Analysis of Agricultural Water Use Efficiency in Shandong Province Based on DEA and Malmquist Model

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Abstract. Water resource shortage has become a restricting factor for social and economic development. Improving water use efficiency of agriculture is an important way to alleviate water resource pressure and ensure food security. Based on DEA and Malmquist models, this paper calculated and analyzed the technical efficiency, scale efficiency and pure technical efficiency of agriculture using panel data from 17 cities in Shandong province from 2007 to 2017. Then, panel data of grains, beans, tubers, oils, cotton and vegetables were selected for the analysis of water use efficiency. The results showed that: (1) the water use efficiency of agriculture in Shandong Province increased year by year; (2) there are significant differences in water use efficiency of agriculture among cities; Qingdao, Jinan and Yantai are higher, while Dezhou and Heze are lower. (3) oil and cotton are the crops with the highest water use efficiency in agriculture in Shandong province. Under the premise of ensuring the required crop production, more oil and cotton can be considered to be planted.

1. Introduction

Food and water are important resources affecting human survival and social development, and the water security is an important foundation for food security [1]. As a large agricultural country in China, food is a topic of great concern to farmers, and agriculture is the guarantee of national economic development. In addition, water affects the growth and development of crops, and its relationship with crops is very close, affecting the physiological activities and growth environment of crops. According to the Water Resources Bulletin in 2018, the agricultural water consumption of China was 369.31 billion m$^3$, occupying 61.4% of the total water. Therefore, improving agricultural water efficiency is one of the important ways to alleviate water resource pressure and ensure food security.

Shandong province is an important grain-producing area and a major agricultural province in China [2]. It is also one of severely water-deficient provinces in China. The per capita water resources have been less than 1/6 of the national average for many years, and water resources have become a bottleneck that seriously restricts the economic development of Shandong Province [3]. The rational arrangement and utilization of farmland irrigation water and agricultural water are of great significance to the agriculture and economic development of Shandong Province. This paper focused on the economic efficiency of water resources productivity. Taking 17 cities in Shandong as an
example, based on the panel data from 2007 to 2017, we used DEA and Malmquist models to calculate agricultural water efficiency, analyzed the temporal and spatial changes, and discussed the differences of agricultural water use efficiency among different regions in Shandong, and proposed corresponding countermeasures, which have certain guiding significance for the future water resources utilization in the study area and the formulation of national water resources management related countermeasures.

2. Methods

2.1. Data
This study used DEA and Malmquist models with data from the 2008-2018 "Shandong Statistical Yearbook", the 2008-2018 "China Statistical Yearbook" and the Shandong Provincial Water Resources Management Network. In the DEA model, the agricultural water consumption, agricultural population and irrigated area of 17 cities in Shandong Province were selected as input indicators; agricultural output value was selected as output indicator. In Malmquist index analysis, agricultural water consumption and crop irrigation area were selected as input indicators; agricultural output value (six major crops of cereals, beans, potatoes, oil crops, cotton, vegetables, fruits and edible fungi), agricultural output (six major crops) were selected as output indicators.

2.2. Methodology

2.2.1. Data Envelopment Analysis (DEA).
DEA is a relative effectiveness evaluation method based on input-output data. The system analysis method was proposed by Charnes et al. in 1978, which expanded Farrell's idea of estimating technical efficiency relative to the production frontier, and included multiple inputs and multiple outputs [4,5]. The DEA model allows researchers to establish a deterministic non-parametric production frontier and compare the performance of several decision-making units (DMU). As a scientific input-output productivity system analysis method, the DEA model has been widely used in research fields such as evaluation technology, management science as well as decision science [6-8].

