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# Evaluation and Analysis of Regional Agricultural Eco-Efficiency and Agricultural Economy by the DEA Model

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**Abstract**

*Objectives:* This paper aims to assess the agricultural ecological and economic efficiency of the Yangtze River Economic Belt by using the data envelopment analysis (DEA) model to evaluate the regional agricultural level. *Methods:* Relevant data from 11 provinces and cities in the Yangtze River Economic Belt from 2010 to 2020 was collected from statistical yearbooks. Then, the agricultural eco-efficiency and economic efficiency were evaluated using the slack-based measure (SBM) model in the DEA model. *Findings:* The evaluation result of agricultural eco-efficiency was consistently higher than that of ecological efficiency. From a regional perspective, the eco-efficiency of the downstream area was higher than that of the middle and upper reaches. From the perspective of group division, only Guizhou and Chongqing had a high eco-efficiency. *Improvement:* The findings suggest that the overall agricultural eco-efficiency in the Yangtze River Economic Belt is low, and there is still a large space for development. It is necessary to further reduce agricultural carbon emissions and non-point source pollution and improve agriculture through technological innovation and other means.

*Keywords:* Yangtze River Economic Belt; DEA Model; Agricultural Eco-Efficiency; SBM Model; Agricultural Economy.

## 1. Introduction

In recent years, due to the effects of climate warming [1], the vulnerability of agricultural development has increased. Additionally, technological advances have led to the extensive use of pesticides and fertilizers, significantly harming the agricultural ecological environment [2]. With the ongoing promotion of green and sustainable agricultural growth, enhancing agricultural ecological efficiency and fostering economic development in agriculture have become major concerns [3]. Agricultural ecological efficiency is a comprehensive measure of both environmental and economic performance [4], aiming to maximize expected output with minimal input while reducing environmental pollution as much as possible. The Data Envelopment Analysis (DEA) model is commonly used to measure production efficiency [5]. Thanks to its broad applicability and simple principles, DEA and its extended models are widely applied in various fields [6].

For example, Du et al. [7] analyzed the ecological efficiency of 18 marine pastures in Shandong Province using the super-slack-based measure (SBM) model and reported an average value of 0.6. They found that certain marine pastures suffered from low resource allocation efficiency and inadequate technical support. Similarly, Gómez-Calvet et al. [8] evaluated the environmental efficiency of electricity and heat generation in the European Union using the SBM model, successfully assessing energy efficiency in the presence of undesirable outputs. In the agricultural sector, Wu et al. [9] analyzed agricultural ecological efficiency from 1998 to 2018 using the super-SBM model, finding an average value of 0.665, which was generally low but exhibited a slow upward trend with fluctuations.

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Shuang et al. [10] examined the relationship between Internet development levels and agricultural ecological efficiency using data from 2009 to 2013 across 13 major grain-producing regions in China. They discovered that average agricultural ecological efficiency rose from 0.45 in 2009 to 0.79 in 2018, indicating continuous improvement in coupling coordination. Akbar et al. [11] analyzed panel data from 31 provinces and cities in China from 2007 to 2017, revealing that while overall agricultural ecological efficiency in China increased, it consistently remained higher in the eastern region compared to the central and western regions. Qiao et al. [12] measured the agricultural system's resilience and ecological efficiency across 31 provinces and cities in China from 2001 to 2021, finding that the relationship between agricultural resilience and ecological efficiency evolved from low-level positive synergy to high-level positive synergy.

Liu et al. [13] examined the relationship between agricultural ecological efficiency and poverty using data from the Three Gorges Reservoir Area between 2006 and 2017, concluding that improving regional agricultural ecological efficiency could accelerate poverty reduction. Ji et al. [14] analyzed agricultural ecological efficiency in 136 developing countries and found that selecting appropriate marginal trade-offs would not compromise the relative efficiency of decision-making units below the efficient frontier. Zhang et al. [15] studied the impact of digital inclusive finance on agricultural ecological efficiency and found that it significantly improves efficiency by enhancing the level of agricultural social services.

The Yangtze River Economic Belt is a critical region for agricultural production in China. Evaluating its agricultural ecological and economic efficiency holds significant practical value. However, there are currently relatively few studies focusing on the entire Yangtze River Economic Belt. Therefore, this paper takes this region as the subject of research. The first section provides an overview of agriculture in the Yangtze River Economic Belt. The second section analyzes methods for evaluating agricultural economic and ecological efficiency, introduces the SBM model within DEA, defines input and output indicators, and establishes measurement models for agricultural ecological and economic efficiency. The third section presents and analyzes measurement results, discusses regional differences in agricultural ecology and economic efficiency within the Yangtze River Economic Belt, and offers recommendations for agricultural development in the region. The final section concludes with a brief summary of the research findings. The overall workflow is illustrated in Figure 1.

