the corresponding input matrix, desired output matrix and undesired output matrix, respectively; λ is the weight vector; ρ^* is the objective efficiency value.

Construction of the agricultural eco-efficiency evaluation index system

Agriculture in Shandong Province is dominated by the planting industry, so we used the planting industry of Shandong Province as the evaluation object. Based on previous research, the agricultural eco-efficiency evaluation index system of Shandong Province was constructed from the input and desired output factors as well as undesired output following principles of science, availability and regionality. Input variables included land, fertilizer, pesticide, agricultural plastic film, machines and labour, and the desired output index adopted the agricultural output value; the undesired output was characterized by fertilizer loss and ineffective utilization of pesticide and plastic film residue in agricultural nonpoint source pollution (Table 1).

STIRPAT model

The influencing factors of agricultural eco-efficiency in Shandong Province (Table 2) were selected in combination with the regional characteristics of Shandong Province and with the relevant research achievements as a reference (HOU et al., 2018b, HUANG et al., 2016). From a socioeconomic perspective, the urbanization rate (URBAN) was chosen to represent the population size, and the added value of the primary industry (PIA) and the net income per capita of farmers (INC) were selected to represent the provincial and individual affluence degree, respectively. For the science and technological perspective, the level of agricultural mechanization (MEC) was used to characterize the technical level. For the policy perspective, the level of financial support to agriculture (FIN) was used to reflect the policy influence. For agricultural production activities, the sowing area per capita

Table 1 - Evaluation indexes of agricultural eco-efficiency.

Item	Index	Variable and Unit
Input	Land input	Crop sown area/ha
	Fertilizer input	Fertilizer use (pure)/ton
	Pesticide input	Pesticide use/ton
	Agricultural film input	Agricultural film use/ton
	Machine input	Total power of agricultural machinery/kW
	Labour input	Number of agricultural employees/ten thousand cap
Desirable output outputs	Agricultural output value	Gross output value of planting industry/ten thousand CNY million
Undesirable output	Agricultural non-point source pollution	Loss of chemical fertilizer/ton
		Ineffective use of pesticides/ton
		Plastic film residue/ton

Table 2 - Factors affecting agricultural eco-efficiency.

Influence factor	Description
URBAN	Urban population/Total population (%)
INC	Obtained through relevant statistical yearbooks (CNY)
PIA	Primary industry added value (hundred million CNY)
MEC	Total power of agricultural machinery/Total sown area of crops (kW/ha)
SOW	Total sown area of crops/Agricultural practitioner (ha-cap)
FIN	Agriculture, forestry and water affairs expenditure/Local finance general budget expenditure (%)
PIAN	Sown area of grain crops/Total sown area of crops (%)

(SOW) was used to characterize the production scale, and the planting structure (PIAN) was used to characterize the production structure.

In this paper, the STIRPAT model derived from the IPAT environmental pressure equation (CHEN et al., 2014) was used to analyse the factors affecting agricultural eco-efficiency. The IPAT equation was expressed in a random form based on York et al. (YORK, 2003) to analyze the influence of each driving force on environmental pressure through the random regression analysis of population, affluence degree and technology. The STIRPAT model is as follows: $I=aP^bA^cT^de$

where I is the environmental pressure; P is the population quantity; A is the affluence degree; T is the technology; a is the model coefficient; b, c and d are the driving force indices; and e is the error.

In this study, the econometric model was modified and reconstructed on the basis of the traditional STIRPAT model (HOU et al., 2018, CHEN et al., 2015), and A was revised to A_1 and A_2, indicating the macro and micro wealth degree, respectively. At the same time, the standard STIRPAT model was extended by introducing other driving factors affecting agricultural eco-efficiency. To determine the relevant parameters by regression analysis, the original form was converted into a logarithmic form as follows:

$$\ln I = \ln C + a_1\ln P + a_2\ln A_1 + a_3\ln A_2 + a_4\ln T + a_5\ln X_1 + a_6\ln X_2 + a_7\ln X_3$$

where I is the agricultural eco-efficiency value; C is a constant; P is the urbanization rate; A_1 is the net income per capita of farmers; A_2 is the added value of the primary industry; T is the level of agricultural mechanization; X_1 is the sowing area per capita; X_2 is the level of financial support to agriculture; X_3 is the planting structure; and a_1-a_7 are the elastic coefficients.

