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Article — Published Version

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Water Policy

Provided in Cooperation with:

Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

Suggested Citation: Fang, Lan; Fu, Yong; Chen, Shaojian; Mao, Hui (2021) : Can water rights trading pilot policy ensure food security in China? Based on the difference-in-differences method, *Water Policy*, ISSN 1996-9759, IWA Publishing, London, Vol. 23, Iss. 6, pp. 1415-1434, <https://doi.org/10.2166/wp.2021.045>

This Version is available at:

<https://hdl.handle.net/10419/248718>

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Can water rights trading pilot policy ensure food security in China? Based on the difference-in-differences method

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ABSTRACT

Ensuring food security in China is the primary task in solving the problems of 'agriculture, countryside, and farmers'. Based on Chinese provincial panel data from 2009 to 2018, this paper evaluates the impact of a water rights trading pilot policy (WRTPP) on food security and examines its underlying mechanism. To overcome the estimation bias existing in previous studies, we use the difference-in-differences method, which can separate time effects from policy treatment effects and is an effective tool to compare the effect before and after policy implementation. We, therefore, use this method to evaluate the net effect of the WRTPP on food security. It is found that the WRTPP can help ensure food security. This effect reaches its maximum in the fourth year after the policy's implementation. It is further found that the WRTPP can improve the adoption of agricultural water-saving irrigation technology to increase the grain yield. Our conclusions complement existing evidence on the factors influencing food security. From the perspective of improving farmers' water-saving irrigation technology, we confirm that the mechanism of the water rights trading pilot policy helps ensure food security.

Key words: Difference-in-differences, Food security, Water rights trading pilot policy

HIGHLIGHTS

- Water rights trading pilot policy can help guarantee food security.
- The policy help guarantee food security by improving the adoption of water-saving irrigation technology.
- This effect reaches its maximum in the fourth year after the implementation of the policy.
- The policy will have a long-term effect on helping guaranteeing food security.
- The research does not violate the parallel trend assumption of the difference-in-differences method.

1. INTRODUCTION

Food security is an important foundation for China's economic development and social stability, as well as a basis for stabilizing global food patterns (He *et al.*, 2019; Liu *et al.*, 2020). According to the Food and Agriculture Organization of the United Nations (FAO), food security is defined as 'the availability at all times of material and economic access to adequate, safe and nutritious food to meet their dietary needs and food choices for an active and healthy life'. To ensure food security, the United Nations' Sustainable Development Goals (SDGs) stated aims to eliminate global hunger and achieve food security. The Chinese government attaches great

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importance to maintaining and boosting its domestic food security. Its ‘Central Document No. 1’ of the Communist Party of China (CPC) Central Committee provided guidance on food security from 2012 to 2020. More importantly, the document ‘China’s food security’ in 2019 proposed the implementation of an in-depth national food security strategy. However, food security in China has faced a series of problems such as demand increases (Zhang *et al.*, 2016; Liu *et al.*, 2019), arable land reductions or degradation (He *et al.*, 2019), and water shortages (Dinar *et al.*, 2019; Lan *et al.*, 2021).

Because water is the most basic input element in the food production system, effective management and distribution of water resources are essential to ensure food security in various regions (Li *et al.*, 2010).¹ As a large agricultural country, China’s agricultural water consumption accounts for about 62% of total water used.² Popularizing water-saving irrigation technology and improving agricultural water use efficiency are key steps to promote the intensive use of water resources, save agricultural water, and ensure the stable development of agriculture (Fei *et al.*, 2021). From 2015 to 2020, the government’s ‘Central Document No. 1’ put forward the implementation of national agricultural water-saving actions, acceleration of completion of water-saving renovation facilities in large- and medium-sized irrigated areas, and increase of agricultural water-saving efforts. Among them, the ‘Central Document No. 1’ for 2016, 2017, and 2019, respectively, explicitly pointed out that reform of comprehensive agricultural water pricing should be steadily promoted, agricultural water pricing should be reasonably determined, the mechanism of water-saving incentives and targeted subsidies should be established, and agricultural water use efficiency should be improved. The Ministry of Water Resources of PRC selected Henan, Ningxia, Jiangxi, Hubei, Inner Mongolia, Gansu, and Guangdong as pilot provinces (municipalities) in 2014 and began to implement a water rights trading pilot policy (WRTPP) in these provinces (municipalities).³ This policy uses the economic benefits from water rights trading⁴ as the main incentive for farmers to reduce their water consumption, establishing a water rights trading system, a water price system, and a water-saving incentive system as measures to promote the transformation of agricultural water use into a conservation-oriented way (Bigelow & Zhang, 2018).