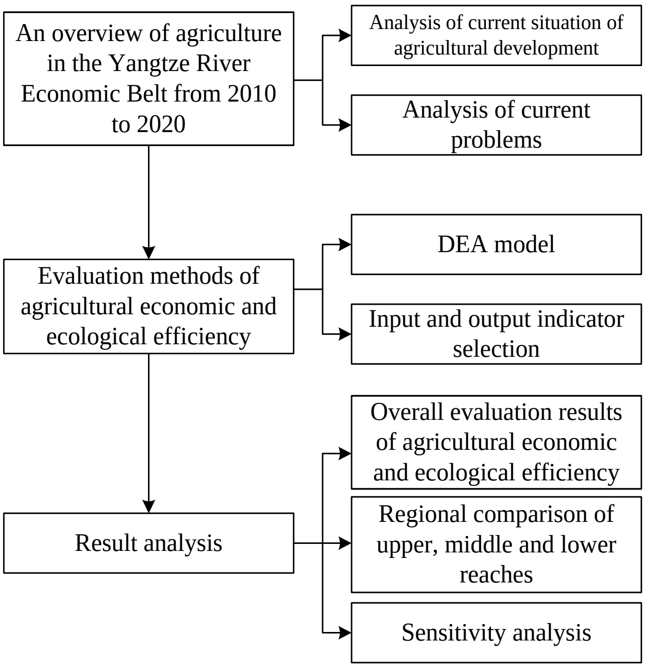


**Figure 1. The workflow**

## 2. Overview of Agriculture in the Yangtze River Economic Belt

The Yangtze River Economic Belt is a prosperous inland economic belt [16], which is one of the regions with the strongest comprehensive strength in China [17], also a core economic area of China [18]. As shown in Figure 2, according to the upper, middle, and lower reaches of the Yangtze River, the regional provinces and cities are distributed as follows.

Upper reaches: Yunnan, Guizhou, Sichuan, and Chongqing;

Middle reaches: Hubei, Hunan, and Jiangxi;

Lower reaches: Jiangsu, Zhejiang, Shanghai, and Anhui.


**Figure 2. The map of the the Yangtze River Economic Belt**

The topography of the Yangtze River Economic Belt covers various types, such as plateaux and hills, and most of the regions are very suitable for agricultural development. With a high level of agricultural development in the region, it has always been an important agricultural production region in China [19]. The changes in water resources and the irrigated area of cultivated land in this region from 2010 to 2020 are presented in Tables 1 and 2.

**Table 1. Changes in total amount of water resources from 2010 to 2020 (unit: hundred million cubic meters)**

| Year | Upper reaches | Middle reaches | Lower reaches | Yangtze River Economic Belt |
|---|---|---|---|---|
| 2010 | 5,937.5 | 5,450.8 | 2,741.7 | 14,130 |
| 2011 | 4,858.6 | 2,922.3 | 1,860.2 | 9,641.1 |
| 2012 | 6,033.1 | 4,977.2 | 2,554.9 | 13,565.2 |
| 2013 | 5,410.7 | 3,796.1 | 1,828.5 | 11,035.3 |
| 2014 | 6,140 | 4,345.5 | 2,357 | 12,842.5 |
| 2015 | 5,702.3 | 4,936.1 | 2,967.4 | 13,605.8 |
| 2016 | 6,100.8 | 5,915.7 | 3,371.2 | 15,387.7 |
| 2017 | 6,377.3 | 4,816.3 | 2,107.1 | 13,300.7 |
| 2018 | 6,662 | 3,349 | 2,119.1 | 12,130.1 |
| 2019 | 5,897.8 | 4,763.6 | 2,141.4 | 12,802.8 |
| 2020 | 7,132 | 5,559.2 | 2,909 | 15,600.2 |