RESULTS AND DISCUSSION

Temporal variations in agricultural eco-efficiency in Shandong Province

MaxDEA Pro 7 software was used to calculate the agricultural eco-efficiency values of each county (city, district). Figure 2 present the changes in agricultural eco-efficiency in Shandong Province from 1998 to 2017. The agricultural eco-efficiency value of Shandong Province showed a fluctuating increasing tendency in general, but it remained at a relatively lower level, and the value of each year was below 0.6. From 1998 to 2001, agricultural eco-efficiency declined slowly, and theredundancy rate of input and undesired output increased from 75% and 77% in 1998 to 88% and 92% in 2001; respectively, reaching its maximum over the whole research period; the redundancy rate of desired output remained unchanged, indicating that the decline in agricultural eco-efficiency in 1998~2001 was mainly due to the increase in redundancy of input and undesired output. Notably, the redundancy of chemical fertilizer, pesticide and agricultural plastic film in the input index were all greater than 50%. Therefore, the excessive use of chemical fertilizer, pesticide and agricultural plastic film in agricultural production activities was the main factor leading to the decline of agricultural eco-efficiency during 1998~2001. From 2001 to 2004, the value of agricultural eco-efficiency fluctuated greatly; it started to decline after rising sharply to 0.6 in 2002, but its amplitude of decrease was less than that of the increase. This scenario occurred mainly because the "Three Agricultural Problems" (the problems of agriculture, countryside and farmers) proposal implemented since 2001 has played a positive role in promoting the development of environmentally friendly agriculture in Shandong Province, and

Figure 2 - Temporal variation in agricultural eco-efficiency and input-output redundancy rate in Shandong Province from 1998 to 2017.
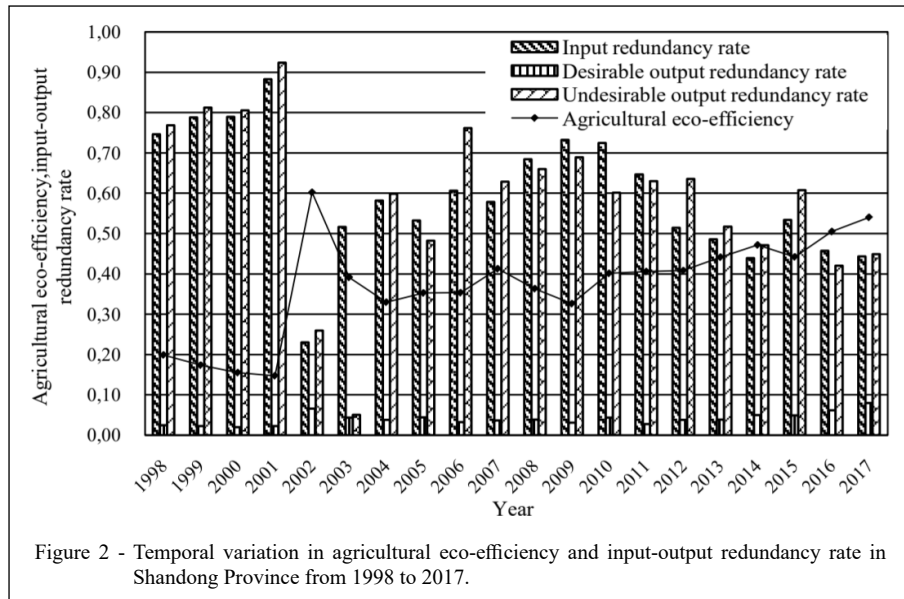
the living conditions of farmers, rural ecology and the control effect of agricultural non-point source pollution have improved remarkably. From 2004 to 2017, the agricultural eco-efficiency exhibited a fluctuating increasing tendency. The deterioration in the current ecological environment has increasingly attracted people's attention, and the government has vigorously developed ecological agriculture and circular agriculture. At the same time, the constant improvement in self-quality and enhancement in the environmental protection consciousness of farmers have also promoted the increase in agricultural eco-efficiency to some extent.

