

Study on Green Efficiency and Rebound Effect of Water Use in China's Grain Production – Based on the Three-Stage Super-Efficiency SBM-Malmquist Model Postprint

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Abstract

Improving the green efficiency of water use in grain production represents one of the effective pathways for reducing agricultural water consumption and achieving green development in agriculture. Based on panel data from 31 provinces (municipalities and autonomous regions) in China spanning 2010–2020, this study employs the water footprint of grain production as an input indicator and the grey water footprint of grain production as an undesirable output. Utilizing a three-stage super-efficiency SBM-Malmquist index model, we evaluate the green efficiency of water use in China's grain production and subsequently measure the rebound effect of water use in grain production under conditions of technological progress. The results indicate that: (1) Factors including planting structure, irrigation technology, and nitrogen fertilizer application rate exert significant influences on water use efficiency in grain production; substantial differences exist in both water footprint and grey water footprint across various grain production contexts; the ranking of average growth rates for grey water footprint follows the pattern: Central region > Eastern region > Western region. (2) The external environment demonstrates a significant impact on the green efficiency of water use in grain production in China; after controlling for environmental factors, the mean comprehensive technical efficiency declines by 0.147, while mean pure technical efficiency and scale efficiency decrease by 0.018 and 0.250, respectively; the total factor productivity of water use in grain production is overall in an optimization phase, primarily dependent on technological progress changes. (3) Technology, as the dominant factor in enhancing agricultural water resource utilization efficiency, substantially influences the evolving pattern of the rebound effect of water use in grain production in China. Except for the Eastern region in 2017 where grain production water use did not generate a rebound effect, rebound effects were present in all other

years, manifesting pronounced regional disparities in the development of agricultural water-saving technologies. It is recommended to strengthen agricultural water resource management, thoroughly explore potential for improving water use efficiency, optimize the input structure of grain production factors, and promote the dissemination and application of water-saving technologies, thereby mitigating water environmental pollution and realizing green and sustainable agricultural development.

Full Text

Preamble

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Green Efficiency and Rebound Effect of Water Use for Grain Production in China: Based on the Three-Stage Super-Efficiency SBM-Malmquist Model

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Abstract

Improving the green efficiency of water use for grain production represents one of the effective pathways to reduce agricultural water consumption and achieve green agricultural development. Based on panel data from 31 provinces (municipalities and autonomous regions) in China from 2010 to 2020, this study evaluates the green efficiency of water use for grain production using a three-stage super-efficiency SBM-Malmquist index model, with the water footprint of grain production as an input indicator and the grey water footprint as an undesirable output. Building upon this evaluation, we further measure the rebound effect of water use for grain production under technological progress conditions. The results indicate that: (1) Factors such as planting structure, irrigation technology, and nitrogen fertilizer application significantly influence grain production water use efficiency; substantial differences exist in the water footprint and grey water footprint across different grain types; the average growth rate of the grey water footprint ranks as follows: central region > eastern region > western region. (2) The external environment exerts a significant impact on the green efficiency of grain production water use in China; after eliminating environmental factors, the mean comprehensive technical efficiency decreases by 0.147, while the mean pure technical efficiency and scale efficiency decrease by 0.018 and 0.250, respectively; the overall green total factor productivity of grain production water use is in an optimization stage, primarily dependent on technological progress

changes. (3) Technology, as the dominant factor in improving agricultural water use efficiency, substantially influences the changing rhythm of the rebound effect of grain production water use in China. Except for the eastern region in 2017, where no rebound effect occurred for grain production water use, a rebound effect was present in all other years, demonstrating obvious regional imbalances in the development of agricultural water-saving technology. We recommend strengthening agricultural water resource management, deepening the potential for improving water use efficiency, optimizing the input structure of grain production factors, and promoting the adoption and application of water-saving technologies to mitigate water environmental pollution and achieve green and sustainable agricultural development.

