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EDITED BY
Dinesh Jinger,
Indian Institute of Soil and Water Conservation (ICAR), India

REVIEWED BY
Gagan Matta,
Gurukul Kangri University, India
Amit Kumar,
Nanjing University of Information Science and Technology, China

*CORRESPONDENCE
Ning Yin
✉ ningyin@hunau.edu.cn

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Policy effects of China's water rights trading on grain production: the role of market incentives in promoting sustainability

Ning Yin[1]*, Sichang Luo[2] and Yulian Xia[1]

[1]College of Economics, Hunan Agricultural University, Changsha, China, [2]Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences, Beijing, China

Introduction: Since water is an essential input in agricultural production, the reform of water rights system can pose significant influence on water resource allocation and utilization within agri-food systems. Water rights trading has been recognized as an innovative market incentive strategy to promote sustainable water use. This study investigates the role of China's water rights trading policy played in promoting the green water use efficiency of grain production.

Methods: A three-stage DEA method is adopted to evaluate the green water use efficiency with a provincial panel data from 2006 to 2020. A PSM-DID model, based on the quasi-natural experiment of China's water rights trading pilots in 2014, is employed to analyze policy effects and to explore the role of market mechanism.

Results: Results have shown that the green water use efficiency of grain production has been significantly improved after the implementation of China's water rights trading policy, and technological innovation is found to exert a mediating effect. The policy effect appears more pronounced and robust in national water rights trading pilots than in provincial ones. Heterogeneity is also detected from the perspective of water resource endowment. The efficiency improvement effect is more pronounced in areas with higher per capita water endowment or in China's main grain-selling areas.

Discussion: The findings reveal benefits of utilizing market mechanisms to improve the water use efficiency considering environmental constraints. This study gives reference for regions aiming to implement resource conservation and environmentally friendly policies, and also provides inspiration for fostering the sustainable development of grain production in developing countries facing resource scarcity.

KEYWORDS

water rights trading, policy effect, green efficiency, grain production, water resource

1 Introduction

According to a report published by the United Nations Educational, Scientific and Cultural Organization (2024), the process of achieving the Sustainable Development Goal 6 (SDG-6) appears to be off track. The utilization of water resource is becoming increasingly unsafe and unpredictable, with deteriorating water quality and greater water pressure due to climate change. In Asia-Pacific region, agricultural production of less developed countries have been significantly affected by water-related extreme events, such as floods and droughts, which hinders the process of SDG-2.

Water shortage has always been a concerned problem in China, particularly concerning agricultural grain production. By the end of 2023, China's water resources per capita amounted to 1828.97 m^3, less than 1/3 of the world's average. Meanwhile, agricultural water use accounted for 62.20% of China's water consumption [Ministry of Water Resources of the Peoples's Republic of China (MWR), 2024]. With the expansion of irrigated areas and the steady growth of total grain output, the conflict between water resource scarcity and the increasing demand for irrigation has become more prominent. The net water consumption per unit of grain output is only 0.36 m^3/kg and the irrigation water consumption per unit of cultivated land is 546 m^3/ha. The Chinese government has implemented series of policies to develop water-saving agriculture. Although the effective utilization coefficient of farmland irrigation water has risen from 0.52 in 2012 to 0.58 in 2023, it remains below the global average level of 0.7–0.8. There is still considerable potential for further conservation in agricultural water use.

Water pollution has exacerbated the shortage. According to the results from national pollution source censuses in the first and second round, crop production and livestock farming are the primary sources of agricultural non-point source pollution (An et al., 2024). Non-point source pollution, including the excessive application of chemical fertilizer and the disposal of non-degradable agricultural film in grain production, intensifies the eutrophication and solid waste pollution of water bodies (Kumar et al., 2023; Yu et al., 2024). Excessive amounts of nitrogen, phosphorus, heavy metals and other pollutants enter the water bodies, which not only hinders the effective utilization of water resources but also affects food safety (Bhat et al., 2024; Deng et al., 2024). In this sense, agricultural water use must develop towards both efficient and green to guarantee food security.

China has been committed to adhering to the policy of resource conservation and environmental protection, and encouraging innovative practices. In 2014, China has launched water rights trading pilot work in 7 provinces (Ningxia, Hubei, Jiangxi, Inner Mongolia, Guangdong, Gansu and Henan), encompassing water rights registration, trading platform construction and water management system design. The pilot work signifies a shift from government-lead water resource management to a co-dominance of the government and market forces in China. The literature on water markets has a long history, but it wasn't until the early 21st century that a distinct branch of literature with water rights trading at its core emerged. Initially, research primarily focused on theoretical analysis and practical experience summaries (Pigram, 1993). In recent years, qualitative and quantitative studies on the implementation effect of water rights trading policies have been proliferating (Grafton et al., 2016; Iftekhar and Fogarty, 2022; Yang et al., 2024). It is noteworthy that scholars have not reached a consensus on whether water rights trading can improve the efficiency of water resources. The establishment of water rights trading system can compensate for the limitations of administrative management by leveraging the market mechanism. The market price mechanism and market competition are believed to stimulate water-saving behavior and promote the circulation of water rights, thereby enhancing the efficiency of resource utilization and allocation (Wang et al., 2022; Tian et al., 2022). Pan et al. (2023) concluded that the water rights trading policy was not conducive to improving water utilization efficiency in provincial border cities, using prefecture-level city samples. Fei et al. (2021) found that the water rights trading mechanism led to a rebound in agricultural water use, which was not beneficial for agricultural water use efficiency increase.

However, most studies concentrate on the impacts of water rights trading among industries or regions (Du et al., 2022; Yang et al., 2024), while the policy effect evaluation from the perspective of agricultural water is still insufficient. The few existing studies focusing on agricultural water use efficiency (Zhang et al., 2021a, 2021b; Xu et al., 2023) do not place the research context within grain production, which is the largest water user in agriculture production. Therefore, this study focuses on agricultural water use in grain production, and empirically analyzes the policy effects of water rights trading on the green water use efficiency (GWUE). A three-stage DEA method is adopted to evaluate the GWUE, considering environmental constraints of water resources. Using this unexpected output model can help to investigate the indirect effect of water rights trading policy on resources utilization and the ecological system. Besides, a PSM-DID model, based on the quasi-natural experiment of China's water rights trading pilots in 2014, is employed to analyze the policy effect. Using this model helps to clarify the role of market mechanism in the allocation of natural resources. In general, this study gives reference for regions aiming to implement resource conservation and environmentally friendly policies. It also provides inspiration for fostering the sustainable development of grain production in developing countries facing resource scarcity.

