Fertilizer Utilization Efficiency in China, 2001-2015

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Abstract. This study employs the biennial-weight-modified Russell model to measure the efficiency of China’s fertilizer utilization during 2001-2015 while investigating the temporal and spatial characteristics. The empirical results showed that fertilizer utilization efficiency (FUE) in the eastern region was the highest, followed by the central region during the sample period. FUE in China and its three regions had only slight fluctuations without an obvious trend. But FUE varied greatly in some provinces. The provinces having higher FUEs mainly included Shanghai and Hainan, whereas those with lower FUEs mainly included Anhui, Shanxi, and Hubei. Therefore, the governments should pay attention to both the improvement of FUE and the inter-regional balance for the coordinated development of agricultural regions.

1. Introduction

China has become the world's largest producer and consumer of fertilizer. China's fertilizer consumption per hectare of farmland was 503.32 kg in 2016, about 3.58 times the world average at 140.55 kg. Although fertilizer can increase grain production, the high intensity of fertilizer input also has a significantly negative impact on the ecology and environment, such as greenhouse gas emissions, water pollution, and deterioration of cultivated land quality as well as ecosystem services. To change these situations, the key lies in improving fertilizer utilization efficiency (FUE). Due to the diversity of climate and soil types in China, spatial differences may exist in FUEs, which is not only unfavorable to agricultural environmental pollution control in different regions but also hinders the formulation and implementation of policies to improve FUE. Therefore, this paper is going to estimate China's FUE and examine its spatial differences, which has great significance in accurately formulating regional policies for narrowing the differences among regions.

Scholars have paid relatively little attention to FUE. Some researchers measured FUE based on experimental plots [1, 2]. But they can only be concentrated in a small area, not to cover other areas. Some studies measured the efficiency scores using stochastic frontier analysis, which ignored environmental pollution [3, 4]. In addition, this result depends on the production function and the probability distribution of the random variables. This study employed a data envelopment analysis method, the biennial weight modified Russell model (BWMRM), to measure China’s FUE during 2001-2015 from the perspective of agricultural green total factor productivity (AGTFP).
2. Materials and methods

2.1. The selection of input and output indicators

The measurement of TFP requires the input and output of each province. This study included eight inputs, including labor (L), land (N), energy (E), fertilizer (F), pesticide (P), agricultural film (R), agricultural water (W), farm animals (A), one desirable output (Y), and one undesirable output (C). We use indicators to represent these factors. L: the actual agricultural production; C: agricultural carbon emissions; L: the number of agricultural practitioners; N: area sown with crops; E: electricity consumption of agricultural machinery; F: applying quantity of chemical fertilizer; P: consumption of chemical pesticides; R: the amount of agricultural film used; W: actual irrigation area; A: the number of farm draft animals. This study used agricultural carbon emissions as undesirable output which can be calculated according to the related literature [5].

2.2. The biennial weight modified Russell model

BWMRM is based on the weighted Russell directional distance model (WRDDM) and the biennial environmental production technology. WRDDM allows researchers to set the weight of inputs and undesirable outputs in the framework and uses the two-period decision making units (DMUs) to construct the benchmarking. The advantage of the technology is the flexibility that it does not need to be recomputed when the sample period is extended and can avoid infeasibility. In addition, outliers have little influence on the measurement result. BWMRM integrates the advantages of both. Supposing \( x, y, \) and \( b \) represents inputs, desirable outputs, and undesirable outputs, respectively, so for DMU \( j (j = 1 \ldots n) \) in period \( t (t = 1 \ldots T) \), its input-output set is \( (x_{j}^{*}, y_{j}^{*}, b_{j}^{*}) \). It is in accord with the three assumptions (weak disposability, null-jointness, and the compact set). The technology is shown as Eq. (1). Note \( Z \) is the intensity variable. \( \sum_{i=1}^{n} z_{j} = 1 \) and \( z_{j} \geq 0 \) means variable returns to scale (VRS). If there is not the condition \( \sum_{j=1}^{n} z_{j} = 1 \), only \( z_{j} \geq 0 \) that means constant returns to scale (CRS).