**Table 2. Changes in irrigated area of cultivated land from 2010 to 2020 (unit: thousand hectares)1**

| Year | Upper reaches | Middle reaches | Lower reaches | Yangtze River Economic Belt |
|---|---|---|---|---|
| 2010 | 5,958.5 | 6,971.2 | 8,991.5 | 21,921.2 |
| 2011 | 6,129.1 | 7,085.8 | 9,022.0 | 22,236.9 |
| 2012 | 6,258.1 | 7,171.8 | 9,184.9 | 22,614.8 |
| 2013 | 5,878.9 | 7,871.3 | 9,684.3 | 23,434.5 |
| 2014 | 6,034.4 | 7,958.6 | 9,831.7 | 23,824.7 |
| 2015 | 6,245.4 | 8,040.1 | 9,973.2 | 24,258.7 |
| 2016 | 6,401.6 | 8,074.8 | 10,127.7 | 24,604.1 |
| 2017 | 6,532.9 | 8,104.5 | 10,271.5 | 24,908.9 |
| 2018 | 6,659.8 | 8,127.9 | 10,349.7 | 25,137.4 |
| 2019 | 6,728.3 | 8,181.2 | 10,382.5 | 25,292.0 |
| 2020 | 6,834.1 | 8,317.4 | 10,414.2 | 25,565.7 |

The development of agriculture cannot be separated from the utilization of water resources. Table 1 shows that from 2010 to 2020, the total water resources of this region were gradually increasing. In terms of regional comparison, the amount of water resources in the upper reaches was always significantly higher than that in the middle and lower reaches. In 2020, the total amount of water resources in the upper reaches reached 713.2 billion cubic meters, that in the middle reaches reached 555.92 billion cubic meters, and that in the lower reaches only reached 290.9 billion cubic meters. This is because the upper reaches have a weak industrial base and focus on the development of the primary industry, while the middle and lower reaches have a high level of industrialization and focus on the development of the secondary and tertiary industries.

The irrigated area of cultivated land can reflect the mechanization level of agriculture, i.e., infrastructure construction. As shown in Table 2, the irrigated area of cultivated land in this region gradually increased from 21,921.2 thousand hectares in 2010 to 25,565.7 thousand hectares in 2020, suggesting the steady development of infrastructure construction. Then, from the perspective of regional comparison, the irrigated area of cultivated land in the lower reaches was always at a high level, obviously higher than that in the upper and middle reaches, and the growth was also fast; the irrigated area of cultivated land in the upper reaches changed relatively little, from 5,958.5 thousand hectares in 2010 to 6,834.1,000 hectares in 2020, showing an increase of only 14.7%.

Table 3 shows the total agricultural output value of provinces and cities from 2010 to 2020.

**Table 3. Total agricultural output value of provinces and cities (unit: 100 million yuan)2**

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Yunnan | 915 | 1,109 | 1,374 | 1,607 | 1,765 | 1,795 | 1,889 | 1,983 | 2,235 | 2,680 | 2,902 |
| Guizhou | 588 | 656 | 865 | 998 | 1,323 | 1,774 | 1,901 | 2,077 | 2,289 | 2,536 | 2,782 |
| Sichuan | 2059 | 2454 | 2765 | 2886 | 3069 | 3316 | 3702 | 4004 | 4154 | 4,395 | 4,702 |
| Chongqing | 600 | 717 | 801 | 856 | 906 | 963 | 1124 | 1166 | 1293 | 1,397 | 1,596 |
| Upper reaches | 4,162 | 4,936 | 5,806 | 6,347 | 7,063 | 7,847 | 8,615 | 9,229 | 9,970 | 11,008 | 11,982 |
| Hubei | 1,883 | 2,245 | 2,416 | 2,585 | 2,651 | 2,674 | 2,795 | 2,962 | 3,034 | 3,258 | 3,493 |
| Hunan | 1,849 | 2,090 | 2,255 | 2,258 | 2,325 | 2,326 | 2,485 | 2,598 | 2,664 | 3,052 | 3,365 |
| Jiangxi | 811 | 931 | 1,021 | 1,095 | 1,171 | 1,362 | 1,435 | 1,489 | 1,549 | 1,624 | 1,690 |
| Middle reaches | 4,543 | 5,266 | 5,693 | 5,937 | 6,147 | 6,362 | 6,716 | 7,049 | 7,247 | 7,934 | 8,547 |
| Anhui | 1,477 | 1,640 | 1,786 | 1,916 | 2,027 | 2,080 | 2,137 | 2,241 | 2,254 | 2,365 | 2,525 |
| Jiangsu | 2,257 | 2,623 | 2,942 | 3,137 | 3,326 | 3,676 | 3,663 | 3,765 | 3,735 | 3,829 | 4,102 |
| Zhejiang | 1,023 | 1,127 | 1,197 | 1,296 | 1,338 | 1,379 | 1,455 | 1,494 | 1,518 | 1,595 | 1,594 |
| Shanghai | 160 | 170 | 177 | 178 | 175 | 168 | 147 | 146 | 150 | 146 | 138 |
| Lower reaches | 4,917 | 5,560 | 6,102 | 6,527 | 6,866 | 7,302 | 7,402 | 7,647 | 7,657 | 7,935 | 8,360 |
| **Total** | **13,622** | **15,761** | **17,601** | **18,811** | **20,076** | **21,511** | **22,733** | **23,926** | **24,874** | **26,877** | **28,889** |