Keywords: green efficiency; water footprint; three-stage super-efficiency SBM-Malmquist; undesirable output; rebound effect

Introduction

Water resources constitute a critical factor for green agricultural development, and improving water resource utilization efficiency is key to addressing the water crisis [1]. Consequently, enhancing the green efficiency of agricultural water use has become an important pathway. Green efficiency of water resources refers to achieving maximum economic output with minimal input while protecting the natural environment and reducing pollutants [2]. Currently, numerous scholars have extensively studied water resource green efficiency and its influencing factors using various models. For instance, Chu Jiaqi et al. [3] calculated the green efficiency of agricultural water resources in Xinjiang's 14 prefecture-level administrative regions using agricultural net carbon sink as the main output variable, revealing significant regional disparities. Cao Shanshan et al. [4] employed a super-efficiency evaluation model based on Data Envelopment Analysis (DEA) to explore the impact of tourism development on water resource green efficiency and its regional differences against the backdrop of green development strategy. Wang Jik et al. [5] utilized a super-efficiency model to measure industrial green water resource efficiency in the Yellow River Basin, identifying localized dynamic and heterogeneous characteristics given the severe water shortage situation. Meanwhile, global scholars have assessed water footprint in grain crops, food consumption, industrial development, and other sectors [6-8], conducting water footprint evaluations at national, provincial, and regional scales [9-11]. However, existing research has paid limited attention to the impact of technological progress on agricultural water use.

The rebound effect is an economic concept originally used to explain the relationship between energy consumption and economic growth [12], which can also be applied to water resource input issues. Some studies suggest that a rebound effect occurs only when total water withdrawal increases rather than decreases after improving agricultural water use efficiency [13]. Additionally, technolog-

ical improvements may offset water savings achieved through efficiency gains, thereby creating a rebound effect, though this does not necessarily mean a rebound effect must exist [14]. This paper assumes that grain production water use is elastic; under conditions of improved technical efficiency, saved water resources partially offset the water increase brought by technological progress, thus generating a rebound effect in grain production water use.

Building upon existing research and integrating water footprint theory, this study evaluates China's grain production water use green efficiency from input-output perspectives and further measures the rebound effect of grain production water use resulting from technological progress.

1.1.1 Calculation Methods for Grain Production Water Footprint and Grey Water Footprint

Drawing on the research model of Chen Hong et al. [15] regarding grain production water footprint and grey water footprint, this study adopts the FAO-56 calculation method recommended by the United Nations Food and Agriculture Organization. Using wheat, rice, and corn as research objects, we employ Cropwat 8.0 software to calculate evapotranspiration for different grain crops. The basic formulas are presented in Table 1. Based on the FAO-56 standard crop coefficient table, this study selects crop coefficients of 0.85, 1.15, and 1.10 for corn, wheat, and rice, respectively [16-18]. The average nitrogen application rates per unit area for rice, corn, and wheat are calculated as $157.7 \text{ kg} \cdot \text{hm}^{-2}$, $185.0 \text{ kg} \cdot \text{hm}^{-2}$, and $138.5 \text{ kg} \cdot \text{hm}^{-2}$, respectively [19]. The nitrogen leaching rate α is determined as 0.1 [20]. According to the "Groundwater Quality Standard" (GB/T14848-2017), the maximum pollutant concentration C_{max} is selected as $20 \text{ mg} \cdot \text{L}^{-1}$, and the minimum natural allowable concentration C_{nat} of water bodies is generally $0 \text{ mg} \cdot \text{L}^{-1}$ [21].

The grey water footprint is a method proposed by Hoekstra [22] for quantitatively evaluating water pollution. The grain production grey water footprint refers to the volume of water required to dilute nitrogen fertilizer leaching loss in grain cultivation to meet water quality standards. Considering that nitrogen fertilizer has large application amounts and high leaching rates in China's agricultural planting sector, nitrogen is used as the pollutant for calculating grain production grey water footprint. To enhance research accuracy and authenticity, this study divides 31 provinces (municipalities and autonomous regions) into three regions: central (Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan), eastern (Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan), and western (Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang).

1.1.2 Three-Stage SBM-DEA Model with Undesirable Outputs and Malmquist Index

Tone [23] proposed the SBM model considering undesirable outputs. The three-stage super-efficiency SBM model conducts initial efficiency evaluation in the first stage, uses SFA regression to strip slack variables in the second stage, obtains corrected variables, and in the third stage, constructs new input-output combinations using adjusted input indicators with original output indicators to rerun the super-efficiency model. Since the SBM model can only analyze efficiency values from a static perspective, this study introduces the Malmquist productivity change index to measure dynamic changes in China's grain production water use efficiency. This index can be decomposed into the product of the comprehensive technical efficiency change index (EC) and the technological progress change index (TC). EC can be further decomposed into pure technical efficiency change (PEC) and scale efficiency change (SEC). The relationship is as follows:

$$ML = EC \times TC = SEC \times PEC \times TC$$

The Malmquist index model is constructed as follows:

$$ML_t^{t+1} = \left[\frac{D^t(x^{t+1}, y^{t+1}, b^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \frac{D^t(x^t, y^t, b^t)}{D^{t+1}(x^t, y^t, b^t)} \right]^{1/2}$$

where ML_t^{t+1} represents the total factor productivity change from period t to $t+1$, primarily applied in research on dynamic efficiency change trends; x^t, y^t, b^t and $x^{t+1}, y^{t+1}, b^{t+1}$ are inputs, desirable outputs, and undesirable outputs in periods t and $t+1$, respectively; D^t and D^{t+1} are distance functions in periods t and $t+1$.