\[
T = \{ (x, y, b): \sum_{i=1}^{n} z_{j}^{*} x_{j}^{*} + \sum_{i=1}^{n} z_{j}^{*+1} x_{j}^{*+1} \leq x_{j}, \sum_{j=1}^{n} z_{j}^{*} y_{j}^{r} + \sum_{j=1}^{n} z_{j}^{*+1} y_{j}^{r+1} \geq y_{j}^{r}, \sum_{j=1}^{n} z_{j}^{*} b_{j}^{*} + \sum_{j=1}^{n} z_{j}^{*+1} b_{j}^{*+1} = b_{j}^{*} \} \quad (1)
\]

Eq. (2) shows the linear programming of BWMRM for DMU \( j \) in period \( t \). The linear programming is for the DMU \( j \) in the period \( t \), and those for other DMUs in another period can be built similarly. \( M, Q, \) and \( H \) are the total number of inputs, desirable output, and undesirable output, respectively. \( s_{j}^{bt} x_{m}, s_{j}^{bt} y_{q}, \) and \( s_{j}^{bt} b_{h} \) are slack variables of them, respectively. The subscript \( V \) means VRS.

\[
\overline{D}^{bt}_{jV}(x^{*}, y^{*}, b^{*}; g^{*}) = \beta^{bt}_{j} = \text{Max} \frac{1}{2} \left[ \frac{1}{2M} \sum_{m=1}^{M} \frac{s_{j}^{bt} x_{m}}{x_{m}^{*}} + \frac{1}{2(Q + H)} \left( \sum_{q=1}^{Q} \frac{s_{j}^{bt} y_{q}}{y_{q}^{*}} + \sum_{h=1}^{H} \frac{s_{j}^{bt} b_{h}}{b_{h}^{*}} \right) \right] + \frac{1}{3M} \sum_{m=1}^{M} \frac{s_{j}^{bt} x_{m}}{x_{m}^{*}} + \frac{1}{3Q} \sum_{q=1}^{Q} \frac{s_{j}^{bt} y_{q}}{y_{q}^{*}} + \frac{1}{3H} \sum_{h=1}^{H} \frac{s_{j}^{bt} b_{h}}{b_{h}^{*}} \right] \right]
\]

\[
s.t. \quad \sum_{j=1}^{j} z_{j}^{*} x_{j}^{m} + \sum_{j=1}^{j} z_{j}^{*+1} x_{j}^{m} \leq x_{j}^{m} - s_{j}^{bt} x_{m}, \text{for } \forall m = 1, 2, \ldots, M
\]

\[
\sum_{j=1}^{j} z_{j}^{*} y_{j}^{q} + \sum_{j=1}^{j} z_{j}^{*+1} y_{j}^{q} \geq y_{j}^{q} + s_{j}^{bt} y_{q}, \text{for } \forall q = 1, 2, \ldots, Q
\]
\[
\sum_{j=1}^{J} z_j^t b_j^t + \sum_{j=1}^{J} z_j^{t+1} b_j^{t+1} = b_j^t + s_{j}^{Rt}/b_h, \text{ for } \forall h = 1, 2, \ldots, H
\]
\[
z_j \geq 0; z_{j'}^{Rt}/q \geq 0; s_{j'}^{Rt}/b_h \geq 0; s_{j'}^{Rt}/x_m \geq 0; \sum_{j=1}^{J} z_j^t + \sum_{j=1}^{J} z_j^{t+1} = 1;
\]
\[
j = 1, \ldots, J; t = 1, \ldots, T
\]

(2)

2.3. Fertilizer utilization efficiency

The biennial environmental production technology uses the two-period DMUs to construct the production frontier. The biennial environmental production frontier in period \( t \) is constructed by DMUs of period \( t \) and \( t+1 \) and that in period \( t+1 \) by DMUs of periods \( t+1 \) and \( t+2 \). Therefore, DMU \( j \) in period \( t+1 \) can get two static AGTFP values in two biennial environmental production frontiers, respectively. Because we calculate FUE from the perspective of AGTFP, FUE also has two values in the two situations. For the robustness of the results, the average value of the two was taken as real FUE in this study, as shown in Eq. (3).

\[
FUE_{j}^{t+1} = \frac{1}{2} \left( \frac{F_{j}^{t+1} - S_{j}^{Rt}}{F_{j}^{t+1} + S_{j}^{Rt}} \right) (3)
\]

2.4. Data source

The sample included data from 31 provinces in China (excluding Hong Kong, Macao, and Taiwan) from 1997 to 2016, obtained from the China Rural Statistical Yearbook, the China Agricultural Yearbook, the China Animal Husbandry Yearbook, and the Statistical Yearbook of China.