Since the DEA model was proposed, many researchers have conducted in-depth research on it. Common models are C2R and BC2. In this paper, C2R model is used for calculation and analysis. Suppose there are n decision-making units DMUj (j=1, 2, ..., n), each DMU has m input indicators and s output indicators. The input vector is Xj=(x1j, x2j,..., xmj) T, and the output vector is Yj=(y1j,y2j,...,ysj)T. The model is as follows:

$$
\begin{align*}
& \min \left[ \theta - \varepsilon \left( e_j^T S^- + e_i^T S^+ \right) \right] \\
& \text{s.t.} \quad \sum_{j=1}^{n} \lambda_j X_j + S^- = \theta X_0 \\
& \quad \sum_{j=1}^{n} \lambda_j Y_j - S^+ = Y_0 \\
& \quad \lambda_j \geq 0, \ j = 1, 2, \ldots, n; S^+ \geq 0, S^- \geq 0 \\
& \quad e_j^T = (1,1,\ldots,1) \in E_m, e_i^T = (1,1,\ldots,1) \in E_i
\end{align*}
$$

Where $\theta$ is the comprehensive relative efficiency value of the system operation, the larger the value, the higher the system operation efficiency; $\lambda_j$ is the combined proportion of the j-th decision-making unit DMUj in the effective DMU combination which is reconstructed relative to DMU0; S+ and S- are slack variables, which represents insufficient output and redundant input, and $\varepsilon$ is a non-Archimedean infinitesimal.
2.2.2. Malmquist models.
The Malmquist productivity index model was proposed on the basis of the DEA model and is mainly used in the study of dynamic efficiency trends. It can get rid of the stricter assumptions involved in the aggregate production function estimation method to the greatest extent, and decompose the total factor productivity (TFP index) into the technical change (TC) and the technical efficiency change (TEC). Moreover, it has good adaptability to both panel data and multi-input and multi-output data calculation improving the reliability of production efficiency measurement [9,10].

Suppose \((xt, yt)\) and \((xt+1, yt+1)\) represent the production relations during \(t\) and \(t+1\) respectively, and the production relations changing from \((xt, yt)\) to \((xt+1, yt+1)\) is the production efficiency changes. The Malmquist productivity index based on output can be expressed as:

\[
TFP = \left( \frac{D^*(x_{t+1}, y_{t+1})}{D^*(x_t, y_t)} \times \frac{D^{**}(x_{t+1}, y_{t+1})}{D^{**}(x_t, y_t)} \right)^{\frac{1}{2}} = \text{TEC} \times \text{TC}
\]

Under the assumption of variable return to scale (VRS), Fare further decomposed technical efficiency change (TEC) into pure technical efficiency change (PEC) and scale efficiency change (SEC) [6].

3. Result
Using Deap2.1 software to calculate the statistical data of 17 cities in Shandong Province from 2007 to 2017, the overall efficiency, pure technical efficiency and scale efficiency of agricultural water in each city in Shandong Province are obtained (Table 1).

Table 1. Agricultural water efficiency of each city in Shandong Province from 2007 to 2017