From Table 3, it can be found that from 2010 to 2020, the total agricultural output value of various provinces and cities showed a gradual upward trend, increasing from 1,362.2 billion yuan in 2010 to 2,888.9 billion yuan in 2020. From the perspective of inter-provincial differences, the total agricultural output value of Jiangsu, Sichuan, Hubei, and Hunan was high. From the perspective of regional differences, in 2010, the difference between the upper, middle, and lower reaches was small and then became larger, and the total agricultural output value of the upper reaches continued to increase, reaching 1,1982 billion yuan in 2020, while the gap between the middle reaches and the lower reaches was always small, reaching 854.7 billion yuan and 836 billion yuan respectively in 2020. The difference in industrial emphasis causes this difference.

The existing problems of agricultural development in this region were analyzed.

**(1)** ***Uneven distribution of resources:***

From the perspective of water resources distribution, there is a big gap between the total amount of water resources in the middle and lower reaches and the upper reaches, which restricts agricultural development to a certain extent and is not conducive to improving overall efficiency.

**(2)** ***Unreasonable industrial structure:***

Although the total output value of agriculture is growing, the growth rate has slowed down gradually in recent years, indicating that the primary industry is in a relatively passive position, which is not conducive to the development of the regional economy.

**(3)** ***Uncoordinated infrastructure construction:***

From the perspective of the irrigated area of cultivated land, there are obvious regional differences in infrastructure construction, and the gap between the upper reaches and the middle and lower reaches is large, indicating that the development imbalance between regions is relatively severe.

## 3. Evaluation of Agricultural Economic and Ecological Efficiency

### 3.1. DEA Model

As a method to measure production efficiency, the DEA model only considers input-output efficiency instead of non-expected output, resulting in certain bias in evaluation results [20]. The SBM model, which was designed on the basis of the DEA model, can effectively take into account the redundancy of input factors [21] and includes the non-expected output, making the evaluation results more realistic. The evaluation of agricultural economic efficiency only involves expected outputs, but the evaluation of agricultural ecological efficiency also needs to consider undesired outputs. The indicator data required for calculation have different units. The SBM model can not only handle both expected and undesired outputs simultaneously but also effectively deal with the diversity of indicator units, providing a more comprehensive efficiency assessment. Therefore, the SBM model is chosen as the evaluation method. For several decision-making units (DMU), input $x$, expected output $y$, and unexpected output $b$ are defined. The SBM model can be written as:

$$\rho = min\frac{1-\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{x_{kn}^t}}{1+\frac{1}{M+L}\left(\sum_{m=1}^{M}\frac{s_m^y}{y_{km}^y}+\sum_{i=1}^{L}\frac{s_i^b}{b_{ki}^t}\right)} \quad (1)$$

$$s.t.\sum_{k=1,k\neq j}^{K} z_k^t\, x_{kn}^t + s_n^x = x_{kn}^t, n = 1,2,\cdots,N \quad (2)$$

$$\sum_{k=1,k\neq j}^{K} z_k^t\, y_{km}^y - s_m^y = y_{km}^y, j = 1,2,\cdots,M \quad (3)$$

$$\sum_{k=1,k\neq j}^{K} z_k^t\, b_{ki}^t + s_i^b = b_{ki}^t, i = 1,2,\cdots,I \quad (4)$$

$$z_k^t \geq 0, s_n^x \geq 0, s_m^y \geq 0, s_i^b \geq 0, k = 1,2,\cdots,K \quad (5)$$

where $s$ is the relaxation variable and $\left(x_{kn}^t, y_{km}^y, b_{ki}^t\right)$ is the input-output variable of the $k$-th region in the $t$-th year.

### 3.2. Indicator Selection

The selection of calculation indicators should take into account their availability and scientificity. With reference to the current research on agricultural ecological efficiency, the indicators shown in Table 4 were selected.