Spatial differences in agricultural eco-efficiency in Shandong Province

ArcGIS10.5 (ESRI) software was used to classify agricultural eco-efficiency values of counties in 1998, 2004, 2010 and 2017 into four categories: low efficiency (0 ~ 0.3), medium efficiency (0.3 ~ 0.6), higher efficiency (0.6 ~ 0.9), and high efficiency (> 0.9), as presented in figure 3. Overall, the middle and high value areas of agricultural eco-efficiency in Shandong Province showed an expansion trend around the central region of Shandong Province as well as in the Qingdao and Yantai regions of Shandong Peninsula, which gradually formed a "low-high-low-high" zonal distribution from west to east.

In 1998, only Shizhong district, Tianqiao district and Lixia district of Ji'nan city, Pingdu city,

Anqiu city, Shouguang city, Yantai development zone, Shizhong district of Jining city, Dongchangfu district and Guanxian County achieved complete efficiency, while Zhangqiu city, Tengzhou city, Qixia city, Qingzhou city, Yanggu County and Shenxian County were at a medium efficiency level. This is mainly because the agricultural economy in these areas develops rapidly, and the agricultural management mode shifted from pursuing economic interests to paying attention to the ecological benefits.

In 2004, the number of high efficiency areas increased. These areas were mainly concentrated in Jinan city, Zibo city and Taian city in the central region of Shandong Province, and Jining city and Zaozhuang city in the southern part of Shandong Province as well as counties (cities and districts) supervised by Yantai city and Qingdao city in the Shandong Peninsula region. However, the agricultural eco-efficiency of Qixia city, Qingzhou city, Dongchangfu district and Yanggu County all decreased significantly from a high efficiency value to a low efficiency value, indicating that a fluctuation existed in the agricultural eco-efficiency value of each region.