2 Theoretical framework

2.1 Water rights trading system

The utilization of market mechanisms and economic instruments has been internationally recognized as a significant approach to enhance water use efficiency. As early as the 1980s, countries such as Chile, the United States, and Mexico began to establish water rights trading markets. At the start of the 21st century, China began to explore the construction of water rights trading system. The practice and exploration during China's nascent stage of water rights trading demonstrated that agricultural participants possessed both water conservation potential and enthusiasm that could be spurred by institutional innovation. In 2000, the first trading in Dongyang city and Yiwu city of Zhejiang province marked the beginning of water rights trading practice in China. In 2002, farmers in Honghe Irrigation District in Zhangye City, Gansu Province attempted to exchange water tickets. In 2003, water rights for the Yellow River in Inner Mongolia and Ningxia was transferred from agricultural to industrial sector. In 2005, Yidu city in Hubei Province initiated the reform of the "property right beneficiary ownership system" for small rural water conservancy facilities. In 2014, China officially launched the water rights transaction. Pilot projects were conducted in Ningxia, Hubei, Jiangxi, Inner Mongolia, Guangdong, Gansu and Henan provinces, taking into account preliminary work experience, regional differences and representativeness. After 2014, the pilot areas established a contact guidance mechanism with and the Ministry of Water Resources, guaranteed with professionals and funding supports. Explorations continued in water approval registration, water rights transfer and system construction. In 2016, the national water rights trading platform was established and the Yellow River Basin water rights trading platform was officially established in 2023. According to data from the National Water Rights Trading

System, the end of 2023, the number of water rights trading orders had exceeded 10,000 and the volume of water traded had surpassed 4,000 million m^3. Following the national pilot program, 10 provinces (Xinjiang, Hebei, Shandong, Shanxi, Zhejiang, Shaanxi, Fujian, Liaoning, Jilin and Hunan) have launched province-level pilot projects for water rights reform. Relevant documents on water rights trading in China are sorted out in Table 1.

2.2 Theoretical analysis

The Water Law of the Peoples Republic of China stipulates that water resources are owned by the state. According to the Interim Measures for the Management of Water Rights Trading, water rights trading is defined as that 'on the basis of reasonably defining and distributing the right to use water resources, water rights are transferred between regions, basins, industries and water users through market mechanism.' The confirmation and registration of water rights, water rights trading and the construction of water rights trading market are the three kernel components of the pilot projects, which can be regarded as the policy treatment of the quasi-natural experiment of water rights trading pilot. Therefore, the theoretical analysis is unfolded from the following three aspects, respectively.

2.2.1 The resource-protection effect of water rights confirmation

As a typical form of public resource, water resource can also run against the market failure such as 'the tragedy of the Commons' during allocation. According to the property right theories in the institutional economics, institutions are endogenous variables that determine the efficiency of economic operation. The clear definition of property rights can effectively mitigate the externalities and correct the market failure of public resource allocation, so as to improve social welfare (Coase, 2013). Therefore, It is a prerequisite for water rights transaction to clearly delimit the right to use water resources and conduct standardized confirmation registration. This system strengthens the exclusivity of water resources and highlights their economic value through market mechanism. Once farmers and organizations recognize the importance and value of water resources, it is cogent to advocate for farmers' or regional pollution prevention. Studies have proved that building a clear and effectively protected property rights system is essential to encourage individuals to engage in productive activities and foster economic growth. There is a significant positive relationship between farmland right confirmation and farmers' investment in the quality protection of cultivated land and green production (Qian et al., 2021; Zhou et al., 2023). This demonstrates that the effective delimitation and protection of property rights can stimulate the resource protection behaviors.

2.2.2 The water-saving effect of water rights trading

Even if the property rights are determined, there are various manifestations to express rules of competitive property rights. The price mechanism is one of the efficient ways to compete property rights. According to the theory of transaction cost in the institutional economics, one of the kernel goals of economic activities is to reduce the transaction cost. The direct impact of water rights trading on agricultural water use is reflected in the rising opportunity cost of increasing water use. To make the hidden cost of irrigation water explicit can promote water-saving in grain production. Studies have indicated that the low price of irrigation water is a significant contributor to water waste (Webber et al., 2008). The implementation of the water rights trading system has increased the opportunity cost of irrigation water, which has a similar effect to raising water price. Farmers constrained by costs will choose to improve their management mode of water use for grain production and reduce excessive water use. Conversely, water-saving farmers can increase their income through water rights trading. The continuous inefficient water use equals to the loss of potential income from water rights trading, which also encourages farmers to save water. In addition to changing water use habits and irrigation patterns, water rights trading can improve irrigation water efficiency by encouraging farmers to adopt water-saving technologies. Ma et al. (2022) found that the confirmation of water rights leads to increasing irrigation opportunity cost and guides farmers' adoption of water-saving technologies, such as sprinkler and drip irrigation, to reduce the unit

TABLE 1 Documents on China's water rights trading system.

Year	Documents	Main content
2004	"Guidance on the pilot work of changing water rights of the Yellow River in Inner Mongolia and Ningxia" issued by the Ministry of Water Resources	An exploration of new ways to allocate water in arid areas
2011	"Decision of the State Council on accelerating the reform and development of water conservancy"	The establishment of a water rights trading system clearly proposed
2012	"Opinions of the State Council on implementing the strictest water resources management system"	Ameliorating and improving the water rights system
2014	"A notification on carrying out the pilot work of water rights trading" by the Ministry of Water Resources	Pilot water rights trading in seven provinces
2016	China Water Rights Exchange Institution launched in Beijing	The operation stage of China's water rights market reform
2023	"Guidance on promoting water rights reform" by the Ministry of Water Resources, the National Development and Reform Commission and the Ministry of Finance	Setting the goal of advancing water rights reform by 2025 and 2035
2024	"The administrative rules on water rights trading (Trial)" by the Ministry of Water Resources	Basic trading rules formulated and departments' responsibilities divided

water consumption rate of grain output. Green agricultural technologies, such as the integration of water and fertilizer, not only help to save water, but also effectively promote the reduction of chemical fertilizers and pesticides use. Thus, water rights trading may improve the green efficiency of water use in grain production by raising irrigation opportunity cost and stimulating farmers' adoption of green technologies. In this sense, the following hypothesis is put forward.

> H_1: the implementation of water rights trading can promote the green water use efficiency of grain production.

2.2.3 The promoting effect on technological innovation and factor flow

According to the induced innovation theory, disparities in the relative price of factors lead to the emergence of technological progress in different fields, thus affecting the direction of technological advancement and the path of agricultural development (Ruttan, 1977). As the transaction price reflects economic values of water resources within market mechanism, water rights trading market can shape the direction of technological progress by altering the relative price of water and other input factors. Specifically, water rights trading increases the opportunity cost of irrigation water and changes the relative price of grain production inputs, thus encouraging water-saving technology innovation in agricultural production (Fang and Zhang, 2020). In terms of the facilitating effect of factor flow, the transaction cost can be reduced by clarifying the relevant property rights of water resources. This enables water users with higher marginal benefits to secure their desired amount of water, thereby promoting the rational allocation of water resources (Yang et al., 2024). Consequently, water resources flow from agricultural operators with low marginal utility to those with high, achieving a Pareto improvement through optimized resource allocation.

> H_2: the implementation of water rights trading can promote the green water use efficiency by the mediating effects of technological innovation and factor flow.

3 Materials and methods

3.1 Model specification

3.1.1 The three-stage DEA model

The three-stage DEA model was selected to measure the GWUE of grain production, while the isomeric pollution load computing method (Chen and Xu, 2023; Ji and Jiang, 2024) was used to measure the unexpected output. The three-stage DEA model, originally proposed by Fried et al. (1999), posits that the efficiency loss is caused by random disturbance items, ineffective management and external factors. When influences of random disturbance and external factors eliminated, the measured management efficiency becomes more accurate.

In the first stage, the efficiency values and the slack values are calculated by using the ultra-efficiency mixed distance function including the unexpected output, see Equation (1).

$$F_i = \min \frac{\theta - \lambda^- \sum_{n=1}^{m} \frac{w_n^- s_n^-}{x_{ni}}}{\gamma + \lambda^+ \left(\sum_{r=1}^{t} \frac{w_r^+ s_r^+}{y_{ri}} + \sum_{p=1}^{q} \frac{w_p^{e-} s_p^{e-}}{e_{pi}} \right)} \quad (1)$$

where F_i denotes the GWUE of grain production of the i^{th} decision unit; x, y and e represent the input variable, expected output variable and undesired output variable respectively; s^-, s^+ and s^{e-} are the slack values while w^-, w^+ and w^{e-} are the weights of x, y and e, respectively; λ^- and λ^+ show the importance of the non-radial part of the undesired output index; θ and γ represent the input and output radial components.