1.1.3 Rebound Effect Measurement

Referring to relevant scholars' definitions of energy use intensity [24], this study defines W as grain production water use intensity, with the specific formula as follows:

$$W_{n,t} = \frac{TVW_{n,t}}{Y_{n,t}}$$

where TVW is the grain production water footprint (10^8 m^3), Y is grain production GDP (10^8 yuan), n and t represent province and time period, respectively.

The theoretical water savings from improving grain production water use efficiency in each province is:

$$S_{n,t} = TVW_{n,t} - TVW_{n,t+1} \times \frac{Y_{n,t}}{Y_{n,t+1}}$$

The increased water demand for grain production driven by technological progress is:

$$\Delta TVW_{n,t} = TVW_{n,t+1} - TVW_{n,t} \times (1 + GML_{n,t})$$

where $GML_{n,t}$ and $GML_{n,t+1}$ are the total factor productivity change indices for a region in periods t and $t + 1$; Y_t and Y_{t+1} are grain production GDP growth rates in periods t and $t + 1$; $T_{n,t}$ is the contribution rate of technological progress. This study uses the total factor productivity index method for calculation, and the rebound effect of grain production water use brought by technological progress is:

$$RE = \frac{\Delta TVW_{n,t}}{S_{n,t}} \times 100\%$$

Using the magnitude of water “crowding-out” in grain production as the judgment basis, the rebound effect (RE) can be categorized as follows: $RE < 0$ indicates no rebound effect; $0 \leq RE < 0.5$ indicates weak rebound effect; $0.5 \leq RE < 1$ indicates strong rebound effect; $RE \geq 1$ indicates backfire effect [25].

1.2 Indicators and Data Sources

Based on relevant literature [1,13,19], this study uses 31 provinces (municipalities and autonomous regions) (excluding Hong Kong, Macao, and Taiwan) as decision-making units to calculate and analyze panel data on grain input-output from 2010 to 2020. Selected input indicators include grain sown area, chemical fertilizer application amount (pure conversion), grain production water footprint, and total agricultural machinery power. Grain production GDP serves as the desirable output, while grain production grey water footprint is the undesirable output (Table 2). Data are sourced from the *China Statistical Yearbook*, *China Rural Statistical Yearbook*, and China Meteorological Data Network.

Results

2.1.1 China’ s Grain Production Water Footprint

Based on formulas (1)-(4), we calculated China’ s grain production water footprint from 2010 to 2020 and computed its average annual growth rate (Figure 1). Analysis by grain type shows that the average annual growth rates of production water footprint for corn, rice, and wheat in China were -1.2%, -1.0%, and -0.8%, respectively. All three grain production water footprints exhibited a declining trend, reflecting water conservation benefits in Chinese agriculture

since the implementation of the “Strictest Water Resources Management System.” From a regional perspective, Qinghai’s rice water footprint average annual growth rate declined significantly, while Hainan’s corn and wheat water footprint average annual growth rates fluctuated considerably. This phenomenon may be related to differences in regional resource endowments, grain planting structures, and sown areas. Constrained by high-cold climate conditions, Qinghai mainly cultivates drought-resistant crops with limited rice planting area; in contrast, Hainan’s superior natural conditions and more refined rice cultivation management result in distinct regional characteristics in water footprint changes across grain types.

2.1.2 China’s Grain Production Grey Water Footprint

The total grey water footprint of the three grain types remained relatively stable from 2010 to 2020 (Figure 2), with nitrogen fertilizer application significantly influenced by planting structure and sown area. Among the comparisons, corn had the largest grey water footprint, causing the most severe pollution, while wheat had the smallest. This difference primarily stems from corn’s lower water requirements during its growth period, combined with its larger sown area and higher nitrogen fertilizer application. Regionally, grey water footprint changes in eastern and western China remained stable, while the central region showed an upward trend. In 2020, China’s total grain production grey water footprint reached $308 \times 10^8 \text{ m}^3$, with the central region’s increase being particularly notable, likely related to its core responsibility in ensuring national food security through grain structure adjustments and planting area changes. Although China has achieved remarkable success in balancing grain production quantity and quality, vigorous implementation of fertilizer and pesticide reduction policies remains essential to promote quality and efficiency improvements in grain production.