Existing studies have shown that water rights trading can promote water redistribution (Wang, 2012). It can also improve the economic efficiency of agricultural irrigation water and help guarantee food security in countries with water shortage (Gohar & Ward, 2010). However, some studies showed that due to the high implementation

¹ China is facing a serious water shortage, with per capita water supply accounting for only a quarter of the global average. The shortage of agricultural water is a key constraint on agricultural production and food security (Wang *et al.*, 2015).

² According to the National Bureau of Statistics, the total national water consumption is 602.12 billion cubic meters, of which agricultural water accounted for 368.23 billion cubic meters in 2019; see <https://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0C03&sj=2020>.

³ Different measures to promote agricultural water saving were enacted in these pilot provinces (municipalities) in order to implement the water control policy of ‘water saving priority and space balance’. Specifically, Jiangxi and Henan were proposed for implementing tax incentives for water saving. The two provinces encourage the adoption of water-saving irrigation technology by means of direct investment, investment subsidies, and operation subsidies. Also, they encourage financial institutions to give priority support to water-saving projects that meet loan conditions. Hubei, Inner Mongolia Autonomous Region, and Ningxia Hui Autonomous Region have established precise subsidies and water-saving incentive mechanisms to reward scale operators, farmers’ water cooperation organizations, and farmers’ water-saving measures adoption and adjust their planting structures to save water according to the amount of water saving, so as to spur farmers’ enthusiasm for water-saving. Gansu has put forward measures such as improving the water-saving system, raising water-saving subsidy standards, and implementing water-saving equipment subsidies to promote the development of water-saving agriculture in the province. On the basis of improving the water pricing mechanism, Guangdong has mobilized farmers’ enthusiasm for water saving through various forms, such as cash return, water right repurchase, awards and subsidies for the purchase of water-saving facilities, and preferential use of water.

⁴ In order to ensure the smooth implementation of water right transactions, China’s water right trading service platform is set to provide farmers with information on water right transactions, which will reduce transaction costs and promotes water right transactions (Moore, 2015). Furthermore, water rights trading can not only effectively alleviate water conflicts but also significantly improve the economic benefits of farmers (Gohar & Ward, 2010), which encourages farmers’ trading behavior through economic incentives.

cost, farmers' profits from water rights transactions are limited (Sun *et al.*, 2016). In addition, higher water rights trading prices may cause farmers to switch to higher-value cash crops (Danso *et al.*, 2021). Although this can increase farmers' incomes, it has a negative impact on helping ensure food security. Thus, the question of how the WRTTP affects food security remains open, along with the question of whether reducing water use in agriculture will have a negative impact on ensuring food security. Therefore, it is important to evaluate how the WRTTP can improve agricultural water-saving irrigation technology and help ensure food security.

The WRTTP mainly affects China's aim to ensure food security in the following ways. First, by raising the water price and establishing water-saving incentive mechanisms, the policy encourages farmers to improve the irrigation system and replace the traditional irrigation method with effective water-saving irrigation technology, which can help ensure sufficient water supply for the cultivating grains and increasing grain output (Yoo *et al.*, 2013; Deng *et al.*, 2020). Second, the WRTTP, which formulates effective agricultural water allocation guidelines and promotes optimal allocation of water resources, can improve agricultural water use efficiency to help guarantee food security (Misra, 2014; Wang *et al.*, 2017).⁵ Third, the WRTTP adjusts agricultural irrigation water prices, which raises the cost of using agricultural water and increases the risks of planting cash crops. In order to reduce costs and avoid risks, farmers would then tend to plant fewer high-water-consuming crops and plant more food crops with low water consumption (Berbel & Gómez-Limón, 2000; Doppler *et al.*, 2002), which can increase grain yield.