In 2010, agricultural eco-efficiency increased significantly compared with that in 2004. The counties (cities and districts) with medium efficiency and higher efficiency accounted for 28%, while 21 counties (cities, districts), including Jiyang County, Zhangqiu city, Boshan district,
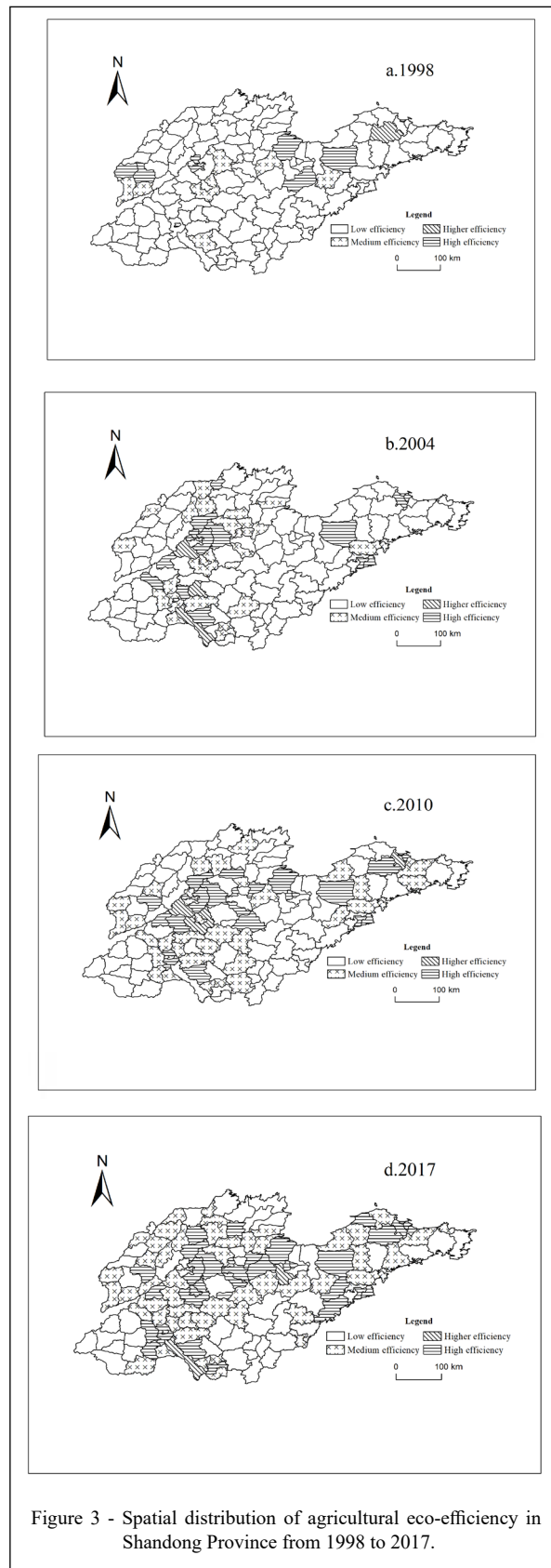
Figure 3 - Spatial distribution of agricultural eco-efficiency in Shandong Province from 1998 to 2017.

Linzi district and Zhoucun district, achieved full efficiency. Therefore, the "low-high-low-high" zonal distribution pattern from west to the east was formed.

In 2017, the total number of areas with low efficiency only accounted for 34% of all counties (cities and districts), showing that the agricultural eco-efficiency of Shandong Province reached a relatively higher level. Although the Yellow River delta is a national efficient ecological economic zone and national nature reserve, poor agricultural conditions and fragile ecological environment resulted in the agricultural eco-efficiency of Dongying city, Wudi County and Zhanhua County of Binzhou city, Laoling city of Dezhou city, Hanting district and Changyi city of Weifang city, and Gaoqing County of Zibo city persistently being lower. West of Shandong Province is an important grain production area, and its grain output accounts for 47% of the total of the province. The agricultural production mode of "high input, high output and high pollution" has restrained the improvement of agricultural eco-efficiency in Heze city, Decheng district and Qihe County of Dezhou city, Dongchangfu district and Dong'e County of Liaocheng city, and Yutai County and Yanzhou district of Jining city. Linyi city is located in the central and southern mountainous and hilly areas of Shandong Province and is an important conservative water source. This area has severe soil erosion, significant topographic relief, a large area of sloping farmland and a relatively low degree of agricultural mechanization, making the agricultural development of this region relatively unsustainable, and farmers pay more attention to the income increase in agricultural products and neglect the non-point source pollution caused by agricultural production activities, which leads to low agricultural eco-efficiency in the region.

Analysis of factors affecting agricultural eco-efficiency in Shandong Province

Panel data from 1998 to 2017 were used to construct a multivariable nonlinear model of STIRPAT based on the agricultural eco-efficiency value of Shandong Province. On the basis of regression analysis by the least square (OLS) method, the quantile regression (QR) method was used to further investigate the differences in different influencing factors of the interpreted variables (CHEN et al., 2018). The fitting results can be seen in table 3.

Results of OLS regression QR regression showed that the net income per capita of farmers, the added value of the primary industry, the mechanization level, the sowing area per capita, the level of financial support to agriculture and the planting structure had significant effects on agricultural eco-efficiency in Shandong Province. However, the urbanization rate had no remarkable effects on agricultural eco-efficiency. Conversely, increasing levels of urbanization can spread the dividend of economic growth (science and technology, education, health care, etc.) from cities to rural areas through the growth pole function, thus improving the material and spiritual civilization of rural areas. However,

Table 3 - Fitting results of the STIRPAT model.