**Table 4. Input and output indicators**3

| | Indicator | Explanation |
|---|---|---|
| Input | Labor force | People employed in agriculture |
| | Water resources | Effective irrigated area |
| | Land | Actual sown area |
| | Machinery | Mechanical total power |
| | Chemical fertilizer | Fertilizer purity |
| | Pesticides | Pesticide usage amount |
| | Farm film | Agricultural film usage amount |
| Expected output | Total agricultural output | Total agricultural output value |
| Non-expected output | Agricultural carbon emissions | Carbon emission from agriculture |
| | Agricultural non-point source pollution | Comprehensive index of agricultural non-point source pollution |

In Table 4, input indicators are various input factors in the process of agricultural production, the expected output is the total output value of agriculture, which can reflect the economic level of agricultural development, and the non-expected output is used to reflect the adverse impact of agricultural production on the environment. One is agricultural carbon emission, and all input factors except labor force will lead to the generation of carbon emission. The estimation formula is:

$$C_t = \sum_{j=1}^{6} P_{jt} * d_j \tag{6}$$

where $P_{jt}$ is the amount of various carbon emission sources and $d_j$ is the carbon emission coefficient.

The comprehensive index of agricultural non-point source pollution refers to the pollution caused by unused fertilizers, pesticides, and agricultural film on the ecosystem [22], and the formula is:

$$W_t = \sum_{i=1}^{3} E_{it} * \sigma_i \tag{7}$$

where $E_{it}$ is the amount of pollution sources and $\sigma_i$ is the pollution production coefficient (Table 5), obtained from the Manual of the First National Pollution Sources Census.

**Table 5. Pollution production coefficient of pollution sources4**

| | Nitrogen fertilizer | Phosphate fertilizer | Agricultural film |
|---|---|---|---|
| Jiangxi | 1.079% | 0.616% | 8.7% |
| Jiangsu, Shanghai, and Anhui | 1.555% | 0.275% | 19.2% |
| Hubei, Hunan, Zhejiang, Chongqing, Sichuan, Guizhou, and Yunnan | 1.848% | 1.547% | 16.5% |

The data of input and output indexes were derived from the *China Statistical Yearbook*, the *China Rural Statistical Yearbook*, and the statistical yearbooks of provinces and cities.

All the data were imported into MAXDEA [23] for calculation. During the calculation, two models were established:

(1) The SBM model, which did not consider the non-expected output and was used to measure agricultural economic efficiency,

(2) The SBM model, which considered undesired output and was employed to measure agricultural ecological efficiency.

## 4. Analysis of Results1

From Table 6, it can be found that from 2010 to 2020, economic and ecological efficiency generally showed a declining trend. Since 2013, eco-efficiency has increased due to more attention to the ecological environment in the Yangtze River basin after the implementation of relevant policies. In 2020, agricultural efficiency has decreased significantly, which may be affected by the COVID-19 outbreak. With the continuous acceleration of the urbanization process, agricultural land has been squeezed. It is pointed out in a literature [24] that from 1995 to 2015, the total damaged area of land in the Yangtze River Economic Belt was larger than the restored area. Both cultivated land and forest land showed a downward trend. Coupled with the excessive reliance on fertilizers, pesticides, etc., agricultural pollution has been further exacerbated. The industrialization development has also had a certain impact on agricultural development, resulting in the decline of the agricultural economy and ecological efficiency in the past ten years. When comparing the economic efficiency without considering the undesired output with the ecological efficiency without considering the undesired output, it was found that there was a large gap, but the fluctuation was nearly the same - the economic efficiency was always higher than the ecological efficiency, indicating that the evaluation results are not realistic without considering the undesired output.

**Table 6. The evaluation results of the agricultural economic and ecological efficiency of the Yangtze River Economic Belt**

| Year | Agricultural economic efficiency | Agricultural ecological efficiency |
|---|---|---|
| 2010 | 0.80 | 0.73 |
| 2011 | 0.79 | 0.73 |
| 2012 | 0.78 | 0.71 |
| 2013 | 0.76 | 0.69 |
| 2014 | 0.75 | 0.70 |
| 2015 | 0.75 | 0.69 |
| 2016 | 0.71 | 0.64 |
| 2017 | 0.70 | 0.64 |
| 2018 | 0.74 | 0.69 |
| 2019 | 0.69 | 0.64 |
| 2020 | 0.65 | 0.60 |

Agricultural ecological efficiency was analyzed by region. The results are presented in Tables 7 and 8.