In the second stage, the SFA method is used to analyze the slack value, and then the influence of external factors and random disturbance on the slack is excluded, so as to calculate the adjusted value of S under the same external condition and random disturbance, see Equation (2).

$$S_{jit} = f\left(Z_{it}; \beta_{jt}\right) + v_{jit} + u_{jit} \quad (2)$$

$$i = 1, 2, \cdots\cdots, i; \; j = 1, 2, \cdots\cdots, j; t = 1, 2, \cdots\cdots, t$$

where S_{jit} represents the slack value of j^{th} kind of input of i^{th} decision-making unit in the investigation period t; Z_{it} is a set of external variables affecting and β_{jt} is the under-valuation coefficient of Z_{it}. Besides, v_{jit} denotes a random disturbance term and follows a normal distribution, u_{jit} is a management inefficient term, assumed to obey a semi-normal distribution.

After eliminating influences of external factors and random disturbance terms, all decision units are adjusted to the same external environment, and the adjusted input items become X_{jit}^{A}, see Equation (3).

$$X_{jit}^{A} = X_{jit} + \left[\max\left(f\left(Z_{it}; \hat{\beta}_{jt}\right)\right) - f\left(Z_{it}; \hat{\beta}_{jt}\right)\right] + \left[\max\left(v_{ijt}\right) - v_{ijt}\right] \quad (3)$$

where X_{jit} represents the input data of each decision unit before the adjustment; $\hat{\beta}_{jt}$ indicates the amount of input that each decision unit needs to adjust to realize the same external condition; v_{ijt} denotes the amount of input that each decision unit needs to adjust for the same random disturbance condition. In the third stage, estimating the GWUE again, using the adjusted inputs with the same external conditions and random disturbance as in the second stage.

3.1.2 The PSM-DID model

A PSM-DID model is the combination of propensity score matching and difference-in-difference method, accounting for both the sample selectivity bias and self-selection bias to address endogeneity issues. This model is frequently used for the quantitative evaluation of public policies and project implementation outcomes. Specifically, the water rights trading pilot implemented in 2014 is regarded as a quasi-natural experiment, enabling an effective analysis of net impacts of policy implementation across various provinces. The pilot areas were designated as the experimental group, while other provinces and regions serving as the control group. The construction of the model is presented as follows (Equation 4):

$$\mathrm{eff}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{treated}_{\mathrm{i}} * \mathrm{time}_{\mathrm{t}} + \alpha_2 \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \eta_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (4)$$

where i denotes the i^{th} province (city, autonomous region) and t represents the time; eff_{it} is the GWUE of grain production calculated by DEA method; $time_i$ represents the time dummy variable, where the value is 1 at t = 2014, otherwise the value is 0; $treated_i$ represents the dummy variable of the region, where the value equals 1 if the province is a pilot area of water rights trading; μ_i shows the regional fixed effect; η_t denotes the time-fixed effect; and ε_{it} is a random error term. α_0, α_1 and α_2 represent a fixed intercept term, the policy effect of water rights trading and the coefficient of the control variable, respectively.

3.1.3 The mediating effect model

Based on the above theoretical analysis, in order to verify the mediation effect of water rights trading mechanism, the mediating effect model is constructed by stepwise regression method as follows (Equations 5–7):

$$\mathrm{eff}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{treated}_{\mathrm{i}} \times \mathrm{time}_{\mathrm{t}} + \alpha_2 \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \eta_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (5)$$

$$\mathrm{M}_{\mathrm{it}} = \beta_0 + \beta_1 \mathrm{treated}_{\mathrm{i}} \times \mathrm{time}_{\mathrm{t}} + \beta_2 \mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}} + \eta_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (6)$$

$$\mathrm{eff}_{\mathrm{it}} = \gamma_0 + \gamma_1 \mathrm{treated}_{\mathrm{i}} \times \mathrm{time}_{\mathrm{t}} + \gamma_2 \mathrm{X}_{\mathrm{it}} + \gamma_3 \mathrm{M}_{\mathrm{it}} + \mu_{\mathrm{i}} + \eta_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (7)$$

where M_{it} represents the intermediary variable, selecting the technical improvement variable and the factor flow variable among industries; α_0, β_0, γ_0 represents the fixed intercept term in each type; $\alpha_1 \sim \alpha_2$, $\beta_1 \sim \beta_2$, $\gamma_1 \sim \gamma_3$ represent the regression coefficients in each category, respectively.

3.2 Data sources and variable selection

Subjected to data availability, the study samples were selected from 30 provinces in China (excluding Hong Kong, Macao, Taiwan, and Tibet). As the Ministry of Water Resources issued the Notice on Water Right Pilot Work in 2014, setting 2014 as the policy time point in the model constitutes a quasi-natural experiment. In order to observe changes before and after the policy implementation and to capture long-term policy effects, the time span is set from 2006 to 2020. The data for each variable primarily originated from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Rural Statistical Yearbook and China Water Resources Bulletin. For any missing data, the statistical yearbooks of each province were consulted.

3.2.1 Dependent variable

The input–output indicators of three-stage DEA model to measure the GWUE are displayed in Table 2. The load of chemical fertilizer pollution and solid waste are taken as the undesired output variables in grain production. The GWUE, considering undesired output, is corrected to avoid exaggerating or underestimated the impact of water rights trading on the efficiency of food production.

3.2.2 Independent variables

The core explanatory variable is $treated_i$*$time_i$, indicating whether the pilot water rights trading is carried out in the region. The pilot water rights trading is regarded as a quasi-natural experiment, where provinces with national and provincial pilot are regarded as treatment group, and non-pilot provinces belong to the control group. Specifically, seven provinces conducting the national water rights trade are Inner Mongolia, Jiangxi, Henan, Hubei, Guangdong, Gansu

TABLE 2 Description of input–output variables.

Variable	Indicator	Mean	S. E.[a]	Min	Max
Expected output	Grain output (10,000 t)	2014.483	1719.226	28.760	7615.780
Undesired Output-1	Load[b] of chemical fertilizer	3494.450	3631.659	77.682	15574.300
Undesired Output-2	Load[b] of solid waste	170.768	83.828	45.308	462.301
Labor input[c]	Employment in agricultural sector (1,000 people)	568.733	414.813	13.976	2054.688
Land input	Grain sown area (1,000 hm^2)	3787.917	3091.569	46.520	14438.380
Water input[c]	Agricultural water use (100 million m^3)	80.549	62.716	1.594	304.551
Machinery input[c]	Agricultural machinery use (10,000 kw)	2236.173	2169.848	40.059	9863.674
Fertilizer input[c]	Agricultural chemical fertilizer use (10,000 t)	127.968	105.517	2.777	538.312

[a]S. E. is standard error.
[b]The load is computed with the isomeric pollution load computing method.
[c]Input variables are all weighted by the ratio of regional grain sown area to the total crop sown area.

TABLE 3 Descriptive analysis of explanatory variables.