Variable	Ordinary Least Squares (OLS)	---------------------------------Quantile Regression (QR)---------------------------------		
		Quantile 0.25	Quantile 0.50	Quantile 0.75
P	0.03 (1.01)	-0.01 (-0.20)	0.01 (0.38)	0.04 (0.57)
A_1	0.55*** (7.15)	0.63*** (4.87)	0.49*** (5.97)	0.51*** (3.64)
A_2	0.04* (1.58)	0.03* (1.11)	0.06** (2.22)	-0.01 (-0.25)
T	-0.15*** (-4.15)	-0.20*** (-3.77)	-0.21*** (-5.23)	-0.13* (-1.78)
X_1	-0.18*** (-10.22)	-0.17*** (-4.49)	-0.27*** (-6.87)	-0.28*** (-5.24)
X_2	-0.07*** (-2.42)	-0.08* (-1.58)	-0.10** (-2.49)	-0.04 (-0.77)
X_3	-0.13*** (-2.90)	-0.11 (-1.01)	-0.11* (-2.19)	-0.09 (-1.78)
Constant	-5.53*** (-10.58)	-6.82*** (-7.68)	-4.91*** (-9.78)	-4.85*** (-4.77)
AdjustR^2	0.63	0.62	0.55	0.71

Note: The values in parentheses are the t values of the elastic coefficients. *, ** and *** are significance levels of 10%, 5% and 1%, respectively.

conversely, a large number of highly qualified young and middle-aged people from rural areas are moving into cities, the agricultural management with surplus labour is extensive, and the production efficiency is low, which negates improvements in agricultural eco-efficiency.

The coefficients of net income per capita of farmers decreased gradually with the increase in the quantile, but they were all significant at the level of 1%, showing that agricultural eco-efficiency was more affected by the low-level net income per capita of farmers than by other factors. The net income per capita of farmers reflects the average income of rural residents in the region, the increase in net income per capita of farmers indicates an improvement in farmer life quality, and they are more likely to accept advanced production techniques and ecological concepts under high living standards. Therefore, employment through various channels and income increases for rural labourers in the province should be promoted energetically, rural infrastructure should be improve, and advanced and green production ideas should be broadly expanded.

The added value of the primary industry was significantly positively correlated with agricultural eco-efficiency in the 0.25 and 0.5 quantiles and had no significant effect in the 0.75 quantile, indicating that the added value of the primary industry was not a factor that restricted improvements in agricultural eco-efficiencyfor counties (cities and districts) above the 0.75 quantile. The high added value of the primary industry means that the local agricultural economy is well developed. In addition, the government and farmers will pay more attention to the efficiency of agricultural production and the treatment of agricultural pollution. However, the high added value of the primary industry will inhibit the development of the industrial economy. Therefore, it is very important for the development of the ecological economy and the economic development of different departments be coordinated to improve agricultural eco-efficiency at the same time in Shandong Province.

The mechanization level was negatively correlated with agricultural eco-efficiency in all the quantiles. The increase in the level of mechanization will improve agricultural production efficiency and promote the development of agricultural production to a great extent. However, it is difficult to accurately input production materials for large-scale operations, which greatly reduces the utilization rate of resources. Therefore, it is necessary to rationally allocate production materials and reduce agricultural pollution on the premise of ensuring agricultural modernization.

The sowing area per capita had a significant impact on agricultural eco-efficiency in all the quantiles, and the coefficients were all negative. Expansion of the agricultural production scale was unfavourable for the optimal allocation of production factors such as land, capital, and labour. It is difficult to achieve appropriate crop management if the planting area per capita is too large. Therefore, for counties (cities and districts) with lower and higher quantiles, there is an urgent need to improve the rural land allocation system and prohibit land reclamation and disorderly land occupation.