| Area/Years   | Overall efficiency | Pure technical efficiency | Scale efficiency |
|--------------|--------------------|---------------------------|------------------|
|              | 2007    | 2017 | Mean | 2007    | 2017 | Mean | 2007    | 2017 | Mean |
| Jinan City   | 1.000   | 0.967 | 0.997 | 2007    | 0.972 | 0.997 | 1.000   | 0.995 | 1.000 |
| Qingdao City | 1.000   | 1.000 | 1.000 | 2007    | 1.000 | 1.000 | 1.000   | 1.000 | 1.000 |
| Zibo City    | 0.767   | 0.834 | 0.794 | 2007    | 0.842 | 0.828 | 0.939   | 0.991 | 0.959 |
| Zhaozhuang City | 0.760 | 0.954 | 0.880 | 2007    | 0.956 | 0.910 | 0.936   | 0.998 | 0.966 |
| Dongying City| 0.489   | 0.946 | 0.703 | 2007    | 0.812 | 0.924 | 0.612   | 0.946 | 0.752 |
| Yantai City  | 1.000   | 1.000 | 1.000 | 2007    | 0.799 | 1.000 | 1.000   | 1.000 | 1.000 |
| Weifang City | 0.869   | 1.000 | 0.919 | 2007    | 1.000 | 1.000 | 0.869   | 1.000 | 0.918 |
| Jining City  | 0.622   | 0.963 | 0.782 | 2007    | 0.995 | 0.944 | 0.754   | 0.968 | 0.826 |
| Taian City   | 0.643   | 0.975 | 0.725 | 2007    | 0.825 | 0.979 | 0.737   | 0.975 | 0.983 |
| Weihai City  | 0.625   | 1.000 | 0.867 | 2007    | 0.659 | 1.000 | 0.943   | 0.832 | 1.000 |
| Rizhao City  | 0.610   | 0.893 | 0.717 | 2007    | 0.751 | 0.917 | 0.761   | 0.886 | 0.974 |
| Laiwu City   | 0.732   | 1.000 | 0.912 | 2007    | 0.688 | 1.000 | 0.732   | 1.000 | 0.912 |
| Linyi City   | 0.674   | 0.947 | 0.798 | 2007    | 0.975 | 0.843 | 0.896   | 0.971 | 0.923 |
| Dezhou City  | 0.483   | 0.884 | 0.675 | 2007    | 0.752 | 0.884 | 0.684   | 0.966 | 0.986 |
| Liaocheng City | 0.599 | 0.914 | 0.762 | 2007    | 0.500 | 0.916 | 0.803   | 0.908 | 0.945 |
| Binzhou City | 0.585   | 0.879 | 0.710 | 2007    | 0.660 | 0.889 | 0.728   | 0.952 | 0.989 |
| Heze City    | 0.392   | 0.519 | 0.462 | 2007    | 0.614 | 0.521 | 0.472   | 0.884 | 0.997 |

0.980
3.1. Overall efficiency
It can be observed from Figure 1 that there are differences in the average annual agricultural water efficiency of each city in Shandong Province. The average overall efficiency of Jinan, Yantai and Qingdao is higher than 0.99 followed by Weifang, Laiwu, all of which are above 0.9, and the lowest is Heze which is below 0.5. The overall efficiency of agricultural water in Heze is only 0.462, mainly due to the relatively low local economic development and relatively backward agricultural production technology. In addition, local farmers lack the awareness of rational use of water resources. There are still many improvements that need to do for improving agricultural water efficiency.

3.2. Pure technical efficiency
Pure technical efficiency is the impact of changes in technical efficiency on agricultural water efficiency. From 2007 to 2017, the agricultural water efficiency of various cities in Shandong Province has the characteristics of uneven spatial distribution and increasing year by year, with the east being higher than the west (Figure 2). The average pure technical efficiency in Qingdao, Weifang, Yantai and Laiwu are all equal to 1. And this index of Jinan, Zaozhuang, Dongying, Jining, and Weihai are all higher than 0.9, indicating the allocation of resources in these regions is relatively reasonable and the technical level is relatively high. The average pure technical efficiency of agricultural water in Zibo, Taian, Rizhao, Linyi, Dezhou, Liaocheng and Binzhou are at a medium level. While in Heze, the pure technical efficiency is relatively low at only 0.472, followed by Dezhou at 0.684. The resource allocation of these two cities is low, and there is plenty of room for improvement in the technical level.

3.3. Scale efficiency
Scale efficiency is the impact of changes in scale on agricultural water efficiency. It can be observed from Table 1 that the scale efficiency of agricultural water in Dongying and Jining is at a medium level. The scale efficiency of agricultural water in Jinan, Qingdao, and Yantai is equal to 1, and the scale efficiency of agricultural water in other cities are all higher than 0.9, at a relatively high level. It shows that the production input scale of various cities in Shandong Province is controlled well, and the utilization of water resources and other production factors are relatively reasonable. In addition, Dongying, Jining, Weifang, Weihai, Laiwu and Linyi should reduce the scale of production input to improve the efficiency of agricultural water. On the contrary, the other cities should expand the scale of production input to improve the efficiency of agricultural water.