Variable	Variable interpretation	Mean	S. E.	Min	Max
Urbanization	Urban population/total population (%)	0.558	0.137	0.275	0.896
Industrial structure	The added value of the primary industry/GDP (%)	0.082	0.052	0.001	0.261
The proportion of grain production	Grain sown area/crop sown area (%)	0.661	0.139	0.355	0.971
Effective irrigation	Effective irrigated area/ cultivated land area (%)	0.429	0.175	0.166	1.234
Damage degree	Disaster-affected area/crop sown area (%)	0.198	0.150	0	0.696
Mechanization	Agricultural machinery input/land input (10 watts/ ha)	0.619	0.258	0.220	1.416
Tech-innovation	The number of utility model patents granted	9.059	1.631	3.807	12.914
Factor flow	Agricultural water use/ total water use (%)	5.483	8.223	0.198	54.651

and Ningxia; while 10 provinces conducting the provincial water rights trade are Xinjiang, Hebei, Shandong, Shanxi, Zhejiang, Shaanxi, Fujian, Liaoning, Jilin and Hunan.

The descriptive analysis of intermediary and control variables selected is presented in Table 3. Previous studies have demonstrated that agricultural production efficiency is influenced by the level of urbanization development, the regional economic development level and its industrial institutions (Li et al., 2022; Chang et al., 2023). The technical efficiency of grain production is associated with the proportion of regional grain production, the irrigation conditions, mechanization conditions and other factors (Zhang et al., 2021a, 2021b). Technological innovation and factor flow are selected as intermediary variables. Technological innovation is measured by the number of utility model patents. Compared with the total amount of patents granted as referenced in existing literature, the amount of utility model patents more accurately reflects the improvement of actual water use through technological innovation. The proportion of agricultural water consumption within the total water consumption is utilized to measure the inter-industry flow of factors.

4 Results and discussion

4.1 The estimation of the three-stage DEA model

4.1.1 Spatio distribution of the green water use efficiency of grain production

The GWUE of grain production before and after 2014 were calculated using *MatlabR2022a* software. Estimation results of the DEA model at both the first and third stage were demonstrated from a comparative perspective (Table 4). Column (1) and (2) displayed results from the first stage, while column (3) and (4) showed efficiency values from the third stage. Results of the SFA regression in the second stage can be found in the Appendix.

Generally, the mean efficiency value decreases from 0.7 at the third stage to 0.5 at the third stage, which proves the existence of influences posed by external factors and random error on efficiency. A more accurate green water use efficiency is obtained using the three-stage DEA model. For most provinces, the GWUE and ranks at the first stage keep accordance with those at the third stage, verifying the robustness of results. Exceptions are Chongqing and Shanghai, two municipalities under direct controls of central government. Reasons are that external factors in the two municipalities pose strong influences, resulting in the variance of efficiency values at the first and the third stage of DEA model. Cao et al. (2023) have also found that the regional economic development level has a significant impact on the GWUE. Besides, the function of grain production in the four municipalities, Beijing, Shanghai, Tianjin and Chongqing, is far from obtaining the outputs because agriculture is organized in different patterns and modernized agriculture takes a large share. In this light, more attention should be paid to the main grain production area of China, including 13 provinces, Heilongjiang, Henan, Shandong, Sichuan, Jiangsu, Hebei, Jilin, Anhui, Hunan, Hubei, Inner Mongolia, Jiangxi and Liaoning. The GWUE of these 13 provinces rank in the first half of the sampled 30 provinces. Therefore, a heterogeneity analysis is conducted in this study, concentrating on the policy effects of water rights trading in different grain production functional areas.

Besides, the GWUEs of provinces in the northern part of China are averagely ranked higher than those in the southern part, indicating that GWUEs have regional differences. On the premise of considering environmental factors, there are 15 provinces obtaining efficiency values lower than the national average level and with great water saving potential, including Guizhou, Yunnan, Shanxi, Guangxi, Shaanxi, Guangdong, Gansu etc. Most of these provinces are located in the southern part of China with better water endowment. A lack of perceptions of water scarcity, weak management of water resources

TABLE 4 The GWUE values measured by three-stage DEA model.

Province	First-stage[a] before		First-stage[b] after		Third-stage before		Third-stage[b] after	
	Efficiency	Rank	Efficiency	Rank	Efficiency	Rank	Efficiency	Rank
Inner Mongolia	1.233	1	1.258	1	1.233	1	1.258	1
Heilongjiang	1.194	2	1.193	2	1.194	2	1.193	2
Jilin	1.136	3	1.083	5	1.106	4	1.074	5
Chongqing	1.117	4	1.068	7	0.558	15	0.499	14
Henan	1.116	5	1.121	3	1.116	3	1.118	3
Shanghai	1.113	6	1.092	4	0.143	28	0.115	28
Shandong	1.080	7	1.082	6	1.076	5	1.078	4
Sichuan	1.057	8	1.010	12	1.033	7	0.638	10
Jiangsu	1.043	9	1.018	9	1.037	6	1.014	6
Xinjiang	1.035	10	1.045	8	0.64	10	0.667	9
Hunan	1.025	11	1.010	11	1.023	8	1.003	7
Jiangxi	0.887	12	1.014	10	0.719	9	0.550	11
Hubei	0.819	13	0.590	16	0.628	11	0.543	15
Guizhou	0.713	14	0.823	13	0.441	16	0.411	16
Liaoning	0.613	15	0.701	14	0.625	12	0.610	12
Hebei	0.588	16	0.640	15	0.608	13	0.644	13
Anhui	0.584	17	0.562	17	0.583	14	0.562	8
Yunnan	0.447	18	0.446	18	0.417	17	0.40 2	17
Zhejiang	0.442	19	0.377	24	0.34 8	23	0.281	23
Guangxi	0.417	20	0.347	27	0.391	19	0.327	20
Guangdong	0.415	21	0.372	25	0.374	21	0.317	21
Shanxi	0.387	22	0.438	19	0.391	19	0.327	20
Shaanxi	0.384	23	0.351	26	0.377	20	0.333	19
Gansu	0.374	24	0.395	22	0.351	22	0.358	22
Fujian	0.367	25	0.313	28	0.300	24	0.236	24
Ningxia	0.355	26	0.397	21	0.239	25	0.233	25
Beijing	0.332	27	0.276	29	0.128	29	0.054	30
Qinghai	0.326	28	0.398	20	0.110	30	0.103	29
Tianjin	0.306	29	0.392	23	0.156	26	0.183	26
Hainan	0.274	30	0.264	30	0.156	27	0.128	27
Mean	0.706	-	0.702	-	0.583	-	0.545	-

[a]Column (1) and (3) show efficiency and ranks before the establishment of the water rights market.
[b]Column (2) and (4) show those after.

and less promotion of water-saving measurements may be the reason. There are 8 provinces obtaining a GWUE of grain production greater than 1, including Inner Mongolia, Heilongjiang, Henan, Jilin, Shandong, Jiangsu, Sichuan and Hunan.

Results are further summed up from a comparing perspective of the changing range and ranking of the GWUE before and after water rights trading implementation (Table 5). Generally, water rights trading pilot areas have a better performance in improving the GWUE of grain production, which preliminary confirms the research hypothesis (H_1) of this study. The efficiency values of 13 provinces are significantly improved after the implementation of water rights trading, including 5 national pilot areas, 5 provincial pilot areas and 3 non-pilot areas. Although efficiency values of national and provincial pilot areas decreased, the positive effect of water rights trading on efficiency can still be revealed. There are 3 of the 7 national-level pilot provinces still increase their efficiency after water rights trading market establishment, and 4 of the 10 provincial-level pilot areas likewise.