**Table 7. Evaluation results of regional agricultural economy and ecological efficiency**

| | Agricultural economic efficiency | | | | Agricultural ecological efficiency | | | |
|---|---|---|---|---|---|---|---|---|
| **Upper reaches** | **Yunnan** | **Guizhou** | **Sichuan** | **Chongqing** | **Yunnan** | **Guizhou** | **Sichuan** | **Chongqing** |
| 2010 | 0.58 | 0.94 | 0.85 | 1.00 | 0.45 | 0.81 | 0.78 | 1.00 |
| 2011 | 0.58 | 0.85 | 0.84 | 1.00 | 0.46 | 0.79 | 0.76 | 1.00 |
| 2012 | 0.62 | 0.81 | 0.83 | 1.00 | 0.47 | 0.75 | 0.74 | 1.00 |
| 2013 | 0.62 | 0.84 | 0.82 | 1.00 | 0.48 | 0.78 | 0.72 | 1.00 |
| 2014 | 0.61 | 0.85 | 0.77 | 1.00 | 0.49 | 0.91 | 0.65 | 1.00 |
| 2015 | 0.57 | 0.91 | 0.76 | 1.00 | 0.45 | 0.84 | 0.66 | 1.00 |
| 2016 | 0.55 | 0.91 | 0.78 | 1.00 | 0.42 | 0.85 | 0.68 | 1.00 |
| 2017 | 0.55 | 0.88 | 0.77 | 1.00 | 0.43 | 0.84 | 0.67 | 1.00 |
| 2018 | 0.62 | 0.91 | 0.76 | 1.00 | 0.51 | 0.85 | 0.66 | 1.00 |
| 2019 | 0.65 | 0.93 | 0.73 | 1.00 | 0.55 | 0.88 | 0.64 | 1.00 |
| 2020 | 0.53 | 0.93 | 0.61 | 1.00 | 0.43 | 0.91 | 0.55 | 1.00 |
| Mean | 0.60 | 0.89 | 0.77 | 1.00 | 0.47 | 0.84 | 0.68 | 1.00 |
| **Middle reaches** | **Hubei** | **Hunan** | **Jiangxi** | | **Hubei** | **Hunan** | **Jiangxi** | |
| 2010 | 0.94 | 0.53 | 0.61 | | 0.89 | 0.42 | 0.52 | |
| 2011 | 0.93 | 0.54 | 0.59 | | 0.88 | 0.43 | 0.51 | |
| 2012 | 0.91 | 0.53 | 0.58 | | 0.83 | 0.42 | 0.50 | |
| 2013 | 0.88 | 0.45 | 0.57 | | 0.68 | 0.38 | 0.51 | |
| 2014 | 0.75 | 0.46 | 0.58 | | 0.67 | 0.39 | 0.52 | |
| 2015 | 0.74 | 0.47 | 0.61 | | 0.66 | 0.39 | 0.567 | |
| 2016 | 0.69 | 0.48 | 0.61 | | 0.65 | 0.42 | 0.56 | |
| 2017 | 0.68 | 0.43 | 0.62 | | 0.64 | 0.36 | 0.58 | |
| 2018 | 0.67 | 0.43 | 0.62 | | 0.64 | 0.41 | 0.58 | |
| 2019 | 0.68 | 0.43 | 0.62 | | 0.64 | 0.35 | 0.62 | |
| 2020 | 0.69 | 0.44 | 0.58 | | 0.64 | 0.34 | 0.61 | |
| Mean | 0.78 | 0.47 | 0.60 | | 0.71 | 0.39 | 0.55 | |
| **Lower reaches** | **Shanghai** | **Jiangsu** | **Zhejiang** | **Anhui** | **Shanghai** | **Jiangsu** | **Zhejiang** | **Anhui** |
| 2010 | 1.00 | 0.88 | 0.83 | 0.65 | 1.00 | 0.85 | 0.77 | 0.56 |
| 2011 | 1.00 | 0.88 | 0.82 | 0.64 | 1.00 | 0.84 | 0.76 | 0.55 |
| 2012 | 1.00 | 0.88 | 0.81 | 0.63 | 1.00 | 0.84 | 0.75 | 0.54 |
| 2013 | 1.00 | 0.87 | 0.74 | 0.61 | 1.00 | 0.83 | 0.68 | 0.51 |
| 2014 | 1.00 | 0.86 | 0.76 | 0.58 | 1.00 | 0.82 | 0.71 | 0.52 |
| 2015 | 1.00 | 0.85 | 0.74 | 0.61 | 1.00 | 0.81 | 0.71 | 0.51 |
| 2016 | 0.66 | 0.84 | 0.73 | 0.55 | 0.48 | 0.79 | 0.73 | 0.48 |
| 2017 | 0.65 | 0.83 | 0.72 | 0.53 | 0.47 | 0.78 | 0.71 | 0.58 |
| 2018 | 1.00 | 0.82 | 0.71 | 0.55 | 1.00 | 0.77 | 0.71 | 0.48 |
| 2019 | 0.64 | 0.73 | 0.70 | 0.52 | 0.48 | 0.71 | 0.71 | 0.45 |
| 2020 | 0.45 | 0.68 | 0.71 | 0.51 | 0.33 | 0.65 | 0.69 | 0.48 |
| Average | 0.85 | 0.83 | 0.75 | 0.58 | 0.80 | 0.79 | 0.72 | 0.51 |

