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Agricultural Production Efficiency and Ecological Transformation Efficiency in the Yangtze River Economic Belt

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Abstract: Measuring the agricultural production efficiency (APE) and the ecological transformation efficiency (ETE) is key to agricultural modernization and regional ecological civilization construction. Based on the agricultural input–output dataset of the Yangtze River Economic Belt (YREB) from 2000 to 2015, we use the panel stochastic frontier analysis (SFA) to measure the APE and ETE to explore the spatiotemporal patterns of regional APE and ETE from the geographical perspective. We rely on the quantitative association characteristics to explore the key threshold of ecological economic development in agriculture. The results show that: (1) In the study period, the APE increased from 0.2993 to 0.5495, indicating that the cumulative growth of the whole period was 83.60%, and the high-value units gradually changed from point distribution to spatial distribution; (2) Although the ETE of the YREB increased from 2000 to 2015, the proportion of the first-class species was still only 7.26% in 2015, and the inverted U-shaped polarization distribution characteristics of the high-efficiency cities and the band-like structure of global decision-making units were formed at the same time; (3) The improvement of ETE has obvious segment distribution and threshold crossing characteristics, and the APE is equal to 0.661, which is the threshold for high-speed growth and low-speed growth of ETE. The research framework, spatiotemporal rules and key thresholds have reference value for agricultural modernization and ecological civilization construction.

Keywords: agricultural production efficiency; ecological transformation efficiency; SFA; spatiotemporal pattern; Yangtze River Economic Belt

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1. Introduction

As economic and ecological indicators play a central role in government performance evaluation, decision makers will inevitably make urban development and ecological conservation a higher priority [1–3], resulting in an increasing shortage of agricultural space to support sustainable agricultural development [4–6]. Agriculture not only occupies a basic position in the national economy, but it is also an important part of the synchronization of the four modernizations. Therefore, there is an urgent need to scientifically deal with the risk of insufficient agricultural output growth power and even shrink the output capacity caused by the lack of agricultural space under the background of total agricultural space constraints [7,8].

On the one hand, the characteristics of the economy from extensive growth to intensive growth objectively require that the core driving force of development changes from increasing increment to tapping stock, which points out the important content and basic connotation of promoting economic growth as the logic of development in the new era [9–11]. Therefore, it has become a connotation and requirement of high-quality agriculture to examine the current characteristics of regional agricultural production from the perspective of efficiency and put forward corresponding countermeasures for agricultural development [12]. On the other hand, compared with other industrial types, agriculture is more sensitive to the background characteristics of land resources, especially the land ecology, which directly reflects the comprehensive characteristics of regional climate, hydrology and other elements, resulting in a significant difference between barren land and fertile land [13–15]. The traditional research on agricultural production efficiency (APE) mostly depicts the input of land resources from the quantitative dimension, ignoring the positive impact of land quality on agricultural output, which has long been recognized in pedology. Land ecological characteristics not only provide a good external environment for agricultural production but also objectively reflect the richness of local land resources, which has good economic and physiological significance [7]. Therefore, the land ecological indicators characterizing resource endowment and ecological environment should be brought into the framework of agricultural input–output analysis [16]. Recently, in order to more accurately describe the role of land in agricultural production, some scholars began to examine the impact of indicators other than land quantity on agricultural output and brought it into the analysis framework of agricultural production efficiency.

Combined with the differences in territorial types and geo-spatial scales, scholars carry out input–output analysis of regional economic production activities based on the connotation of technical efficiency theory and model methods. These studies focus on the systematic analysis of the nonagricultural economic benefits of construction land in urban areas, the agricultural production benefits in rural areas and the economic and ecosystem benefits of the whole region. Related studies provide strong support for the formulation of a series of policies on urban development, agricultural protection and ecological conservation. Guo et al. [17] employed the semiparametric metafrontier approach and spatial convergence model to analyze the spatiotemporal convergence of APE in the Yangtze River Economic Belt (YREB). They discovered that there was a differential convergence law between agricultural production areas and nonagricultural production areas, emphasizing the need for regulating regional agricultural activities from both input and output to optimize the utilization of land resources. Deng and Gibson [18] used the estimation system of land production and stochastic frontier analysis models to investigate the ecological efficiency of agriculture in Shandong Province. The study revealed that most ecological efficiency values were higher than 0.9, indicating a trade-off between agricultural production and urbanization. Xie et al. [19] employed the nonradial directional distance function model and Luenberger productivity index to evaluate the green efficiency of arable land in provincial-level administrative units in China from 1995 to 2013. The study indicated a trend of decreasing followed by an increase in China's green efficiency of arable land use. Jin et al. [20] applied stochastic frontier analysis and spatial correlation models to estimate urban land use efficiency and its spatial correlation characteristics in China from 2005 to 2014. The study highlighted the regional convergence trend upstream, midstream and downstream in China's urban land use efficiency. Furthermore, Huang et al. [21] adopted the directional distance function analysis method and directly embedded net primary productivity (NPP) as a characterization index of land quality and land ecology into the agricultural input–output analysis framework, making it clear that land ecology has the ability to improve output based on the case of animal husbandry in the Qinghai-Tibet Plateau. Zhang et al. [22] took land production potential as the characterization index of land quality and used the SFA model beyond the logarithmic production function to reveal that land ecology played a positive role in stimulating the potential of maize production efficiency. However, there is still an urgent need to supplement the empirical analysis of APE including land ecological indicators in different regions, subjects, types and scales [23]. In particular, the current understanding of the potential demand for eco-environmental protection is not clear, and the transformation path of clear waters and green mountains into mountains of gold and silver is not in-depth. It is necessary to further reveal the academic and practical connotation of the transformation potential of land ecology. In addition, the current concept of agricultural production efficiency comes from the technical efficiency of the economy, which only examines the comprehensive efficiency level of regional input and output, that is, the mathematical relationship between total input and total output, and pays less attention to the efficiency characteristics of a single resource input. In particular, it fails to reveal the efficiency of land ecological variables and how they affect agricultural production efficiency, which makes the understanding of ecological input not clear enough. Therefore, we not only supplement the ecological variables in the efficiency measurement, making the efficiency measurement results more accurate, but also make a comparative analysis before and after to reveal the transformation ability of ecological variables and their effect on efficiency.