4.1.2 Dynamic analysis of the green water use efficiency of grain production using Malmquist index

The Malmquist index model is used to further capture the dynamic changes of GWUEs (Figure 1), decomposed into technical efficiency and technological progress, among which the technical efficiency can be further decomposed into net technical efficiency and

TABLE 5 Changes of efficiency values after implementing water rights trading.

Pilot type	The first stage		The third-stage	
	Efficiency improving provinces	Proportion%	Efficiency improving provinces	Proportion%
National	Inner Mongolia, Jiangxi, Henan, Gansu, Ningxia	71.43	Inner Mongolia, Henan and Gansu provinces	42.86
Provincial	Hebei, Shanxi, Liaoning, Shandong, Xinjiang	50.00	Hebei, Shanxi, Shandong and Xinjiang	40.00
Non-pilot	Tianjin, Guizhou and Qinghai	23.08	Tianjin, Heilongjiang	15.38

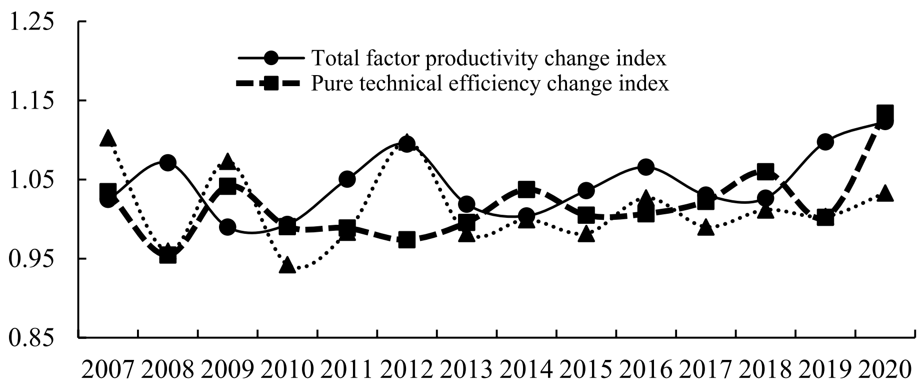

FIGURE 1
The changing trend of the mean values of Malmquist productivity indexes.

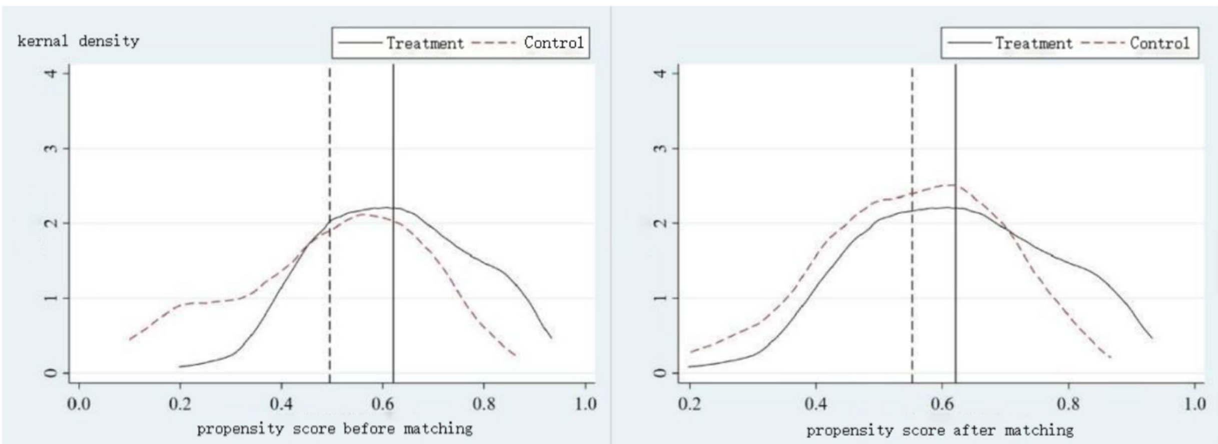

FIGURE 2
The nuclear density before and after propensity score matching.

scale efficiency. It is found that the GWUE of China's grain production is on the rise, with an average annual growth rate of 5.02%. Indicators fluctuated greatly before the implementation of water rights trading and became relatively flat after 2014. It is worth noting that the net technical efficiency change index has always been greater than 1 since 2014 and showed an overall upward trend. The change of net technical efficiency is mainly related to the water management level, referring to the implementation of comprehensive agricultural water price reform in China and the orderly establishment of water rights trading mechanism since 2014.

4.2 Policy effects of water rights trading

4.2.1 Propensity score matching results and parallel trend test

Considering the matching effect, the pair of two-caliper nearest neighbor matching method is selected. A year-by-year matching method was adopted to find a matched control group for the treatment group in each year in 2014–2020. The nuclear density before and after matching is shown in Figure 2. It is easy to conclude that the matching effect is acceptable because the propensity score of both treatment group and control group have improved in the values and distribution after matching. The time trend chart of the treatment group and the control group after matching the propensity score is presented in Figure 3. Basically, the efficiency trend of both treatment group and control group changed before the start of the water rights trading pilot. The policy dynamic effect diagram (Figure 4) passes the parallel trend test. To sum up, the matched data basically meet the parallel trend requirements.

4.2.2 Benchmark regression results

The hypothesis H_1 has been verified that the GWUE of grain production has significantly improved in the pilot provinces of water rights trading (Table 6). Results are still robust after adding control variables and with the simultaneous fixation of time and region. This result is in line with the view of scholars that the implementation of water rights trading mechanism can promote the efficiency of water use and agricultural water resources allocation (Wang et al., 2023; Gao et al., 2024). This reveals that policies of water right registration, water right trading and system construction implemented have significant influences on improving the quality and efficiency of grain production. Reasons may be that it increases the welfare of water rights trading participants through market tools, rationally distribution of scarce water resources, and improvements of water use efficiency (Shi et al., 2022).

The implementation of water rights trading can also help to realize the goal of the 'dual control' policy in China, which requires strict control over the total amount and intensity of water use. On one hand, water rights trading system breaks down the total water consumption to regional, industrial and user levels. This lays a foundation for the control of total water consumption. On the other hand, the water use intensity of the northern part in China can be alleviated through the balance of the uneven distribution of water resources among regions. The Chinese government has invested in a 'South-to-North Water Diversion Project' to alleviate the water shortage problem in the north through water transfer across river basins. However, the water-receiving areas often prefer local water sources, such as groundwater, due to the high cost of transferring water from outside. Water trading rights system provides a market-based tool to solve the problem, promoting the same quality and price for different water sources. Therefore, the optimal allocation and conservation of water resources are achieved under the joint effects of water use policies in China.

In addition, the GWUE of grain production in model (6) is positively affected by the industrial structure, grain production area proportion and effective irrigation degree. This result is consistent with Pan et al. (2023). Good irrigation conditions in major grain-producing areas, investment in water-saving and conservancy infrastructure are conducive to the improvement of agricultural water use efficiency. The coefficient of urbanization and mechanization degree is significantly and negatively connected with the GWUE of grain production, indicating that there is redundancy in grain irrigation water input. Literature has also found a certain coupling relationship between agricultural modernization and urbanization (Jiang and Yan, 2021). The negative coefficient of mechanization degree may be due to the substitution relationship between agricultural mechanization and water saving irrigation. For example, mechanized operations such as land leveling and deep plough enhance the capacity of soil water storage and water retention, and thus increasing the water demand of soil in the current season.