4. Discussion
In order to further discuss the differences in agricultural water efficiency among various crops in Shandong Province, the Malmquist index was introduced to analyze the total factor productivity (TFP)
of each crop and its decomposition index. We used Deap2.1 software to perform Malmquist analysis of the statistical data of the six major crops including cereals, beans, potatoes, oilseeds, cotton, vegetables, fruits and edible fungi, which contribute more to agricultural economy in Shandong Province, and the following results are obtained. (Table 2)

| Crops                  | TEC   | TC    | PEC   | SEC   | TFP Index |
|------------------------|-------|-------|-------|-------|-----------|
| Cereals                | 1.029 | 1.120 | 1.027 | 1.002 | 1.152     |
| Beans                  | 0.903 | 1.123 | 0.903 | 1.000 | 1.014     |
| Potato                 | 0.983 | 1.123 | 0.978 | 1.005 | 1.104     |
| Oil                    | 1.185 | 1.083 | 1.141 | 1.039 | 1.283     |
| Cotton                 | 1.040 | 1.123 | 1.031 | 1.009 | 1.168     |
| Vegetables, fruits and edible fungi | 1.001 | 1.077 | 1.000 | 1.001 | 1.077     |

From the calculation results of the TFP index, it can be observed that the agricultural water TFP index of the six major crops that account for a relatively larger amount of agricultural output value is higher than 1.0 to achieve growth, indicating that the agricultural water efficiency of most crops in Shandong Province is relatively high. Among these six types of crops, oil has the highest average TFP index at 1.282, followed by cotton. Therefore, under the premise of ensuring the production of crops needed, more oil plants and cotton should be planted.

From the perspective of the TFP index decomposition, both the technical efficiency change (TEC) and the technical change (TC) have an impact on the agricultural water efficiency of each crop. The crops with a technical efficiency index higher than 1 include cereals, oilseeds, cotton, vegetables, fruits and edible fungi. And the technical progress index of agricultural water for the six major agricultural crops is all greater than 1.0, showing that the development and evolution of technique have made a greater contribution to the TFP index. Pure technical efficiency change (PEC) and scale efficiency change (SEC) constitute technical efficiency changes. The technical efficiency changes are mainly caused by pure technical efficiency changes, and the scale efficiency of various crops are basically unchanged, so the impact of this change is small. It shows that the improvement of agricultural water efficiency of main crops in Shandong Province mainly depends on the advancement of agricultural production and planting technology and the improvement of agricultural irrigation technology. There is still plenty of room for improvement in the crop planting pattern and scale in Shandong Province.

5. Conclusion

Water resources play an important role in agricultural development, improving the agricultural water efficiency and even the entire water resources use efficiency in Shandong Province to achieve the goal of alleviating pressure and ensuring food security. This paper used DEA and Malmquist models and selected relevant statistical data from 2007 to 2017 to calculate and analyze the efficiency of agricultural water in Shandong Province. The results show that

- The efficiency of agricultural water in Shandong Province is gradually increasing, and there are significant regional differences.
- The oil crops and cotton have the best agricultural efficiency among several crops which have a relatively large contribution to agricultural output.

During the process of analysis, the problems faced by agricultural water in Shandong Province were discovered. Combined with the calculation results of the model, the following suggestion was proposed to improve the agricultural water efficiency:

- Strengthen the investment in water conservancy facilities, and combine the current situation and distribution characteristics of water resources in Shandong Province to improve construction and management of the water conservancy facilities.
- Strengthen the development and promotion of agricultural water-saving irrigation technology and production technology, adjust the amount of agricultural water consumption scientifically and rationally.
- On the premise of meeting the production and living needs of other crops, expand the planting area of cotton and oil appropriately, and select the optimal scale of agricultural planting to maximize the resources use efficiency. At the same time, each city should also change the scale and structure of agricultural planting in a targeted manner according to actual factors such as water resources, topography, and soil conditions etc., in order to maximize limited water resources.
- Strengthen relevant policy guidelines, raise the awareness of water resources protection and supervision of the whole people, and realize the sustainable use and development of water resources.

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