Land ecology refers to the local environment of land, which not only provides necessary fertilizers and nutrients for crop growth but also affects water flow and material transfer. The current research basically recognized the promoting effect of land ecology on crop yield and discussed the nonlinear relationship between land ecology and agricultural output. However, from the perspective of economic production theory, how to choose appropriate indicators and how to reflect the ecological characteristics of land and connect production activities is a problem that many scholars think about. NPP, net primary productivity, reflects the comprehensive characteristics of light, temperature, water, soil and air in the region and can better feedback on the eco-environmental quality of crop growth in the region, so it is feasible to bring it into the study of agricultural production efficiency.

The Yangtze River, as the mother river of the Chinese nation, supports the development of the Chinese nation [10]. The YREB includes two important grain-producing areas, the middle and lower reaches of the Yangtze River and the Sichuan Basin, as well as regional grain production bases such as Chengdu Plain, Jianghan Plain, Dongting Lake Plain, Poyang Lake Plain, Jianghuai region and Taihu Lake Plain, which shoulder the responsibility and mission of ensuring national food security [17]. However, with the continuous improvement of urban development and ecological priority, the stability and sustainability of agricultural production in the YREB are facing the dual threats of insufficient agricultural space and low output benefits. It is urgent to put the evaluation of agricultural productive benefits and eco-economic potential into the same research framework under the guidance of the regional coordinated development strategy guided by “joint protection and no large-scale development” [23]. Therefore, this paper takes the YREB as a case study area, calculates the APE and ETE of the YREB and describes its spatiotemporal pattern characteristics. The research results, which overcome the disadvantages of experience and cognition such as subjectivity, arbitrariness and blindness, can not only directly serve the agricultural modernization policy of the YREB but are also conducive to the understanding and practice of the concept of “two mountains”.

With the help of a hypothesis test, the SFA model can judge the correctness and scientificalness of the existing hypothesis of efficiency and the selective setting of production function [24–26]. In particular, the nonlinear production frontier is drawn based on the production function setting and the unstable random error term is introduced based on the complex reality, so that it can more accurately evaluate the quantitative characteristics and changing rules of the technical efficiency of the decision-making unit. Based on this, the SFA model is used to calculate the APE (APE) and ecological transformation efficiency (ETE) in the YREB from 2000 to 2015 and to clarify the input–output level characteristics of regional agricultural production and the economic transformation potential of land ecology in order to provide a decision-making reference for agricultural green development and regional strategy in the YREB.

In this study, we take NPP as the characterization index of land ecology and use the stochastic frontier analysis (SFA) model to calculate the agricultural production efficiency and ecological transformation efficiency of the Yangtze River Economic Belt. It is found that the agricultural production efficiency and ecological transformation efficiency of the Yangtze River Economic Belt have significant temporal and spatial differences, and they show the law of nonlinear change. This study not only enriches the land characterization index system in the process of measuring agricultural production efficiency but also reveals the threshold and fitting characteristics of agricultural production efficiency and land ecological transformation efficiency.

2. Materials and Methods

2.1. Data

Following the basic theory of input–output analysis and synthesizing the existing technical efficiency research results, the index system is constructed based on labor, capital, land and economic output [27]. Among them, considering that the ecological index should have the dual requirements of the attribute of input factors of production activities and the description of land ecological change, NPP is used as the input variable to characterize land ecology in the calculation of APE. Therefore, according to the principles of representativeness, accuracy and conciseness, the number of employees in the primary industry, the amount of chemical fertilizer, the total power of agricultural machinery, the sown area and the total value of NPP are selected as input variables, and the added value of the primary industry, which comprehensively reflects the agricultural economic output, is selected as the output variable [7,16–18]. The above data come from the China Regional Economic Statistical Yearbook, the statistical yearbooks of provinces and the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. The added value of the primary industry is calculated by the GDP deflator method up to 2000. National economic and social development plans are drawn up at an interval of five years, and economic production activities have strong phased and periodic characteristics. Therefore, the basic data of 2000, 2005, 2010 and 2015 are sorted out to construct the regional-level agricultural production panel data.