4.2.3 Robustness tests

Results of robustness check are shown in Table 7. In model (1) and (2), results are significant after excluding the provincial water right pilots in the treatment group, indicating that the pilot work of water

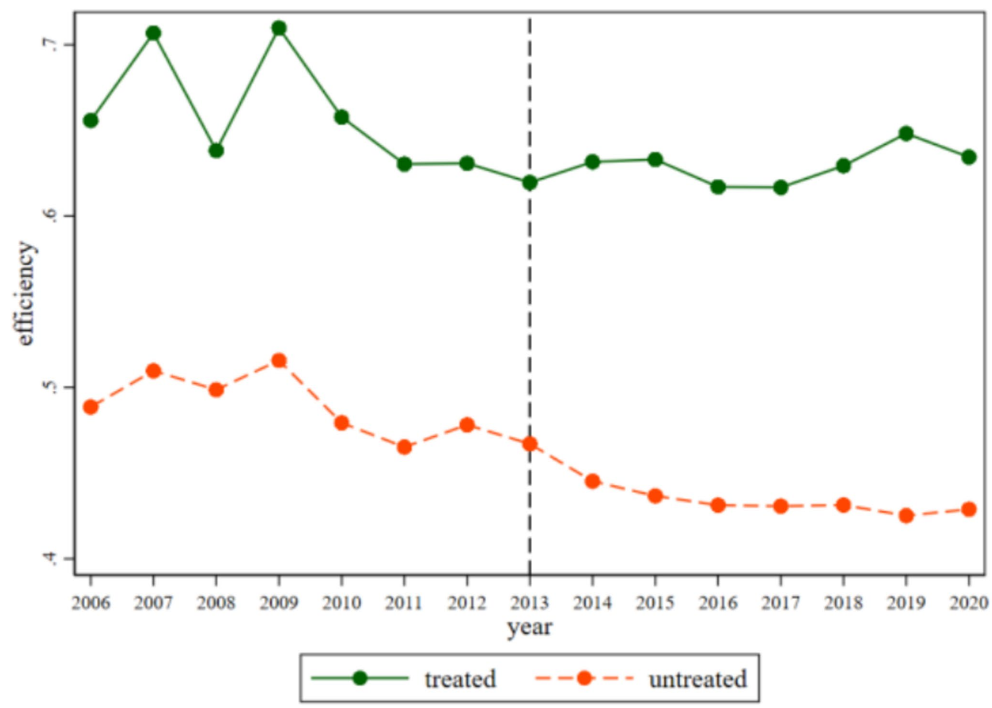

FIGURE 3
Time trends of efficiency values by group.

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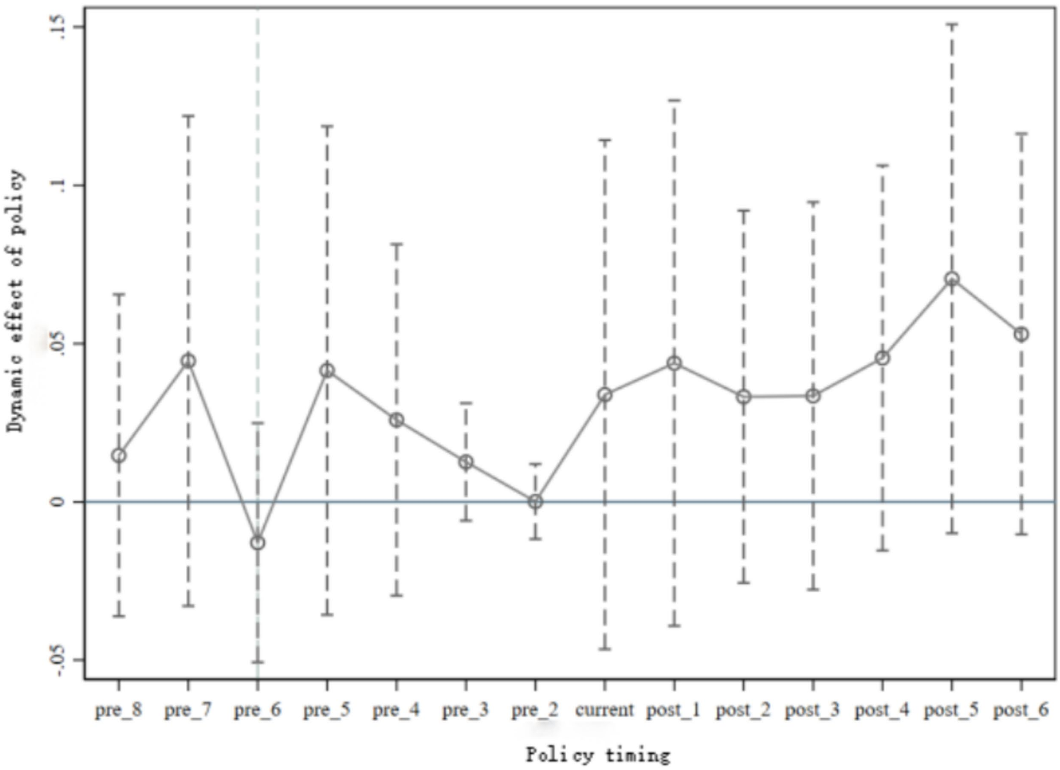

FIGURE 4
Confidence interval plot. Pre_ * and post_ * is the year before and after the policy implementation, respectively; the short-dotted line shows the confidence interval.

TABLE 6 Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)	(6)
Water rights trading	0.088 (0.079)	0.088*** (0.018)	0.088** (0.037)	0.069 (0.067)	0.069*** (0.020)	0.069** (0.033)
Urbanization				−0.646** (0.290)	−0.646*** (0.065)	−0.646*** (0.110)
Industrial structure				1.371*** (0.475)	1.371*** (0.293)	1.371*** (0.231)
Proportion of grain production				1.483*** (0.275)	1.483*** (0.048)	1.483*** (0.081)
Effective irrigation				0.431** (0.168)	0.431*** (0.103)	0.431*** (0.084)
Damage degree				−0.237 (0.270)	−0.237** (0.092)	−0.237** (0.105)
Mechanization				−0.356* (0.182)	−0.356*** (0.043)	−0.356*** (0.059)
Constants	0.542*** (0.069)	0.542*** (0.017)	0.542*** (0.020)	−0.104 (0.244)	−0.104 (0.075)	−0.104 (0.088)
Time fixed effect	No	Yes	Yes	No	Yes	Yes
Regional fixed effect	Yes	No	Yes	Yes	No	Yes
R^2	0.012	0.012	0.012	0.429	0.429	0.429
Adjusted R^2	0.010	0.010	0.010	0.420	0.420	0.420

***, ** and * represent significance levels of 1, 5 and 10%, respectively, with standard errors in parentheses.

rights trading policy has significantly improved the GWUE of grain production. Results are still stable in the quasi-natural experiment of national pilots. However, estimates in Model (3) and (4) are not significant with the provincial water rights trading pilots. The reason may be that the policy implementation practices in each pilot province has large disparity. For example, the implementation mode and timeline are not unified. So the effects of the provincial water rights trading are hardly to be captured. Generally, it can be inferred that the effect of national pilots trading on the GWUE is more significant than that of provincial pilots. Some scholars have also reached similar findings that the effect of water rights trading is more obvious in national pilots (Gao et al., 2024). Possible reasona may be that national pilots have received more attention and support in policy implementation, having established guidance and contact relationship with the Ministry of

TABLE 7 Policy effects of water rights trading in national and provincial pilots.