2.2.1 Static Efficiency Evaluation

Using the grain production water footprint of 31 provinces (municipalities and autonomous regions) as input indicators and grey water footprint as undesirable outputs in the three-stage super-efficiency SBM model, we analyzed factors influencing grain production water use efficiency after eliminating environmental variables. Without considering environmental factors, the first-stage results show that the average scale efficiency value is the largest, with a gap of 0.189 between the maximum and minimum pure technical efficiency values, and a gap of 0.282 between the maximum and minimum comprehensive technical efficiency values. In the second stage, based on actual conditions, we selected regional GDP per capita, water resources per capita, and the proportion of grain production GDP to regional GDP as environmental variables to construct an SFA regression model. As shown in Table 3, the one-sided generalized likelihood ratio (LR) tests for grain production water footprint, grain sown area, chemical fertilizer application, and total machinery power all exceed the critical values within

the specified range, indicating reasonable model specification. Regional GDP per capita shows negative correlations with sown area, total machinery power, and chemical fertilizer application, all passing significance tests; the proportion of grain production GDP to regional GDP has negative regression coefficients with all input variables, indicating that slack variables decrease as this environmental factor increases; water resources per capita shows positive correlations with all input variables, all passing significance tests.

In the third stage, referencing the second-stage SFA regression results, we adjusted input variables and incorporated the adjusted data into the super-efficiency model to analyze green efficiency of grain production water use after eliminating environmental factors (Table 4). Environmental factors significantly impact China's grain production water use green efficiency. After removing environmental factors, the mean comprehensive technical efficiency decreased by 0.147, while mean pure technical efficiency and scale efficiency decreased by 0.018 and 0.250, respectively, indicating that environmental factors inflated pure technical efficiency and scale efficiency, leading to overstated comprehensive technical efficiency. Specifically, in the third stage, Heilongjiang's comprehensive technical efficiency equals 1, indicating comprehensive effectiveness in its grain production water input-output. In contrast, Qinghai had the lowest comprehensive technical efficiency in both first and third stages. Regarding efficiency factors, after eliminating environmental factors, Shanghai's comprehensive technical efficiency ranking dropped by 7 positions, Tianjin by 5, and Fujian and Zhejiang by 4 each, likely reflecting the importance of economic development level and technological support in eastern China for improving agricultural water use efficiency. Shanghai and Beijing experienced major ranking changes in pure technical efficiency, dropping by 7 and 6 positions, respectively; Jiangsu, Shandong, and Henan showed the largest ranking improvements in scale efficiency, rising by 7, 6, and 5 positions, respectively, possibly due to significant efficiency gains through optimized resource allocation. Notably, in the third stage, Heilongjiang ranked first in comprehensive technical efficiency, pure technical efficiency, and scale efficiency, likely because its agricultural water resource management and utilization efficiency development is more mature, fully leveraging its role as a "ballast stone" for China's food security.

2.2.2 Dynamic Efficiency Evaluation

By inputting variables with environmental factors stripped in the second stage into the Malmquist index model, we analyzed dynamic changes in green efficiency of grain production water use (Table 5). Overall, the average Malmquist index was 1.089, indicating optimal dynamic efficiency of grain production water use. Regions with Malmquist indices above the average include Beijing, Liaoning, Shanghai, Jiangsu, Guangdong, Inner Mongolia, Jiangxi, Guangxi, and Tibet, while regions below the average are mainly affected by technical efficiency changes and technological progress changes. China's grain production water use technological progress change index exceeds 1 in all cases, indicating compre-

hensive growth in water use efficiency, with the mean ranking of technological progress change indices being: eastern > central > western. Hebei, Liaoning, Shandong, and 7 other regions have grain production water use pure technical efficiency change index means below 1, with Shandong having the smallest and Hainan the largest. Central and western regions have scale efficiency change indices below 1, indicating that current agricultural water allocation in these regions needs improvement.

2.3 Rebound Effect Measurement of Grain Production Water Use

The existence of rebound effects complicates the relationship between technological progress and grain production water use efficiency, influencing the improvement of water use efficiency through technological advancement. Ignoring rebound effects limits research on how technological progress affects water savings in grain production. Therefore, it is necessary to deeply study the impact of rebound effects on grain production water use efficiency under technological progress conditions, which is significant for formulating water policies and promoting water-saving agriculture. Based on formula (9), we obtained the rebound effect of grain production water use caused by technological progress (Table 6). Comparing water demand and savings in grain production helps understand technological progress' s impact on water consumption. Although rebound effects fluctuate over time across regions, no significant rebound effect has occurred overall. Due to decreased technology contribution rates, grain production water consumption has increased, indirectly indicating that technological progress helps improve water resource utilization efficiency and reduce agricultural water use. Therefore, rationally adjusting water resource development and utilization structures, expanding agricultural irrigation technology promotion, and implementing refined management can improve grain production water use green efficiency.