2.2. Methods

2.2.1. Technical Efficiency

Technical efficiency refers to the ability that input remains unchanged and output can be increased under a certain technical level; output remains unchanged and input can be reduced, which is often used to describe the comprehensive output capacity of all kinds of inputs and outputs in the region. Since the SFA model was proposed, Battese and Coelli have successively supplemented the influencing factors of technical efficiency and time-varying coefficient modules, expanding the original theory from a single numerical measure to influence mechanism analysis and cross-sectional data to panel data, which have been widely used in academia and industry [28]. As a hypothesis test for econometric methods, the SFA model is not only an important means to select the type of production function but is also the main basis for evaluating the applicability and scientificalness of the technical efficiency research framework and the accuracy and correctness of regression parameter estimation. In order to describe the scientific connotation of APE from the perspective of agriculture, an input–output conceptual model based on production function is constructed [29]. The formula is as follows:

$$y_{it} = f(x_{it}; \beta) \cdot \exp(v_{it}) \cdot \exp(-u_{it}) \tag{1}$$

In the formula, y_{it} represents the added value of the primary industry; $f(x_{it}; \beta)$ is the form of production function in which x_{it} is the input and β is the output elasticity of the corresponding input; $\exp(v_{it})$ is the random disturbance term, which is used to simulate the random factors; and $\exp(-u_{it})$ is the technical efficiency item, which is used to characterize the distance between the actual output and the maximum output under a certain technical level, that is, the agricultural production efficiency in this study.

This paper uses the panel SFA model, so it is necessary to set the time change characteristics of APE.

$$\mu_{it} = \exp\{-\eta \cdot (t - T)\} \cdot \mu_i \tag{2}$$

In the formula, η is a time-varying coefficient, which reflects the interannual variation trend of APE in urban units. If $\eta > 0$, it indicates the increase in APE. If $\eta = 0$, it shows that APE does not change with time. If $\eta < 0$, it shows that APE is decreasing year by year.

The advantage of the SFA model as a parameter method to estimate APE lies in its scientific verifiability, including the existence test of agricultural production inefficiency and the rationality test of production function selection, based on the likelihood ratio test and error term structure [30].

$$\gamma = \frac{\sigma_\mu^2}{\sigma_\mu^2 + \sigma_v^2} \tag{3}$$

$$\lambda = -2[LR(H_0) - LR(H_1)] \tag{4}$$

In the formula, γ is used to quantitatively describe the proportion of technical inefficiency in mixed error terms. If the value is large, it indicates that the influence of APE cannot be ignored in input–output analysis. If the value is too small, it shows that there is no need to bring APE into the framework of agricultural input–output analysis. The maximum likelihood function of the constrained condition LR (H_0) is compared with the logarithmic likelihood ratio statistic (λ) of the unconstrained condition LR (H_1) in order to optimize the best model in accordance with the study, which obeys the mixed chi-square distribution.

2.2.2. Factor Efficiency

Factor efficiency is developed from the definition of technical efficiency. Unlike technical efficiency, which examines the quantitative relationship between all inputs and outputs, factor efficiency measures the ability of specific inputs to be reduced when technology, other inputs and outputs remain the same. It can reflect the utilization level of ecological input after putting it into the equation [31]. Taking the translog production function including a quadratic term as the production function form, the SFA model including the land ecological index is expressed as follows [17]:

$$\ln(y_{it}) = \underbrace{\underbrace{\beta_0 + \sum_{k=1}^{k} \beta_k \ln(x_{kit}) + \beta_e \ln(x_{eit}) + v_{it} - u_{it}}_{\text{Cobb-Douglas Production Function}} + \frac{1}{2}\sum_{k=1}^{k}\sum_{l=1}^{l} \beta_{kl} \ln(x_{kit}) \ln(x_{kit}) + \frac{1}{2}\beta_{ee}(\ln(x_{eit}))^2 + \sum_{k=1}^{k} \beta_{ke} \ln(x_{kit}) \ln(x_{eit})}_{\text{Translog Production Function}} \tag{5}$$

After confirming that the SFA model can be used to analyze APE, the definition and connotation of technical efficiency are compared, and ETE is defined as the ratio of minimum ecological input to actual ecological input, that is, under the premise that other inputs remain unchanged, the minimum ecological input is set to x_{em} and the corresponding APE is u_{mit}; then, the SFA model expressed in Formula (5) can be rewritten as follows [32]:

$$\ln(y_{it}) = \beta_0 + \sum_{k=1}^{k} \beta_k \ln(x_{kit}) + \beta_e \ln(x_{emit}) + \frac{1}{2}\sum_{k=1}^{k}\sum_{l=1}^{l} \beta_{kl} \ln(x_{kit}) \ln(x_{kit}) + \frac{1}{2}\beta_{ee}(\ln(x_{emit}))^2 + \sum_{k=1}^{k} \beta_{ke} \ln(x_{kit}) \ln(x_{emit}) + v_{it} - u_{it} \tag{6}$$

By subtracting the Formulas (6) and (5), the correlation formula between the actual input and the minimum input of land ecological variables can be obtained.

$$\frac{1}{2}\beta_{ee}(\ln(x_{emit}) - \ln(x_{eit}))^2 + (\beta_e + \beta_{ee}\ln(x_{emit}) + \sum_{k=1}^{k} \beta_{ke} \ln(x_{kit})) \cdot (\ln(x_{emit}) - \ln(x_{eit})) - u_{mit} + u_{it} = 0 \tag{7}$$