	Provincial pilots excluded from the treatment group		Provincial pilots as the treatment group	
	(1)	(2)	(3)	(4)
Water rights trading	0.118** (0.058)	0.080* (0.043)	0.067 (0.056)	0.069 (0.047)
Controlled variables	No	Yes	No	Yes
Constant	0.507*** (0.023)	−0.394*** (0.100)	0.558*** (0.018)	−0.136 (0.089)
Time fixed effect	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes
Sample size	300	300	450	450
R^2	0.014	0.612	0.003	0.425
Adjusted R^2	0.010	0.603	0.001	0.416

***, ** and * represent significance levels of 1, 5 and 10%, respectively, with standard errors in parentheses.

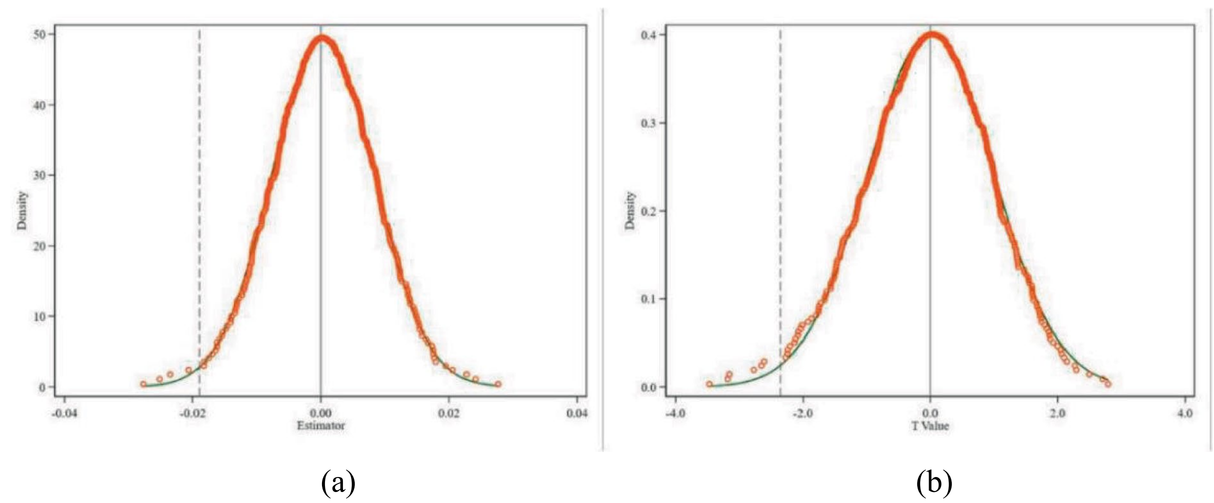

FIGURE 5
Distribution of estimators and T-values in the placebo test. **(A)** The captures the distribution of estimators, $\hat{\beta}^{random}$; and **(B)** the depicts the distribution of T-values of the placebo test.

Water Resources. Also, most national pilot projects have initiated water rights trading attempts in the earlier period and have richer experience in this exploration.

A placebo test is used to further test the effect of unobservable features (Figure 5). Randomly generating a list of pilot areas for water rights trading, creating a false estimate $\hat{\beta}^{random}$. This process is repeated 500 times to produce 500 false $\hat{\beta}^{random}$. The distribution of $\hat{\beta}^{random}$ is depicted (Figure 5A) and follows a normal distribution with only four sampling coefficients located to the right of the benchmark regression coefficient. The distribution of t-values is depicted in Figure 5B and only six t-values locate to the right of the benchmark regression t-values. In conclusion, the randomly generated false estimates were not significant, passing the placebo test.

4.3 Mediating effects of tech-innovation and factor flow

The estimated results for the mediating effects model are shown in Table 8. The coefficient of technological innovation is significantly positive in model (1) and (2), indicating that the implementation of water right trading has a significant positive promotion effect on tech-innovation, which is in line with the finding of Fang and Zhang (2020). After joining the tech-innovation intermediary variable, the positive relationship between water rights trading system and the GWUE is no longer significant, implying that tech-innovation can work as a mediator (model 5 and 6). The hypothesis H_2 is verified that the water rights trading mechanism promotes the GWUE of grain production through tech-innovation. According to the theory of induced agricultural technology innovation, water rights trading changes the relative price of input factors in agricultural production, thus inducing the innovation and adoption of water-saving technology. Mu et al. (2022) have also found that promoting technological innovation is one of the paths for water right trading to play a water-saving effect.

Results of model (3) and (4) prove that water rights trading can promote the flow of water resource factor. The existing researches have fully demonstrated that the factor flow can promote the efficiency of water resources utilization (Fang and Zhang, 2020; Zhang et al., 2021a, 2021b). But based on the strict three-step method of mediation effect model (Table 8, model 7 and 8), the coefficient of factor flow

TABLE 8 Results of intermediate effect model.

	Tech-innovation	Tech-innovation	Factor flow	Factor flow	The GWUE of grain production			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water rights trading	1.253*** (0.144)	0.736*** (0.116)	0.047*** (0.014)	0.043*** (0.008)	0.061 (0.040)	0.007 (0.033)	0.033 (0.034)	0.074** (0.033)
Tech-innovation					0.022** (0.011)	0.084*** (0.009)		
Factor flow							1.166*** (0.077)	−0.116 (0.152)
Controlled	No	Yes	No	Yes	No	Yes	No	Yes
Constant	8.727*** (0.090)	5.609*** (0.506)	0.388*** (0.009)	−0.117*** (0.041)	0.353*** (0.097)	−0.575*** (0.090)	0.08 9*** (0.029)	−0.117 (0.092)
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.115	0.519	0.019	0.751	0.020	0.499	0.253	0.429
Adjusted R^2	0.113	0.511	0.017	0.747	0.016	0.490	0.250	0.419

***, ** and * represent significance levels of 1, 5 and 10%, respectively, with standard errors in parentheses.

TABLE 9 Results of heterogeneity analysis.

Variable	The GWUE of grain production			
	(1)	(2)	(3)	(4)
Water rights trading	0.077** (0.038)	0.087*** (0.032)	0.076** (0.035)	0.074** (0.032)
Per capita water resources endowment	−0.246*** (0.064)	−0.03 1 (0.068)		
Water rights trading * per capita water resources endowment	0.160 (0.212)	0.525** (0.239)		
The proportion of surface water			−0.261*** (0.097)	−0.289*** (0.103)
Water rights trading * the proportion of surface water			−0.770*** (0.207)	−0.108 (0.205)
Controlled variable	No	Yes	No	Yes
Constant	0.597*** (0.026)	−0.042 (0.097)	0.766*** (0.091)	0.341** (0.170)
Time fixed effect	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes
R^2	0.042	0.432	0.048	0.428
Adjusted R^2	0.049	0.443	0.054	0.439

***, ** and * represent significance levels of 1, 5 and 10% respectively, with standard error in parentheses.

intermediary variable is not significant when control variables added. It indicates that the path of water rights trading mechanism to promote GWUE through factor flow is not robust. Reasons may be that the mediating effect model uses water flow between industries as proxy variables due to data availability, namely the index of agricultural water consumption proportion, which should have been the water consumption proportion of grain production.

4.4 Heterogeneity analysis

Differentiated factors such as resource endowment, surface water resource proportion and the proportion of grain production area are necessary to be considered when evaluating water-saving effect of water right trading, since traces have been found in the descriptive analysis of the GWUE of grain production. The heterogeneity analysis can be realized by a triple difference model (DDD) with results shown in Table 9.