For this reason, this research attempts to determine whether the WRTTP will have a positive impact on helping ensure food security. If so, will food security be ensured by improving agricultural water-saving irrigation technology? Based on the data of 29 provinces (municipalities) in China from 2009 to 2018, this study uses a difference-in-differences (DID) model to examine the effects of WRTTP on helping ensure food security, which is measured by total grain yield, grain yield per area, and grain yield per capita. The empirical results show that: firstly, compared with the non-pilot provinces (municipalities), the WRTTP is conducive to helping ensure food security in the pilot provinces (municipalities). Specifically, the pilot policy has improved the total grain yield, grain yield per unit area, and grain yield per capita in the pilot provinces (municipalities). It has significantly increased the total grain yield and yield per unit area of rice, wheat, and corn. Secondly, after discussing the mechanism, it is found that the WRTTP can encourage farmers to adopt agricultural water-saving irrigation technology, which can improve irrigation water efficiency and increase the total grain yield and grain yield per unit area. Finally, further analysis shows that the WRTTP has a dynamic effect on the promotion of total grain yield and grain yield per unit area. This positive effect begins to increase after the third year of policy implementation, and reaches the maximum in the fourth year of policy implementation. Therefore, the WRTTP will help ensure food security for a long time.

This paper mainly has the following three important contributions. Firstly, it confirms the promoting effect of the WRTTP on grain yield, thus complementing the existing theoretical basis for studies on the influencing factors of helping ensure food security (Abebaw *et al.*, 2020; Kansiime *et al.*, 2021). Currently, in the relevant literature on the relationship between water rights policies and ensuring food security, more attention is paid to water price reform (Aidam, 2015), water rights trading (Xu *et al.*, 2020), or other single systems on food production. Little attention is paid to the impact of the WRTTP on helping ensure food security from an overarching perspective. Secondly, from the perspective of agricultural water-saving irrigation technology, the paper studies the influence mechanism of the policy on food security. The findings indicate that facing increased water costs, farmers will

⁵ Water shortages are a major challenge to the world's food production system (Castillo *et al.*, 2021). Improving agricultural water use efficiency is the key to easing the conflict between water shortages and food security, and can increase food production (Hanjra & Qureshi, 2010).

actively adopt water-saving irrigation techniques to increase grain yields. The evidence can not only provide a comprehensive analysis of how the policy affects food yields but also help to clarify the key role of water-saving irrigation technology in contributing to helping ensure food security. Thirdly, we use the DID method to evaluate the net effect of the policy on food security. We took the provinces (municipalities) implementing the policy as the experimental group to construct a double difference at the regional and temporal levels, which overcame the estimation bias existing in previous studies.

2. LITERATURE REVIEW AND THEORETICAL ANALYSIS

2.1. Literature review

Some prior studies have focused on the impact of water rights reform on food production. Optimizing the allocation of irrigation water resources through water rights reform has been found to be an effective way to improve grain production efficiency and realize food security (Li & Guo, 2014). Existing studies have focused on the positive impact of water rights on food production (Gohar & Ward, 2010). The study found that confirming water rights can reduce the competition for water and ensure the grain yield (Theesfeld, 2018). However, some studies have shown that water rights reforms have led to low-income small farmers becoming unwilling to adopt advanced irrigation technology or increase grain planting area, which has a negative impact on grain production (Mamitimin *et al.*, 2015).

Some studies focused on the effect of water-saving irrigation technology on grain production. In terms of the impact of water-saving technology on food security, many studies concentrate on water-saving facilities construction, water-saving subsidies, and water-saving technology adoption. Their research results show that water-saving technology can effectively alleviate water resource constraints on agricultural production to improve agricultural economic benefits and stabilize grain yield (Berbel & Mateos, 2014). Especially in China, which has a serious agricultural water shortage, promoting water-saving technology through incentive mechanisms is conducive to resolving the water shortage crisis and promoting food security (Feike & Henseler, 2017).

Other studies have confirmed the roles of climate change, government intervention and many other factors in promoting or inhibiting food security. No unified conclusion has been reached regarding the impact of climate change on helping ensure food security. Some studies suggest that climate change has significant negative effects on food availability and stability (Bocchiola *et al.*, 2019). Other studies suggest that climate change improves agricultural production conditions and thus positively impacts crop yields (Shi *et al.*, 2014). Moreover, the conclusion of the impact of government intervention on helping ensure food security is also not unified. Some studies prove that government agricultural intervention policies, such as subsidies, will be conducive to helping ensure food security (Nhantumbo *et al.*, 2016). However, other studies have shown that government interventions have limited impacts on ensuring food security (Lunduka *et al.*, 2013).