**Table 8. The comparison of the average values of agricultural economy and ecological efficiency in the upstream, midstream, and downstream from 2010 to 2020**

| | Upstream | Midstream | Downstream |
|---|---|---|---|
| Agricultural economic efficiency | 0.82 | 0.62 | 0.75 |
| Agricultural ecological efficiency | 0.75 | 0.55 | 0.71 |

From Tables 7 and 8, it can be observed that significant gaps exist in economic and ecological efficiency across different regions, indicating that agricultural development in all areas is influenced by ecological conditions. Specifically, among the upstream provinces and cities, Chongqing exhibited the highest ecological efficiency, followed by Guizhou, while Sichuan and Yunnan recorded the lowest levels. The upper reaches are characterized by the Yunnan-Guizhou Plateau and the Sichuan Basin. Due to geographical constraints, agricultural development in Yunnan has historically lagged behind, resulting in lower agricultural efficiency.

In the middle reaches, Hubei Province showed high ecological efficiency, whereas Hunan and Jiangxi provinces had lower values. Provinces and cities in the middle reaches are predominantly traditional agricultural regions, with the Jianghan Plain and Dongting Lake Plain as their main terrains. Although the planting industry in these areas is highly developed, intensive use of chemical fertilizers and pesticides has led to reduced ecological efficiency.

Among the downstream provinces and cities, only Anhui registered an eco-efficiency of 0.51, while Shanghai, Jiangsu, and Zhejiang all reported values above 0.7, suggesting relatively strong agro-ecological conditions in the lower reaches. The Yangtze River Delta's strategic geographical position attracts extensive foreign trade, contributing to rapid economic development. On one hand, compared to Jiangsu, Zhejiang, and Shanghai, Anhui holds a weaker competitive position in industry. Coastal regions benefit from more advanced industrial development, better talent, capital, and technology resources. On the other hand, under regional cooperation and development initiatives, developed regions have relocated some enterprises with surplus production capacity inland, with Anhui assuming these enterprises, leading to a decline in its ecological efficiency.

Overall, both agricultural economic and ecological efficiencies in the Yangtze River Economic Belt follow the trend: upper reaches > lower reaches > middle reaches. Zhao & Cai [25] noted that the economic network of the Yangtze River Economic Belt is centered around Shanghai and Jiangsu, strengthening progressively from west to east, which aligns with the high agricultural economic efficiency observed for Shanghai and Jiangsu in this study. Furthermore, regarding regional differences, Hu & Guo [26] also highlighted disparities in the green total factor productivity across the Yangtze River Economic Belt, with higher values in the lower reaches and lower levels in the middle and upper reaches.

The provinces and cities with an efficiency value of (0.8,1] were divided into the high-efficiency group, (0.6,0.8) was the medium-efficiency group, and (0,0.6) was the low-efficiency group. The 11 provinces and cities were divided according to the average value.

As shown in Table 9, only Guizhou and Chongqing achieved a high level of eco-efficiency. This may be attributed to their location in mountainous regions, where both the terrain and climate are relatively favorable for agricultural development. The local governments in these areas have actively promoted ecological agriculture and have strictly regulated agricultural pollution. Additionally, both regions enjoy relatively high levels of economic development. Sichuan, Hubei, Shanghai, Jiangsu, and Zhejiang fell into the medium efficiency group, while Yunnan, Anhui, Hunan, and Jiangxi were classified in the low efficiency group, indicating substantial room for improvement. Overall, the agricultural ecological efficiency across the Yangtze River Economic Belt remains modest and is experiencing a declining trend, with notable differences among the upper, middle, and lower reaches.

**Table 9. Agricultural eco-efficiency group classification**

| Group classification | Provinces and cities |
|---|---|
| Low efficiency group | Yunnan, Anhui, Hunan, and Jiangxi |
| Medium efficiency group | Sichuan, Hubei, Shanghai, Jiangsu, and Zhejiang |
| High efficiency group | Guizhou and Chongqing |

A sensitivity analysis was carried out to assess how sensitive the input and output indicators are to changes. For each iteration, one variable was excluded, and the efficiency score was recalculated. This recalculated score was then compared with the original score, and both the slope and the coefficient of determination ($R^2$) were computed. Finally, the difference between 1 and the slope was calculated to quantify the degree of change in efficiency.