Based on Formula (7), the efficiency of ecological transformation can be obtained.

$$ETE = \exp(\ln\frac{x_{emit}}{x_{eit}}) = \exp(\frac{-(\beta_e + \beta_{ee}\ln(x_{emit}) + \sum_{k=1}^{k} \beta_{ke}\ln(x_{kit})) \pm \sqrt{(\beta_e + \beta_{ee}\ln(x_{emit}) + \sum_{k=1}^{k} \beta_{ke}\ln(x_{kit}))^2 - 2 \times \beta_{ee} \times (-u_{mit} + u_{it})}}{\beta_{ee}}) \tag{8}$$

3. Results

3.1. Parameter Estimation

We estimate the translog production function including land ecological variables (model 1), the translog production function without land ecological variables (model 2), the Cobb–Douglas production function with production variables (model 3) and the general production function model without an inefficiency term (model 4) (Table 1), and then we used this as the basis for judging the rationality of stochastic frontier analysis and selecting the optimal model. Firstly, the lowest value of γ in the models (1–3) is 0.926, indicating that technical inefficiency accounts for more than 92.6% of the mixed error terms. Agricultural input–output analysis needs to examine the impact of APE. Secondly, the results show that the model (1–3) passes the likelihood ratio test, indicating that the stochastic frontier analysis can more accurately simulate the agricultural input–output characteristics of the YREB. Thirdly, the results of model (1) and models (2–3) show that, compared with the translog production function with no land ecological variables, the Cobb–Douglas production function model with land ecological variables and the translog production function with land ecological variables have a higher ability to explain the agricultural production characteristics of the YREB. Finally, the parameter estimation of model (1) passed at a higher level of significance, indicating that the translog production function with land ecological variables has a higher parameter estimation ability. To sum up, model (1) should be used to analyze the APE and ETE. In addition, the time-varying coefficient η = 0.248 indicates that, from the time variation, the APE of the YREB has gradually improved, and the management behavior and environmental conditions in agricultural production activities have been gradually optimized.

Table 1. Results of stochastic frontier analysis.

	lny1 (Model 1)	**lny1 (Model 2)**	**lny1 (Model 3)**	**lny1 (Model 4)**
cons	−15.233 * (−1.878)	4.053 *** (4.781)	2.109 *** (3.095)	−4.492 (−0.802)
lnx1	−0.836 *** (−3.192)	−0.180 * (−1.720)	−0.038 ** (−2.571)	−0.297 (−0.864)
lnx2	−3.460 *** (−5.238)	0.014 (0.047)	0.128 *** (2.950)	−1.786 ** (−2.503)
lnx3	−1.751 *** (−2.724)	−0.276 (1.173)	0.156 *** (3.294)	−2.409 *** (−3.595)
lnx4	4.160 *** (4.504)	0.179 (0.729)	0.188 *** (4.316)	4.582 *** (4.675)
lnx5	2.140 ** (2.089)		0.119 *** (2.994)	0.317 (0.455)
0.5 * (lnx1)2	−0.017 *** (−3.166)	−0.012 ** (−2.260)		−0.006 (−0.695)
0.5 * (lnx2)2	0.169 *** (3.927)	0.088 ** (2.149)		0.242 *** (6.040)
0.5 * (lnx3)2	0.140 *** (6.038)	0.142 *** (5.197)		0.168 *** (5.069)
0.5 * (lnx4)2	0.098 ** (2.552)	0.080 * (1.867)		0.068 (1.270)
0.5 * (lnx5)2	−0.060 * (−1.744)			−0.001 (−0.002)
0.5 * (lnx1) * (lnx2)	−0.100 *** (−3.855)	−0.028 (−1.224)		−0.099 *** (−2.607)
0.5 * (lnx1) * (lnx3)	0.033 (1.560)	0.048 ** (2.141)		0.029 (0.883)
0.5 * (lnx1) * (lnx4)	0.071 ** (2.155)	−0.024 (−0.748)		0.080 (1.595)
(lnx1) * (lnx5)	0.026 (1.477)			−0.008 (−0.383)

Table 1. *Cont.*

	lny1 (Model 1)	lny1 (Model 2)	lny1 (Model 3)	lny1 (Model 4)
0.5 * (lnx2) * (lnx3)	−0.180 *** (−3.205)	−0.043 * (−0.868)		−0.371 *** (−5.270)
0.5 * (lnx2) * (lnx4)	−0.124 * (−1.833)	−0.023 (−0.353)		−0.225 *** (−2.914)
(lnx2) * (lnx5)	0.263 *** (5.648)			0.233 *** (5.064)
0.5 * (lnx3) * (lnx4)	−0.046 (−0.578)	−0.144 * (−1.928)		0.041 (0.403)
(lnx3) * (lnx5)	0.084 ** (2.073)			0.125 *** (3.078)
(lnx4) * (lnx5)	−0.265 *** (−4.383)			−0.288 *** (−4.701)
σ2	0.475 *** (3.764)	0.599 *** (3.110)	1.496 ** (2.234)	0.151
γ	0.926 *** (37.571)	0.939 *** (37.862)	0.976 *** (69.181)	
η	0.248 *** (11.603)	0.247 *** (12.416)	0.204 *** (7.792)	
log-likelihood	−86.929	−108.523	−155.685	−224.507
Chi(2)	Chi(2)	Chi(2)	Chi(2)	
test (inefficiency)	275.154	282.563	251.953	
test (m1, m2)	Chi(6)	LRT = 43.188	χ2 (21.666)	$p < 0.001$
test (m1, m3)	Chi(15)	LRT = 137.512	χ2 (37.005)	$p < 0.001$
test (m1, m4)	Chi(2)	LRT = 275.154	χ2 (12.810)	$p < 0.001$

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; $\sigma^2 = \sigma_v{}^2 + \sigma_u{}^2$.