To sum up, existing studies have focused on food security from different aspects, but there is still a lack of research on the impact of the WRTTP on helping ensure food security. Because this policy is an effective tool to promote the adoption of agricultural water-saving irrigation technology and reducing water conflict between industry and agriculture, it is necessary to explore its impact on agricultural production, especially on helping ensure food security. In addition, few studies have analyzed the impact of water rights reform on helping ensure food security from the perspective of improving agricultural water-saving irrigation technology. Based on this, we will comprehensively evaluate the impact and mechanism of the WRTTP on helping ensure food security.

2.2. Theoretical analysis and hypothesis development

Water rights and the corresponding trading market can help address water shortages by establishing tradable permits for water resources (Delorit *et al.*, 2019). Rational water rights distribution is conducive to coping with the

pressures caused by uneven water resources distribution, e.g., helping farmers who need more water to obtain sufficient supplies to ensure effective irrigation of land and thus improve agricultural incomes (Bekchanov *et al.*, 2015). As a policy to adjust the water resources allocation and promote the adoption of water-saving irrigation technology, the WRTTP will help ensure food security in the following ways.

First, the WRTTP can promote increased uptake of agricultural water-saving irrigation technology. Under the dual pressure of industrial water crowding and limited agricultural water rights allocation, farmers will have greater incentive to improve their water-saving irrigation technology, thus increasing irrigation efficiency (Fang & Zhang, 2020). Furthermore, the WRTTP provides water-saving subsidies while establishing a water market and adjusting water prices, which encourage farmers to invest in irrigation systems and adopt water-saving technology (Gao *et al.*, 2014; Kahil *et al.*, 2015). Water-saving technologies such as drip irrigation and sprinkler irrigation can improve the water absorption rate of crops and meet the water demand for the growth of food crops to increase crop yields (Brinegar & Ward, 2009; Deng *et al.*, 2020), thus helping ensure food security. In addition, studies have shown that when cotton fields are completely converted to grow wheat, the promotion effect of drip irrigation technology on food yield plays the largest role, so the promotion effect of water-saving technology on food security varies with different crop plantation structures (Lee & Jung, 2018).

Secondly, by adjusting agricultural water prices, the WRTTP can improve agricultural water use efficiency, which will then help ensure food security. The policy adjusts the agricultural water price and increase the irrigation cost. Water pricing is an effective management means to promote the efficient allocation of agricultural water, which can improve the production efficiency of agricultural water and help ensure food security⁶ (Gohar & Ward, 2010; Wang *et al.*, 2017). Because rational irrigation is one of the effective measures to increase grain yield, the policy improves agricultural water efficiency, and alleviates the pressure of water shortage to ensure grain yield by means of water resources integrated management (Kang *et al.*, 2017; He *et al.*, 2019).

Finally, the WRTTP can help ensure food security through adjusting the plantation structure. Existing studies have confirmed that water price reform increases the opportunity cost of agricultural irrigation, which makes farmers plant more food crops with low water consumption instead of cash crops with high water consumption, a change in behavior that helps ensure food security (Berbel & Gómez-Limón, 2000; Ørum *et al.*, 2010).⁷ For example, Doppler *et al.* (2002) took Jordan as an example to prove that the water rights allocation system could help farmers obtain greater economic benefits from agricultural production through the adjustment of plantation structure and water allocation strategy, but a rise of water price would increase the investment risk of farmers and reduce the planting of fruits, vegetables, and other crops with high economic value added. Based on the above analysis, the following hypothesis is proposed:

⁶ Existing studies have shown that the rising water price may lead farmers to use rainwater irrigation or to plant crops with less water demand, such as grains (Ørum *et al.*, 2010). Additionally, the water rights trading pilot policy can promote farmers to use water-saving irrigation technology (Moreno & Sunding, 2005; Baerenklau & Knapp, 2007; Kahil *et al.*, 2015). Water-saving irrigation technology can improve water productivity and increase crop yield while saving water (Deng *et al.*, 2020). Taking drip irrigation technology as an example, drip irrigation can provide water to the root of crops at a fixed speed, which increases the water absorption rate of crops, and then improves crop yield (Brinegar & Ward, 2009). For example, Ali *et al.* (2018) conducted a survey of 950 farmers in Pakistan, which showed that the use of water-saving irrigation technology can improve the yield of wheat and rice, and significantly promote the national food security.

⁷ Generally speaking, the water consumption of food crops is lower than that of cash crops. For example, Shen *et al.* (2013) used FAO Penman-Monteith equation and crop coefficient approach to calculate crop water consumption and found that sugar beet had the highest water consumption, followed by cotton, corn, wheat, and oil crops. He *et al.* (2020) suggested that the water consumption of economic crops is 316–541 mm, that of corn is 234–514 mm and that of wheat is 199–434 mm during the whole crop growth period.