3. Results and discussion

3.1. The regional analysis

FUE in the eastern region was the highest, followed by the western region, and the lowest in the central region during the sample period. FUE of the western region was about the national average. Moreover, the FUE of each other was not close. This indicates that there were distinct levels of FUE in the three regions. This finding was also reported by Liu, Sun and Li [6]. This result may be explained by the fact that agricultural production conditions, technical level, and internal industrial structures vary from region to region. The eastern region had the most developed economy and the most advanced production technology, so the low FUE can be explained from the perspective of technological level. In addition, its natural production conditions such as plain area, climate, temperature, and labor were suitable for agricultural production. Moreover, compared with the national average, the proportion of agriculture consuming a lot of fertilizer, in the eastern region was generally small, while the proportion of fishing was large. Taking 2003 as an example, the national agricultural structure was 48.65:4.98:33.81:12.56 in agriculture, forestry, animal husbandry, and fishery, while the eastern region was 45.92:4.03:30.74:19.30.

The central region had such a low FUE, which is contrary to popular perception. Rich in agricultural resources and superior agricultural development conditions, this region has always been an important base of national commodity grain production and bears the responsibility of guaranteeing national food security and realizing an effective supply of agricultural products. This area bears about 30% of the country's agricultural population and is also a key area in China to solve the "three rural" problems and coordinate urban and rural development. A possible explanation for this might be that the introduction and dissemination of technology that can save fertilizer were neglected. On the one hand, due to the better production conditions in the central region, it maintained a large amount of agricultural output and had no internal motivation to introduce and popularize new technologies, thus neglecting the development of technology. On the other hand, the central provincial governments were tasked with grain production, leaving no attention enough to promoting technology and only pursuing
short-term high yields. In addition, unlike air pollution, which can be monitored and conducive to regulation, the governments had no effective measures to monitor and regulate fertilizer use. Fertilizer-saving technologies have not received as much attention from central provincial governments as other technologies. These governments simply increased fertilizer use to compensate for the decline in agricultural production caused elsewhere.

Compared with the other two regions, the overall agricultural production conditions in the western region are poor and the technical level is not high. Why is FUE higher in the western region than in the central region? The central government has always attached importance to the development of the western region, put forward the strategies, and coordinated the development from the national level. The economy of the western region is backward, and agriculture accounts for a large proportion, which has always been valued by the western provincial government. The agricultural output is relatively low and there is no agricultural production task. Due to a large number of primitive ecological resources, green development has always been in an important position in western agriculture. Sustainable development is emphasized when formulating agricultural policies, declining the use of fertilizer.

Turning now to the analysis from the time dimension. Overall, China and the three regions had slight fluctuations during the sample period, and there was no obvious change direction. One interesting finding is that FUE in the central region rose rapidly from 2004 to 2006 and slowly fell back to the level around 2001. The observed increase could be attributed to which in March 2004, the State Council proposed “the rise of the central region” for the first time, and made further arrangements in the government work report in March 2005. The slow decline may be due to a lack of continuous attention. These findings suggest that the central government should establish a long-term development plan and continue to promote the implementation of various tasks.

3.2. The provincial analysis

This study divided the sample period into three parts: 2001-2005, 2006-2010 and 2011-2015. These three periods correspond to China's 10th, 11th, and 12th Five-Year plan periods, respectively. At the provincial level, this study calculated the mean of FUE in each period and used the heatmap to present, as shown in figure 1-3. From the three graphs, we can see that China's FUE presented obvious spatial differences.