The level of financial support to agriculture had no significant effect on agricultural eco-efficiency in the 0.75 quantile but had a negative effect in the 0.25 and 0.5 quantiles, indicating that the allocation structure of financial funds in Shandong Province was unreasonable, financial support to agriculture was more focused on the development of the agricultural economy, and the quality of agricultural ecology was ignored. Therefore, financial funds for agriculture should be distributed reasonably to promote the development of agricultural in an ecologically friendly manner.

Planting structure had only a significant negative correlation with agricultural eco-efficiency in the 0.5 quantile. Compared with that of economic crops, the production cycle of grain crops was shorter, and water and fertilizer requirements were greater. Therefore, excessive acreage of grain crops will inevitably not only be detrimental to local soil and water conservation as well as sustainable use of agricultural resources but also lead to increased investment in fertilizers and pesticides and exacerbate non-point source pollution. Western Shandong Province is an important grain production area, and its unsustainable grain crop planting structure has seriously hindered improvements in agricultural eco-efficiency.

CONCLUSION

Temporally, the agricultural eco-efficiency of Shandong Province showed a trend of decreasing slowly first and then fluctuating increases from 1998 to 2017. The period of 1998 ~ 2001 experienced the decreasing trend, the fluctuation period was mainly concentrated during 2001 ~ 2004, and the increasing trend in agricultural eco-efficiency value occurred from 2005 to 2017. However, the overall agricultural eco-efficiency value during the period of research was only 0.37, which was at a relatively lower level. In general, there is still substantial development potential for agricultural eco-efficiency in Shandong Province.

In terms of the spatial differences, the number of counties (cities and districts) with medium efficiency and high efficiency increased continuously, while the number of counties (cities and districts) with low efficiency decreased gradually. The high efficiency regions exhibited an expanding trend centred around Jinan city, Qingdao city and Yantai city, and the zonal pattern of "low-high-low-high" from west to the east was gradually formed.

According to the analysis of the factors affecting the agricultural eco-efficiency of Shandong Province, the net income per capita of farmers and the added value of the primary industry had significant positive effects on the agricultural eco-efficiency of Shandong Province, while the mechanization level, the sowing area per capita, the level of financial support to agriculture and the planting structure had mainly negative effects. Among the factors, the net income per capitaof farmers, the mechanization level and the sowing area per capita had significant impacts on the agricultural eco-efficiency of Shandong Province in all quantiles, and the added value of the primary industry and the level of financial support to agriculture had no significant effects in the 0.75 quantile; however, the planting structure affected the agricultural eco-efficiency of Shandong Province only in the 0.5 quantile.

Based on the research results, the overall agricultural eco-efficiency of Shandong Province is still at a low level. To improve the agricultural eco-efficiency of Shandong Province, which is one of the main grain production areas in China under dynamically popularizedecological agriculture, the Yellow River delta region, the mountainous and hilly areas in the middle and south of Shandong Province and the counties (cities and districts) in the western region must be considered priorities. At the same time, the natural environmental conditions and economic development levels of different areas should be fully considered, the operational scales of farmland should be allocated reasonably, the planting structure of crops should be optimized, and areas with excess chemical fertilizer, pesticide and plastic film should be strictly controlled. In addition, by broadening the channels for agricultural development, such as the multilayer utilization of materials, stereoscopic agriculture in mountainous areas and agricultural tourism, the agriculture of Shandong Province can develop in an ecologically and green manner.

DECLARATION OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest. Thefunding sponsors had no role in the design of the study; in thecollection, analyses, or interpretation of the data; in the writing of themanuscript; or in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors have contributed to the present research. Zijun Li was mainly responsible for writing the article and revising the language. Yanlin Xu was fully engaged in the paper. LiangWang played the role of corresponding author.

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Erratum

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