Hypothesis 1: Water rights trading pilot policy can support food security.

Hypothesis 2: Water rights trading pilot policy can help guarantee food security by improving the adoption of water-saving irrigation technology.

3. VARIABLES, MODEL, AND DATA

3.1. Samples and data

Our research objects are 29 provinces (municipalities) in China from 2009 to 2018. The 2013 Central Economic Work Conference proposed to achieve basic self-sufficiency in cereals and absolute safety in rations. It can be seen that rice, wheat, and corn, as the three main grains, are of great significance to ensure food security. According to the ‘China Rural Statistical Yearbook’ over the years, Hainan Province’s rice yield accounts for less than 1% of the country’s total yield and its wheat yield and corn yield have been zero since 2013. The yield of rice in Qinghai Province is zero and the total yield of wheat and corn accounts for about 0.14% of the total yield in the whole country. Therefore, in order to make the estimation results accuracy, we exclude Hainan Province and Qinghai Province and finally use panel data from 29 provinces (municipalities) in China to obtain 285 actual observations. In order to effectively analyze the impact and mechanism of the WRTTP on helping ensure food security, the data in this article comes from the ‘China Statistical Yearbook’, ‘China Rural Statistical Yearbook’, ‘Agricultural Statistical Yearbook’, and Chinese National Bureau of Statistics.

3.2. Specification of variables

3.2.1. Explained variable: food security

FAO measures food security from four dimensions, namely availability, accessibility, utilization, and stability. Using these indicators can accurately measure the food security. However, we cannot get the data at the provincial level in China. Additionally, stabilizing grain yield is still the key to ensuring China’s food security.⁸ Existing studies also show that crops yield is very important to ensure food security (Parker *et al.*, 2020). The long-term low level of food production will threaten global food security (Ray *et al.*, 2015). Furthermore, the Food Security Index of FAO includes the average value of food production in the dimensions of availability.

Therefore, we select food security as the explained variable, which is measured by total grain yield, grain yield per unit area, and grain yield per capita (Ali *et al.*, 2018; Liu *et al.*, 2021). According to the China Rural Statistics Yearbook in 2019, the yield of rice, wheat, and corn accounted for 34.77, 21.55, and 42.16% of China’s total grain yield, respectively, and other food crops only accounted for 1.52% of the total grain yield. Therefore, we select the total yield and yield per unit area of these three main grains to further analyze the impact of WRTTP on helping ensure food security.

3.2.2. Explanatory variables: water rights trading pilot policy

WRTTP is the explanatory variable of this study. If the province (municipality) i belongs to the pilot area in year t , the value is 1; otherwise, the value is 0. Specifically, the Ministry of Water Resources issued the ‘Notice of the Ministry of Water Resources on the Implementation of Water Rights Pilot Work’ in 2014, proposing to launch water rights pilot projects in seven provinces (municipalities), including Ningxia, Jiangxi, Hubei, Inner Mongolia, Henan, Gansu, and Guangdong. Based on this, we select seven pilot provinces (municipalities) as the experimental group, and the remaining provinces (municipalities) as the control group.

⁸ The fourteenth five-year plan for China’s economic and social development and the outline of long-term goals for 2035 clearly put forward that China should improve the security system for the supply of important agricultural products and the system for the purchase, storage, addition and marketing of grain production, stabilize and increase the sown area and yield of grain, and reasonably arrange regional emergency supply bases for agricultural products.

3.2.3. Control variable

Based on previous research (Liu *et al.*, 2021), in the analysis, we control the characteristic variables of provinces (municipalities), including infrastructure construction, industrial structure, disaster degree, effective irrigation rate, pesticide input, machinery input, labor input, fixed asset input, time, and province fixed effects. Table 1 provides the variables' definitions.

3.3. Econometric model

The DID method has been widely applied in econometrics (Ashenfelter & Card, 1985; Girma & Görg, 2007; Wang *et al.*, 2021). Recently, there are also studies that apply the DID method to evaluate the implementation effect of environmental policies (Elrod & Malik, 2017; Gehrsitz, 2017). For example, Mori-Clement (2019) combines the DID method with matching techniques to identify the effect of CDM investments on development and poverty. However, few studies have applied the method to evaluate the implementation effect of the WRTTP. Therefore, this paper uses the DID method to analyze the net effect of the pilot policy on helping ensure food security.