3.2. Agricultural Production Efficiency

On the premise of passing the test of the model and parameters, the APE of the YREB from 2000 to 2015 is obtained (Figure 1). From the perspective of time characteristics, firstly, the APE of the YREB maintained a relatively stable growth, with a cumulative increase of 83.60% during the whole period from 2000 to 2015. Compared with the urbanization efficiency in the same period, APE shows the characteristics of a large base and small growth rate, and the absolute value of urbanization efficiency in 2015 exceeded the APE. The above shows that although the agricultural production of the YREB has initial competitive advantages, it is at a disadvantage and shows a widening gap in the long-term improvement of urbanization efficiency. Measures such as agricultural production management and rational allocation of resources are urgently needed to promote the rapid improvement of the level of agricultural production. Secondly, based on the characteristics of box chart data, it is known that the production efficiency improvement ability of extremely high-value and sub-high-value city units is weaker than that of low-efficiency-level city units. The improvement of global APE should focus on the efficiency improvement mechanism of low-efficiency cities. Thirdly, with the passage of time, the upper and lower edge of the box chart tends to narrow, the overall difference of APE in the YREB gradually weakens and the production efficiency of each urban unit converges. Finally, the phased characteristics in which the average value in 2000 is higher than the median is steadily transformed into that in 2015 when the average is lower than the median. This further validates the overall development trend of APE in the YREB, which is characterized by the slowdown of extremely high-value growth and the acceleration of medium- and low-value growth. Similar to the existing research, in our study, we found that the agricultural production efficiency of the Yangtze River Economic Belt showed a relatively steady upward trend, which indicated that the agricultural production efficiency of the region tended to improve and the management level in the process of agricultural production was further improved [17]. It is worth noting that, compared with the DEA model, which puts all the samples under the same framework, the SFA model brings random disturbance and time function into the equation, which more objectively reflects the gradual law of agricultural production efficiency.

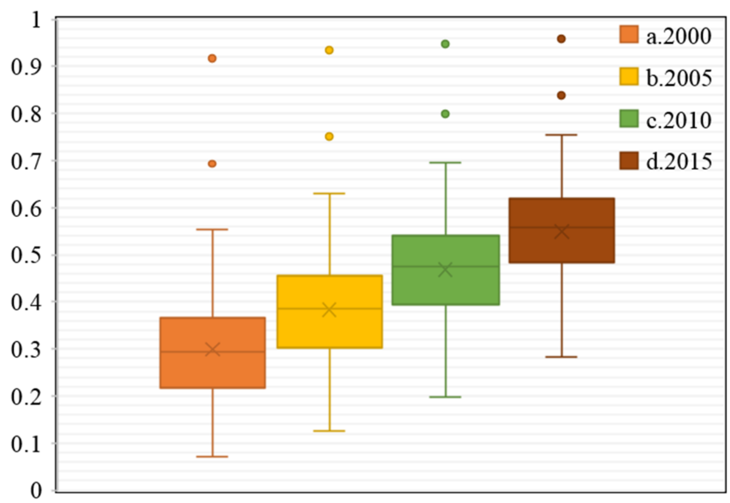

Figure 1. Time variation of agricultural production efficiency in the YREB.

Based on the natural breakpoint method, we draw the following Figure 2. Because of the strong regional characteristics of agricultural production efficiency in various cities, the pattern identification and potential judgment of agricultural production efficiency based on the perspective of geography has become a scientific reference for the strategic planning of the YREB (Figure 2). From 2000 to 2015, the high-value unit gradually developed from the spatial scattered distribution of the core area of the Hanjiang Plain and Sichuan Basin to the spatial agglomeration development model of Chengdu-Chongqing urban agglomeration, Wuhan urban agglomeration, Jiangsu riverside urban agglomeration, Changsha-Zhuzhou-Xiangtan urban agglomeration and central Yunnan urban agglomeration. This shows that agriculture, as a basic industry to support modernization, has basically formed a demand-side efficiency improvement model around the core metropolitan area and key cities under the material demand of industrialization and urbanization. The relatively high-value units of agricultural production efficiency mostly appear in cities with good economic foundation and high technical levels, which shows that human intervention has a more profound impact on agricultural production efficiency than traditional natural factors such as light, temperature, water, soil and atmosphere, which is basically consistent with the conclusions of the current research [26]. Generally speaking, under the specific technical conditions and input level, the overall value of agricultural production efficiency in the YREB is low; at the same time, there is a great spatial asymmetry and time imbalance. However, as far as it is concerned, the growth trend is obvious and forms a rapid development trend and a typical demonstration and guidance pattern around the demand side, which has a good realistic basis for agricultural supply-side structural reform. This provides an important reference for tamping the top-level design of agricultural production in the YREB, exploring the basis of mechanism reform and grasping the overall promotion and key points of agriculture in the YREB, including self-development and regional coordination, to further explore the effectiveness and characteristics of the transformation path between the two mountains.