From a temporal perspective, grain production water use intensity in eastern, central, and western regions shows negative growth in savings, reflecting that technological progress has not significantly reduced grain production water consumption. From 2010 to 2020, grain production water savings increased, indicating that technological progress improved water use efficiency. Although technology contribution rates declined in 2019-2020, leading to increased water consumption, the overall trend shows that technological innovation directly promoted grain production water use efficiency and suppressed agricultural water consumption increases. In terms of rebound effect values, China' s grain production water use rebound effect fluctuates over time, reflecting uneven development of agricultural water-saving technology across regions. Except for the eastern region in 2017, where no rebound effect occurred, rebound effects existed in all other years and regions. However, nationally, the mean rebound effect was 0.37, indicating no significant rebound effect overall, likely due to China' s strict total water consumption control management system, which compels regions to implement rigorous water resource management policies and large-scale

water-saving measures effectively. In 2017, the eastern region's grain production water use rebound effect exceeded 1, indicating a backfire effect, possibly because the eastern region's high economic development and technology application levels create greater technological progress contributions to economic growth than in central and western regions, thereby generating new demand for grain production water use.

Discussion

Based on the water footprint perspective, this study employs a three-stage super-efficiency SBM-Malmquist index model with undesirable outputs to conduct dynamic and static evaluations of China's grain production water use green efficiency from 2010 to 2020, and further explores the rebound effect of technological progress on water use efficiency. The research reveals significant spatial disparities in China's grain production water footprint and grey water footprint, with varying growth rates across different grain types, findings largely consistent with Xu Ruifan et al. [26]. Overall, China's grain production water use efficiency shows an upward trend, with an average total factor productivity change index of 1.089, indicating optimal dynamic performance. Notably, technological progress plays a crucial role in enhancing grain production water use efficiency, with all technological progress change indices exceeding 1, demonstrating superior overall dynamic efficiency of grain production water use.

This study's findings align with Chen Jie et al. [1] regarding regional differences, showing that eastern regions generally have higher grain production water use green efficiency than central and western regions due to advanced technology, management, and policy support, emphasizing technology's importance in promoting regional water use efficiency. Some differences exist with Chen Hong et al. [15], possibly stemming from different research timeframes and geographical units, indicating that grain production water use efficiency evaluation is influenced by multiple factors including geography, timeframe, technology level, and management strategies. While existing research emphasizes that improving grain production water use efficiency depends on technological progress, few studies address the insufficient water savings under technological progress or the potential rebound effect. This study provides new perspectives and strategic foundations for agricultural water savings through in-depth analysis of technological progress's impact on the rebound effect of grain production water use. However, in grey water footprint calculations, limitations in specific data availability required using mean values from previous studies, representing a certain limitation.

Conclusion

- 1) Growth rates differ among water footprints of different grain crops. The water footprints of corn, rice, and wheat all show negative growth trends, reflecting water conservation benefits in Chinese agriculture since the

“Strictest Water Resources Management System” implementation. Regional variations are evident, with Qinghai’s rice water footprint declining significantly and Hainan’s corn and wheat water footprints showing considerable fluctuations.

- 2) The external environment significantly influences grain production water use green efficiency. After eliminating environmental factors, mean comprehensive technical efficiency, pure technical efficiency, and scale efficiency decreased by 0.147, 0.018, and 0.250, respectively. In the third stage, comprehensive technical efficiency remained consistently lower than in the first stage. Shanghai, Tianjin, Fujian, and other regions showed rapid improvements in grain production water use efficiency. Dynamic evaluation results show China’s grain total factor productivity change index averaged 1.089, indicating optimal overall performance, with technological progress as the key factor.
- 3) Technology, as the dominant factor in improving agricultural water use efficiency, substantially influences the rebound effect’s changing rhythm. Except for the eastern region in 2017, rebound effects existed in all other years and regions, demonstrating obvious regional imbalances in agricultural water-saving technology development. Nationally, the mean rebound effect was 0.37, indicating no significant rebound effect overall, likely due to China’s strict water resource management system.

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