The impact of WRTTP mainly comes from two parts. One is the time effect formed with the natural growth of time. The other is the policy processing effect brought by the policy implementation. The key of the research is

Table 1. | Variables definitions.

Variables	Definitions
<i>Explanatory variables</i>	
Total grain yield	Natural logarithm of total grain yield
Grain yield per unit area	Natural logarithm of grain yield per unit area
Grain yield per capita	Natural logarithm of grain yield per capita
Total yield of three main grains	Natural logarithm of the total yield of rice, wheat, and maize
Yield per unit area of three main grains	Natural logarithm of the yield per unit area of rice, wheat, and maize
<i>Explained variables</i>	
Treat	Province i is a water policy pilot area in year t and takes the value 1; otherwise, it is 0
<i>Control variables</i>	
Industrial structure	Natural logarithm of the ratio of the GDP of the secondary and tertiary industries to the GDP of the region
Machinery	Natural logarithm of the ratio of total mechanical power and the added value of the gross agricultural product
Pesticide	Natural logarithm of pesticide input per area
Disaster	The ratio of crop disaster area to total sown area
Irrigation	The ratio of effective irrigated area to cultivated area
Fixed assets	Natural logarithm of investment in agricultural fixed assets and investment in fixed assets of the whole society
Labor	Natural logarithm of the number of employees in the primary industry
Infrastructure	Natural logarithm of the mileage of highways
Year	The value of the sample is 1 for the year; otherwise, it is 0
Province	The sample belongs to the province and the value is 1; otherwise, the value is 0

how to distinguish the change caused by the growth over time from the policy effect. The DID method can accurately separate the time effect and the policy processing effect, which is an effective tool to compare the effect before and after the implementation of the WRTPP. Therefore, we take the policy implementation as a quasi-natural experiment and use the DID method to assess the net effect of helping ensure food security affected by the policy in different provinces (municipalities) and different periods. We set the pilot provinces (municipalities) as the experimental group and sets the other provinces (municipalities) as the control group to evaluate the difference in helping ensure food security between pilot provinces (municipalities) and non-pilot provinces (municipalities). The model is set as follows:

$$Y_{it} = \beta_0 + \beta_1 \text{Treat}_{it} + \beta_2 X_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (1)$$

Among them, i represents province (municipality) and t represents year. Y_{it} represents the food security of province (municipality) i in year t . We use total grain yield, grain yield per unit area, and grain yield per capita to measure food security. Treat_{it} indicates whether the province (municipality) i belongs to the pilot province (municipality) in year t . $\text{Treat}_{it}=1$ means that province (municipality) i is a pilot province (municipality) in year t . Otherwise, $\text{Treat}_{it}=0$. X_{it} represents the control variables at the provincial level. μ_t represents the time fixed effect. λ_i represents the province fixed effect. ε_{it} is the random perturbation term. In formula (1), the coefficient of interest in this paper is β_1 . If the estimated value of β_1 is greater than 0, it means that compared with non-pilot provinces (municipalities), the policy helps guarantee food security in the pilot provinces (municipalities). Table 2 reports the summary statistics for all variables.

4. EMPIRICAL ANALYSIS AND RESULTS

4.1. Water rights trading pilot policy and food security

Table 3 reveals the main conclusions of this study, using the DID method to analyze the impact of WRTPP on helping ensure food security. Column (1) of Table 3 examines the impact of the policy on total grain yield.

Table 2. | Summary statistics.

Variable	N	Mean	SD	Min	Median	Max	Difference
Total grain yield	285	7.157	1.187	3.529	7.324	8.924	0.066
Total yield of three main grains	285	7.016	1.315	3.151	7.222	8.857	0.101
Grain yield per unit area	285	1.659	0.187	1.054	1.690	2.077	0.013
Yield per unit area of three main grains	285	1.784	0.159	1.301	1.804	2.130	0.011
Grain yield per capita	285	5.848	0.828	2.760	6.030	7.594	0.077
Industrial structure	285	-0.104	0.051	-0.221	-0.100	-0.003	0.004
Machinery	285	1.103	0.534	-0.017	1.028	2.638	-0.094
Pesticide	285	-4.708	0.683	-6.242	-4.639	-3.331	-0.016
Disaster	285	47.290	47.810	0.200	36.300	313.000	20.300
Irrigation	285	0.553	0.247	0.204	0.596	1.079	0.007
Fixed assets	285	-3.617	0.894	-8.794	-3.499	-2.008	0.021
Labor	285	7.160	1.006	4.782	7.292	8.508	0.004
Infrastructure	285	-0.342	0.836	-3.128	-0.109	0.742	0.033

Table 3. | Water rights trading pilot policy and food security.