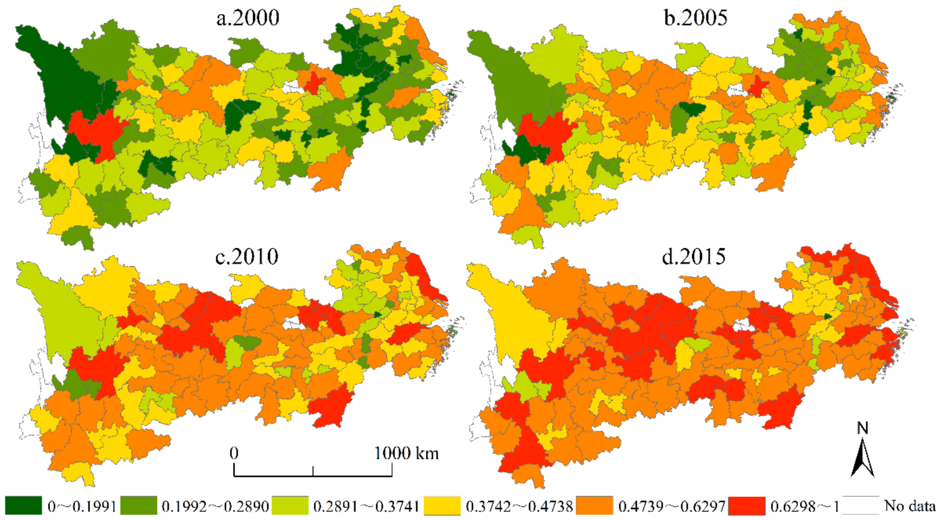

Figure 2. Spatiotemporal pattern of agricultural production efficiency in the YREB.

3.3. Ecological Transformation Efficiency

Based on the natural breakpoint method, we draw the following Figure 3. From the time characteristics, the number of cities with an ETE higher than 0.2053 (Class 1) from 2000 to 2015 is 0, 2, 5 and 9, respectively, and the proportion of class 1 ETE is only 7.26% in 2015 (Figure 3). The characteristics of small and weak ETEs are more prominent. Although agricultural and economic policies tend to develop in regional equilibrium, under the dual effects of geographical conditions and resource endowments, the ETE of the YREB is further characterized by the strengthening of competitive advantages and the increase in regional differences. On the one hand, there are still a large number of urban units with ecological efficiency less than 0.0151 (Class 6) in northwestern Sichuan, northeastern Jiangxi and southeastern Zhejiang in 2015, which have become the main low-value convergence areas of ETE in the whole region. On the other hand, the ETE of urban units represented by southwestern Hubei, southeastern Hunan, Jiangsu along the Yangtze River and central Yunnan has been obviously improved. In particular, with the approval of national experimental areas in the Wuhan urban agglomeration and Changsha-Zhuzhou-Xiangtan urban agglomeration, the ETE of the Hubei and Hunan provinces increased rapidly from 2005 to 2010, and the number of municipal units realizing the category transition of ETE reached 21, accounting for about 77.77% of the total number of municipal units in Hubei and Hunan provinces. Among them, Jingmen, Xianning and Xiaogan, as the strong industrial cities in the provinces at the end of the last century, experienced a transformation of the development path at the beginning of this century and realized the continuous jump of ETE types, which became the main driving force for the replacement of ETE from homogenization to alienation pattern.

Based on spatial characteristics, firstly, the ETE of Jiangsu, Anhui, Hubei, Chongqing and other provinces and cities is significantly higher than that of Zhejiang, Jiangxi, Hunan, Guizhou and other provinces with the same longitude. The ETE of the YREB shows the characteristics of north–south differentiation bounded by the Yangtze River. Secondly, in the same period, the ETE of Hubei and Hunan provinces in the middle reaches of the YREB was significantly higher than that of Zhejiang, Anhui and Guizhou, Yunnan and Sichuan provinces in the upper reaches of the YREB and formed an inverted U-shaped spatial pattern of ETE. Finally, the spatiotemporal characteristics of ETE in the YREB show that the development of ETE follows the evolution model of the "growth point-development axis". The high-value area of ETE has changed from the isolated spot distribution in eastern Hubei and northeastern Jiangsu to the banded distribution along the Yangtze River. It is worth noting that Yunnan Province has become the regional center of the ETE of the YREB. The central Yunnan urban agglomeration with Kunming as the core has rationally allocated agricultural economic and ecological resources under the background of rapid urbanization, which has accelerated the ecological transformation of agricultural development. This shows that economically backward areas do not necessarily maintain disadvantages, and it is still possible to achieve breakthroughs in high-efficiency areas combined with their own characteristics, especially when adopting the development path of ecological priority and green development. Top-level design and macro-control can be adopted to achieve great-leap-forward development under the needs of the new era of "jointly grasping great protection and not carrying out large-scale development".