During the Tenth Five-Year Plan period, there were eight provinces where FUE is 1, including Beijing, Inner Mongolia, Shanghai, Fujian, Hainan, Tibet, Qinghai, and Ningxia. The FUE of Zhejiang, Guangdong, Jiangsu, Tianjin, Liaoning, and Shandong in the east and Xinjiang, Guizhou, Sichuan, and Shaanxi in the west were all above 0.9, including no central provinces. The FUE of Hubei, Anhui, and Shanxi was below 0.5, all of which belong to the central region. Shanxi's FUE was the lowest, only 0.45. During the eleventh Five-Year plan period, there were five provinces where FUE was 1, including Beijing, Shanghai, Hainan, Guangdong, and Tibet. The FUE of Liaoning, Zhejiang, Jiangsu, Shandong, Tianjin, Fujian in eastern China and Qinghai, Sichuan, Shaanxi, Xinjiang, and Ningxia in western China was greater than 0.9. For Anhui, Shanxi, and Hubei, their FUE was less than 0.5, the same as the last Five-year period. In addition, no areas were belonging to the central region with an FUE of more than 0.9. During the twelfth Five-Year plan period, for Shanghai, Hainan, Jiangsu, Gansu, their FUE was 1. The FUE of eastern Liaoning, Guangdong, Zhejiang, Fujian, Beijing, Shandong, and western Sichuan, Xizang, Ningxia, Shaanxi, Qinghai was greater than 0.9. The FUE of Yunnan, Jilin, Anhui, and Inner Mongolia were less than 0.5.

According to the above provincial FUE, we had some major findings. First, the provincial result confirms that of regional analysis that provinces in the central region did not have a good performance. During the three periods, no areas in the central region had an FUE of more than 0.9. In addition, it was always the central areas where had the FUE less than 0.5. Second, for some areas, their FUE varied greatly. Gansu’s FUE was just 0.5013 in the first period and arrived at 1, a nearly double increase. On the contrary, Inner Mongolia declined from 1 in the first period to 0.4399 in the third period, more than half drop. The provinces with the significant improvement of FUE also included Hebei, Henan, and Chongqing. And the areas with the significant decline also included Xinjiang,
Guizhou, Tianjin, and Jilin. Third, we found that the FUE of Shanghai and Hainan always was 1 in the tree period. They are the typical example of two kinds of provinces with FUE arriving at 1, respectively.

**Figure 1.** The mean of provincial FUE during 2001-2005.

**Figure 2.** The mean of provincial FUE during 2006-2010.
Figure 3. The mean of provincial FUE during 2011-2015.

Although Shanghai and Beijing’s agriculture accounts for a small proportion, their economy is very developed and advanced technology is applied first. A high degree of urbanization makes these places pay more attention to green production. It is also easier for governments to regulate small-scale agriculture. Moreover, a lot of demand for food from the city makes farmers get fat income, increasing the enthusiasm for production. The other kind of area is these provinces like Hainan, Fujian. Agriculture accounts for a large proportion of the economy in these provinces. Although their economy may not be developed, the government attaches great importance to agriculture because agriculture greatly affects the local economy and employment. The local promotion of advanced agricultural production technology can get a significant scale effect. As a result, FUE and production efficiency were high in these provinces. Of course, this is also related to local agricultural resources and policies, not all provinces with a high proportion of agriculture can have good FUE performance.

4. Conclusion

Based on the BW MRM, this study calculated the FUE during 2001-2015 and investigated its temporal and spatial characteristics.

The primary findings can be summarized as follows. First, FUE in the eastern region was the highest, followed by the western region, and the lowest in the central region during the sample period. Second, China and the three regions’ FUE had slight fluctuations during the sample period, and there was no obvious trend. But FUE varied greatly in some provinces, including Gansu, Inner, Hebei, Henan, Chongqing, Xinjiang, Guizhou, Tianjin, Jilin. Third, the analysis at the provincial level was consistent with that at the regional level. The provinces with high FUE mainly included Shanghai and Hainan, and those with low FUE mainly included Anhui, Shanxi, and Hubei.

Based on the above findings, this paper proposes that people should pay attention to not only the improvement of FUE but also the inter-regional balance, to promote the coordinated development of agricultural regions. The central provinces are important commodity-grain production areas in China. To pursue higher agricultural output, farmers generally apply larger amounts of fertilizer. So, there exists a large space for FUE improvement. Finally, farmers’ environmental performance needs to be improved potentially by spreading formula fertilization technology.

5. References

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