Variable	Total yield		Yield per unit area		Yield per capita Grain yields per capita
	Total grain yield	Total yield of three main grains	Grain yield per unit area	Yield per unit area of three main grains	
Treat	0.068*** (0.024)	0.111*** (0.024)	0.030** (0.013)	0.024** (0.011)	0.077*** (0.026)
Industrial structure	-1.532*** (0.534)	1.810*** (0.523)	-0.932*** (0.287)	-0.545 (0.355)	-1.518** (0.599)
Machinery	0.033 (0.041)	0.013 (0.041)	-0.034 (0.023)	-0.058*** (0.021)	0.007 (0.047)
Pesticide	-0.244*** (0.093)	-0.151 (0.096)	0.195*** (0.044)	0.188*** (0.038)	-0.207** (0.096)
Disaster	-0.001*** (0.000)	0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Irrigation	1.464*** (0.182)	1.653*** (0.193)	0.196*** (0.070)	0.111 (0.075)	1.730*** (0.193)
Fixed assets	0.052*** (0.018)	0.040** (0.019)	0.009 (0.014)	0.000 (0.009)	0.046** (0.019)
Labor	0.117 (0.128)	-0.124 (0.138)	-0.215** (0.105)	-0.300*** (0.082)	-0.012 (0.161)
Infrastructure	0.233** (0.111)	0.072 (0.137)	0.102 (0.068)	0.043 (0.070)	0.210* (0.123)
_cons	4.502*** (1.147)	6.316*** (1.185)	4.050*** (0.826)	4.818*** (0.674)	4.139*** (1.314)
Year FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
N	285	285	285	285	285
R ²	0.996	0.996	0.942	0.922	0.989

Note: ***, **, and * indicate significance at the levels of 1, 5, and 10%, respectively. The standard errors adjusted by province-year clustering are in brackets.

The results show that the coefficient sign of the DID method estimator *Treat* is positive and significant at the 1% level, indicating that after controlling other influencing factors, compared with non-pilot provinces (municipalities), the policy improves total grain yield in the pilot provinces (municipalities) increased by 6.8 percentage points. This initially supports our hypothesis 1. Columns (3) and (5) further report the results of the policy on the grain yield per unit area and the grain yield per capita, respectively. The results present that the coefficients of the estimator *Treat* were significantly positive at the 5 and 1% levels, respectively, indicating that the results in Table 3 have sufficient accuracy and stability. Hypothesis 1 has been further verified. Moreover, these findings are comparable with the existing literature. Goetz *et al.* (2017) revealed that the water rights allocation agreement can effectively alleviate the drought constraints on food production. The results in columns (2) and (4) are significantly positive at the 1 and 5% levels, respectively, indicating that the policy implementation has increased total grain yield and grain yield per unit area of three main grains in the pilot provinces (municipalities), respectively, 11.1 and 3%. Therefore, the study indicates that the WTRPP can indeed help guarantee food security.

It is worth mentioning that the coefficients of other variables in Table 3 also have important economic significance. The higher the proportion of the secondary and tertiary industries in the industrial structure, the less the

food security can be guaranteed. The higher the amount of pesticide input, the greater threat there is to food security. The higher the disaster degree, the more difficult it is to ensure food security. The greater the effective irrigation area, the more food security can be ensured. The higher the investment in fixed assets, the more possible it is to guarantee food security. Additionally, machinery input, labor input, and infrastructure construction are not statistically significant.

4.2. Robustness check

4.2.1. Parallel trend test

We use the DID method to evaluate the impact of the WRTPP on helping ensure food security. However, the effective premise of the method is that if there is no external impact from the policy, the food production trends of the experimental group and the control group are parallel. To this end, we conduct a parallel trend test.