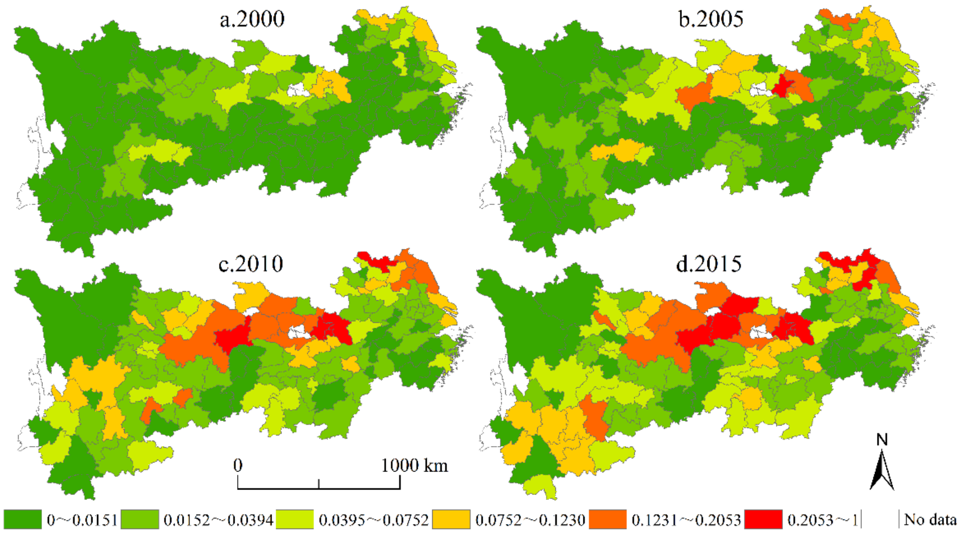

Figure 3. Spatiotemporal pattern of ecological transformation efficiency in the YREB.

3.4. Correlation Analysis between the Two Efficiencies

Agricultural production efficiency is the key index to characterize the comprehensive agricultural output benefits, while the ecological transformation efficiency shows that ecological variables are used to support the utilization efficiency of agricultural output and represent the ability of output maximization and self-transformation, respectively. In a decision, agricultural production efficiency or ecological transformation efficiency may be the focus of decision makers, but simply emphasizing an index will lead to mistakes in decision making. For example, too much emphasis on agricultural production efficiency will lead to the assessment of the impact on the ecological environment, which will lead to a large amount of loss and waste of ecological resources. At this time, the correlation analysis of the two can reveal the changing trend of the two to a certain extent, find out the potential mutation points, take into account agricultural output and ecological protection within the threshold range and realize the coordinated development of the two.

Based on the agricultural production efficiency and ETE of 124 urban units in the YREB, the correlation characteristic scatter diagram is drawn to depict the stage characteristics of agricultural production efficiency and ETE (Figure 4). According to the scatter distribution, the critical points of the section are selected many times and the curve-fitting effect is analyzed. Finally, agricultural production efficiency 0.6 is selected as the critical point, and linear and binomial trend lines are used to fit the scattered points of agricultural production efficiency and ETE in different intervals, respectively, to reveal the ability of agricultural production efficiency to improve ETE at different levels. The results show that the improvement of ETE has obvious characteristics of "threshold crossing", and there is a significant difference in the growth rate of ETE on both sides of the threshold. When the agricultural production efficiency is lower than the critical threshold, the goodness-of-fit and correlation characteristics of linear and binomial curves converge, which shows that the improvement of sufficient agricultural production efficiency can only lead to a small increase in ETE. The rapid improvement of ETE cannot be achieved through the improvement of short-term agricultural production efficiency. However, when the agricultural production efficiency is higher than the threshold, both linear and binomial curves show that a small amount of agricultural production efficiency can stimulate the doubling of ETE, and the improvement of agricultural production efficiency can strongly promote the improvement of ETE in the short term. At this stage, decision makers can explore and implement ways to stimulate the growth vitality of ETE through the exploration and implementation of agricultural production efficiency, so as to fully tap the efficiency of the ecological economy in agricultural production.

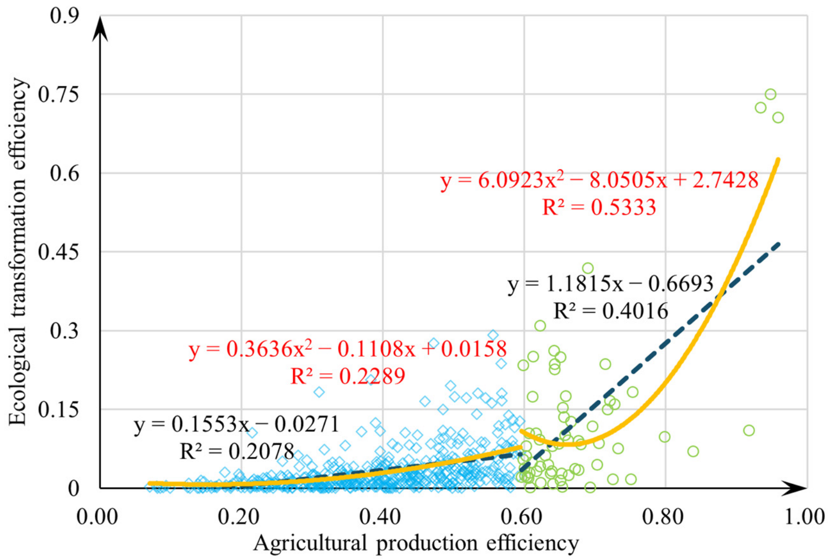

Figure 4. Correlativity of APE and ETE.