(1) *Per capita water resources endowment.* An interaction term of per capita water resources and the core explanatory variable $treated_i$*$time_i$ is added into the benchmark regression model to estimate heterogeneous impacts of water resource endowment. Results (Table 9, model 1 and 2) show that the coefficient of interaction term increased to 0.525 and is significant at the level of 1%, indicating that the influence of water rights trading on the

GWUE is enforced in areas with high per capita water endowment. Reasons may be that areas with higher per capita water endowment have more tradable water rights and are more incentive to save water. The increase of income brought by water rights trading poses a stronger shock for farmer's water protection behavior and for the region to improve water resources utilization efficiency. Other studies also found that the water-saving effect of water rights trading was more significant in areas with high water demand and more tradable water resources. For example, the previous study of Zhang et al. (2021a, 2021b) found that areas with better water resources endowment are often easier to achieve agricultural water saving and improve the water efficiency of agricultural production. In addition, the 'South-to-North Water Diversion Project' balances the uneven distribution of water resources through engineering technology, while the water rights trading system provides market-based tools as a strong supplement. As discussed before, the GWUEs of provinces in the northern part of China are averagely ranked higher than those in the southern part. Market mechanism may play a better role in water allocation and utilization in the southern part.

(2) *The structure of water resource endowment*. The total flow rate of water resources is composed of surface and ground water resources. Due to regional differences in water resource endowment, surface and ground water resources for grain production have also exhibited great discrepancy. Therefore, the proportion of surface water resources was selected to measure the structure of water resources, and its interaction term with the core explanatory variable $treated_i$*$time_i$ was added into the benchmark regression model. As shown in the results of model (3) and model (4) in Table 9, the coefficient of interaction term turns insignificant after adding control variables. The improvement effect of water right trading on GWUE of grain production does not show significant differences in areas with abundant surface water resource.

(3) *Layout of grain production*. As discussed, the proportion of grain production plays an impact on the GWUE of the decision-making unit. Therefore, it is necessary to estimate the regression model according to the food production layout to explore the differentiated effects of food functional regions. Results show that (Table 10), the policy effect of water rights trading in the main grain-selling area is significant. Reasons may be that the implementation of water rights trading in these areas can more effectively stimulate the innovation and application of water-saving technology and improve the efficiency of water resources utilization. In addition, the coefficient of water rights trading in the balanced area is significantly negative, where there may exist biased sampling. The national or provincial pilots are mainly concentrated in the main producing areas and main sales areas. Also, large variance of the GWUE value of grain production exists in the balanced area. So, the negative coefficient of water rights trading does not necessarily mean a negative effect of water rights trading in the balanced region. Conversely, the validity of this conclusion should be discussed after the establishment of more pilots in balanced areas or using county data, which is also a limitation of this study.

5 Conclusion and ways forward

In 2014, China has launched water rights trading pilot work in 7 provinces, which signifies a shift of water resource management from government-lead to a co-dominance of the government and market forces in China. Treating this as a quasi-natural experiment, this study empirically analyzes the role of China's water rights trading policy played in promoting the GWUE of grain production, using a three-stage DEA method and a PSM-DID model.

To conclude, the green water use efficiency of grain production has been significantly improved after the implementation of China's water rights trading policy. The policy effect appears more pronounced and robust in national water rights trading pilots than in provincial ones. Heterogeneity is also detected from the perspective of water resource endowment. The efficiency improvement effect is more prominent in areas with higher per capita water endowment or in China's main grain-selling areas. Besides, transactions of water rights help to foster the technological innovation and thus promoting green and efficient water use.

These findings reveal benefits of utilizing market mechanisms to improve the water use efficiency while considering environmental constraints, and thus provide inspiration for fostering the sustainable grain production in developing countries facing resource scarcity. Both the engineering and market-based measurements are necessary to control the total consumption of water in agricultural production and to balance the water use demand across regions, industries and users. Different measurements may come into play under disparate

TABLE 10 Heterogeneous analysis in different grain production areas.

Variable	Main producing area		Main sales area		Balanced area	
	(1)	(2)	(3)	(4)	(5)	(6)
Water rights trading	−0.031 (0.041)	0.006 (0.051)	0.085*** (0.014)	0.079*** (0.013)	0.022 (0.033)	−0.074** (0.029)
Controlled variable	Yes	Yes	Yes	Yes	Yes	Yes
Constants	0.906*** (0.022)	0.623*** (0.161)	0.193*** (0.011)	0.594*** (0.116)	0.378*** (0.014)	0.180* (0.095)
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Sample size	195	195	105	105	150	150
R^2	0.003	0.129	0.118	0.524	0.003	0.598
Adjusted R^2	−0.002	0.096	0.109	0.490	−0.003	0.578

***, ** and * represent significance levels of 1, 5 and 10% respectively, with standard error in parentheses.

contexts. According to the characteristics of resource endowment, each region can explore the water right confirmation and transaction modes adapting to local conditions. Also, to motivate the innovation and adoption of 'green' technology, such as water-saving technologies, is also indispensable, since it exhibits a mediating effect.

Moreover, references are given for regions planning to formulating resource conservation and environmentally friendly policies, or aiming to carry out water management reforms. It is suggested initially to accelerate the confirmation of water rights and legal protection and to establish a price system reflecting the scarcity of water resources and ecological costs. For example, the ownership of water rights is still ambiguous in some area of China, and the trading prices of water rights are generally low, which is difficult to reflect the scarcity of water resources and weakens the regulatory role of the market. Secondly, the incentive mechanism for water rights trading, particularly for irrigation water users, should be established and improved. The volume of water transaction in China is still weak with an unstable structure of water rights transaction. For instance, water management units could participate in the repurchase of water rights from irrigation water users, which can further facilitate the factor flow. Thirdly, it is suggested to strengthen the technical support and data sharing in the management of water resources. Enhancing the data sharing capacity of the trading platform can promote the refined management and transaction transparency.

The future study can be more concentrated on policy effects within the main production areas with better county-level panel data, because the water consumption of main production areas takes a large proportion. Also, more efforts can be put in the exploration of mechanism through which water rights trading system play a part in the efficiency promotion.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NY: Software, Data curation, Visualization, Funding acquisition, Conceptualization, Resources, Writing – original draft, Investigation, Project administration, Writing – review & editing, Validation, Formal analysis, Methodology, Supervision. SL: Methodology, Visualization, Data curation, Writing – original draft, Software. YX: Visualization, Investigation, Writing – review & editing, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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Appendix

TABLE A1 Results of SFA model in the second stage.

External variable	Labor slack	Land slack	Water slack	Agricultural machinery slack	Fertilizer slack
Annual precipitation	19.310 (13.097)	−17.197 (21.835)	−0.046 (0.883)	56.536 (53.954)	1.316 (1.526)
The proportion of grain production	35.445** (14.111)	6.018 (21.294)	1.328 (0.858)	44.935 (52.450)	−0.275 (2.036)
Value-added of the primary industry	−15.175* (8.529)	16.321 (14.237)	−1.901*** (0.564)	−15.510 (33.692)	2.900*** (1.025)
Constant	−62.510** (25.594)	−87.452*** (30.886)	−3.603** (1.548)	−176.132** (72.552)	-6.976*** (2.381)
σ^2	127621.010*** (1.000)	277482.800*** (1.001)	545.329*** (143.268)	1786 313.800*** (1.001)	1807.643*** (435.289)
γ	0.937*** (0.004)	0.900*** (0.007)	0.935*** (0.018)	0. 917*** (0.006)	0.928*** (0.018)
LR	0.720×10^3	0.561×10^3	$0. 800 \times 10^3$	0.628×10^3	0.781×10^3

***, **, and * represent the significance levels of 1%, 5% and 10%, respectively.