From Table 10, it can be observed that the |1-slope| value for agricultural carbon emissions was the highest, at 0.4426, indicating that agricultural carbon emissions were the most sensitive factor. Additionally, the |1-slope| value for pesticides was 0.2514, which was relatively high and represented the most sensitive factor among the input indicators. In contrast, the |1-slope| value for the labor force was 0.0127, making it the least sensitive factor, suggesting it had the minimal impact on efficiency analysis. Overall, output variables were more sensitive than input variables. Controlling the use of chemical fertilizers, pesticides, and agricultural films, as well as reducing agricultural carbon emissions and non-point source pollution, plays a crucial role in enhancing both the agricultural economic and ecological efficiency of the Yangtze River Economic Belt.

**Table 10. Sensitivity analysis results**

| | | **Slope** | **\|1-slope\|** | **$R^2$** |
|---|---|---|---|---|
| Input | Labor force | 1.0227 | 0.0127 | 0.5214 |
| | Water resource | 1.0216 | 0.0216 | 0.6336 |
| | Land | 1.0233 | 0.0233 | 0.5287 |
| | Machine | 1.0241 | 0.0241 | 0.5236 |
| | Chemical fertilizer | 1.1251 | 0.1251 | 0.5587 |
| | Pesticide | 1.2514 | 0.2514 | 0.6624 |
| | Agricultural film | 1.0952 | 0.0952 | 0.7412 |
| Expected output | Total value of agricultural output | 1.0256 | 0.0256 | 0.6952 |
| Non-expected output | Agricultural carbon emission | 1.4426 | 0.4426 | 0.6611 |
| | Agricultural non-point source pollution | 1.0958 | 0.1958 | 0.8215 |

Based on the current evaluation results of agricultural efficiency in the Yangtze River Economic Belt, the following recommendations are proposed.

(1) Adjust and upgrade the industrial structure

According to the calculation results, the middle and upper reaches of the region should appropriately change the development mode of the agricultural economy, make adjustments on the basis of the traditional agricultural production mode, and vigorously develop the agricultural industry with high efficiency and low pollution. The downstream regions can make use of the advantages of the tertiary industry, such as the financial industry and information technology, to promote the development of the overall economy and adjust and upgrade the industrial structure.

(2) Adjust the agricultural factors and promote the improvement of the technology utilization level

Overusing chemical fertilizers, pesticides, and other factors is an important cause of pollution. Therefore, in order to enhance agricultural ecological efficiency, we should control the investment in these factors that are not conducive to the environment, improve the efficiency of resource utilization by promoting environmental protection policies such as organic fertilizers, and increase the investment in the research and development of green technologies in agriculture.

(3) Find ways to promote regional collaborative development

The results show that there are some differences between different regions. In order to develop together, the regions should break the regional restrictions, strengthen regional cooperation and exchange, and apply the successful experience of the lower reaches to the middle and upper reaches. Moreover, the regions should also put forward targeted improvement measures according to local conditions to achieve the common development and progress of agricultural level.

## 5. Conclusions

This paper took the Yangtze River Economic Belt as an example and used the SBM model to evaluate the agricultural economy and ecological efficiency of 11 provinces and cities from 2010 to 2020. It was found that:

(1) During the period from 2010 to 2020, the agricultural economic efficiency of the Yangtze River Economic Belt was always higher than the agricultural ecological efficiency;

(2) During the period from 2010 to 2020, the agricultural economic efficiency and ecological efficiency of various provinces and cities as a whole exhibited a downward trend;

(3) There were significant differences in the agricultural economy and ecological efficiency among the upper, middle, and lower reaches (upper reach > lower reach > middle reach);

(4) The agricultural ecological efficiency was divided into three groups: low, medium, and high. Only Guizhou and Chongqing were in the high-efficiency group;

(5) The sensitivity analysis showed that agricultural carbon emissions were the most sensitive element, and pesticides were the most sensitive element among the input indicators.

The results verified the regional differences of agricultural economy and ecological efficiency between the middle and lower reaches of the Yangtze River and also proved the usability of the SBM model in the evaluation of agricultural economy and ecological efficiency. According to the results, the overall ecological efficiency in the middle and lower reaches was relatively low, and there was a large space for improvement. Targeted policies need to be implemented based on the characteristics of different regions to promote the development of the overall agricultural level of the Yangtze River Economic Belt.

## 6. Declarations

### 6.1. Data Availability Statement

The data presented in this study are available in the article.

### 6.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

### 6.3. Institutional Review Board Statement

Not applicable.

### 6.4. Informed Consent Statement

Not applicable.

### 6.5. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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