Based on the description of the characteristics of segmented ETE, combined with the previous calculation results of agricultural production efficiency, the division standard of the first class of agricultural production efficiency almost coincides with the symmetry axis of the quadratic fitting curve (the value is about 0.661). Therefore, only the eco-economization process of the first-class urban unit of agricultural production efficiency can open the "acceleration key" and step into the "fast lane". Taking 2015 as an example, the primary and secondary categories of agricultural production efficiency accounted for 22.58% and 50.03%, respectively, indicating that only a few urban units are in the stage of rapid growth of ETE, but the growth potential of ETE is extremely rich. It is of reference significance to formulate strategic guidance, comprehensive coverage and multi-coordinated supporting policies in the new era of comprehensive ecological economy.

4. Conclusions

This study supplements the land ecological variables which take into account both the attribute of agricultural production input and the ability to evaluate ecological quality under the framework of traditional agricultural production efficiency measurement. Considering the influence of random shock and production inefficiency, the SFA model of agricultural production in the YREB is constructed, and the agricultural production efficiency and ETE of the YREB in the fourth period from 2000 to 2015 are calculated. The spatial visualization expression and the summary of the law of spatiotemporal differentiation are formed from the perspective of geography. This study is not only an important reference for the overall planning of agricultural production and ecological conservation at the municipal level of the YREB but is also a useful supplement to the study of agricultural modernization and the transformation of the "Two Mountains Theory".

The results show that, firstly, the existence of unilateral effect, model selection preference and accurate parameter estimation all show that the embedding of land ecological variables in the research framework of agricultural production efficiency meets the requirements of scientific and reasonable empirical research design. The agricultural production characteristics based on this have higher time continuity and efficiency comparability than the efficiency measurement results driven by complete data. Secondly, agricultural production efficiency increased by 83.60% from 2000 to 2015, forming the quantitative characteristics of the slow growth of high-value units of production efficiency, the rapid growth of medium- and low-value units and the gradual expansion of high-value areas of production efficiency from point distribution to area distribution. Third, from 2000 to 2015, the ETE showed the characteristics of low absolute value and low proportion of high value and gradually formed the characteristics of spatial polarization with a high-value strip and spatial inverted U-shape, and the ecological economization in agricultural production was still in the primary cultivation stage. Finally, the rapid growth of ETE is the inevitable result of the improvement of agricultural productivity, which has a very strong threshold effect. At present, the ETE of the YREB has great potential to improve.

5. Discussion

From 2000 to 2015, the agricultural production efficiency of the YREB gradually evolved from relatively isolated spatial scattered distribution to the agglomeration of Chengdu-Chongqing urban agglomeration, Wuhan urban agglomeration and Jiangsu urban agglomeration along the Yangtze River Economic Belt, which further verifies the objective fact that there is a process of spatial transmission in agricultural production and highlights the restriction of geographical location on agricultural production efficiency. This is very similar to the results of other studies on agricultural production efficiency, which believe that with the passage of time, agricultural production efficiency shows a trend of gradual increase [17]. At the same time, the ETE of the YREB forms the rapid promotion area of Hunan and Hubei and the relatively high-value area of central Yunnan. Driven by the approval of the "two-oriented society" pilot zone, the former has been stimulated to improve the ecological transformation efficiency, but the existing research results seldom reflect the new eco-economic characteristics before and after the introduction of the "two-oriented society" pilot zone. Through the rational allocation of agricultural resources and speeding up the ecological transformation, the Central Yunnan urban agglomeration with Kunming as the core has formed the late advantages of ecological priority and green development and revealed the green development status and function of policy guidance and macro-design. In addition, through the characterization of the correlation between APE and ETE, the phased discontinuous quantitative characteristics of them are revealed and the abrupt threshold of ETE is identified, which is also the law of agricultural development that has not been revealed.

As a leading demonstration area of promoting well-coordinated environmental conservation and avoiding excessive development, the YREB has become a hot area for research on the path of ecological priority, green development, top-level design, transformation of development and ecological restoration. Considering agricultural space as the core composition of territorial space, agricultural production as an important starting point for the issues of agriculture, rural areas and farmers and agricultural ecology as the inevitable requirement of agricultural modernization, we scientifically evaluated the quantitative structure, spatiotemporal pattern and correlation characteristics of agricultural production efficiency and ETE on the cities of the YREB and revealed the transformation ability of land ecology to economic output in agricultural production. In the next stage, based on the framework of this research, we can supplement the ecological transformation efficiency and urban land use efficiency and form a trinity land space efficiency analysis system of agricultural production, urban development and ecological protection. Based on the characteristics of social and economic activities, the key ecological variables of different land spaces and their functions are selected. Combined with geographical objects, resource allocation and spatial differences in policy making, the research on input–output evaluation, ecological transformation efficiency characterization and key threshold determination of different scales and regions is carried out. Finally, the action mechanisms and methods of clear waters and green mountains are invaluable assets from the perspective of territorial space integration in order to provide a decision-making reference for macro-control with the characteristics of leading policy making and lagging control measures [33,34].

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