Based on the practice of previous literature, we draw a comparison chart between the experimental group and the control group to illustrate the changing trend of food production. Figures 1–3, respectively, depict the differences in the total grain yield, the grain yield per capita, and the total yield of three main grains between pilot provinces (municipalities) and non-pilot provinces (municipalities). First, the total grain yield, the grain yield per capita, and the total yield of three main grains in the pilot and non-pilot provinces (municipalities) remained basically parallel before 2014. Second, in 2014 and subsequent years, the increase in grain yield in the pilot provinces (municipalities) has obviously expanded. Various indicators in the pilot and non-pilot provinces (municipalities) show greater differences. This result intuitively shows that the policy has a positive effect on helping ensure food security. Third, the changes in grain yield in non-pilot provinces (municipalities) remain stable, namely the policy does not have a significant negative impact on food production in non-pilot provinces (municipalities). Based on this conclusion, it is helpful to further understand the impact of WRTPP on helping ensure food security.

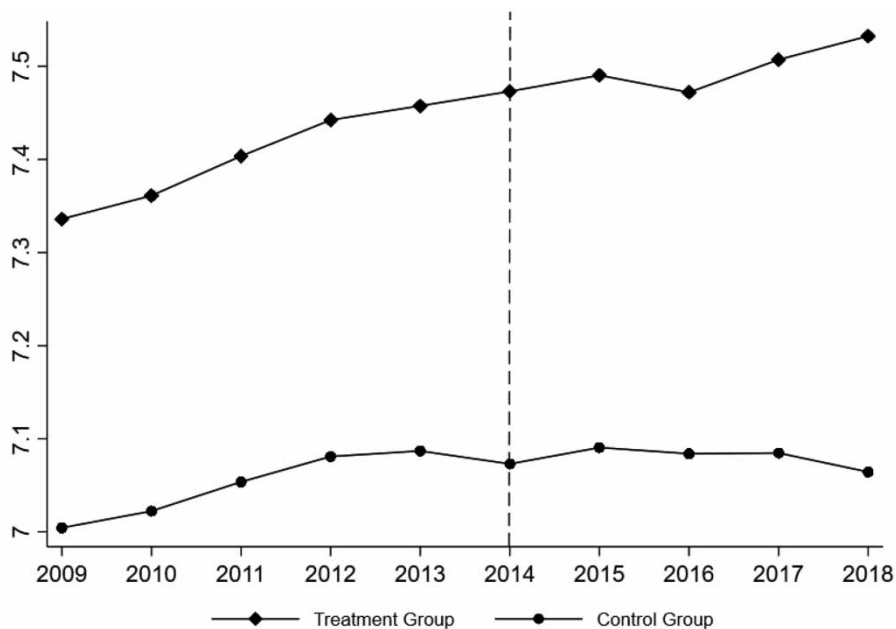


Fig. 1. | Parallel trend test of total grain yield.

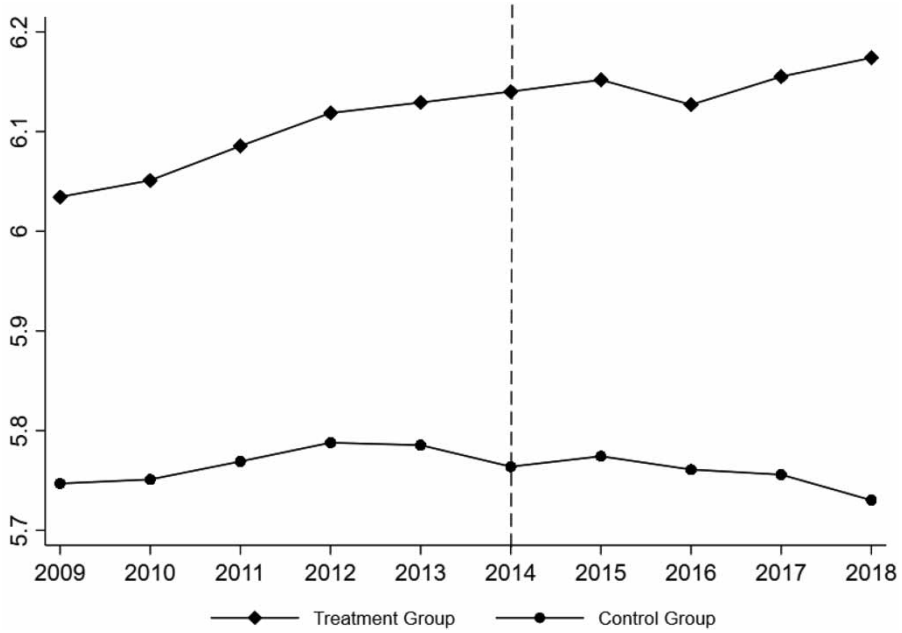


Fig. 2. | Parallel trend test of grain yield per capita.

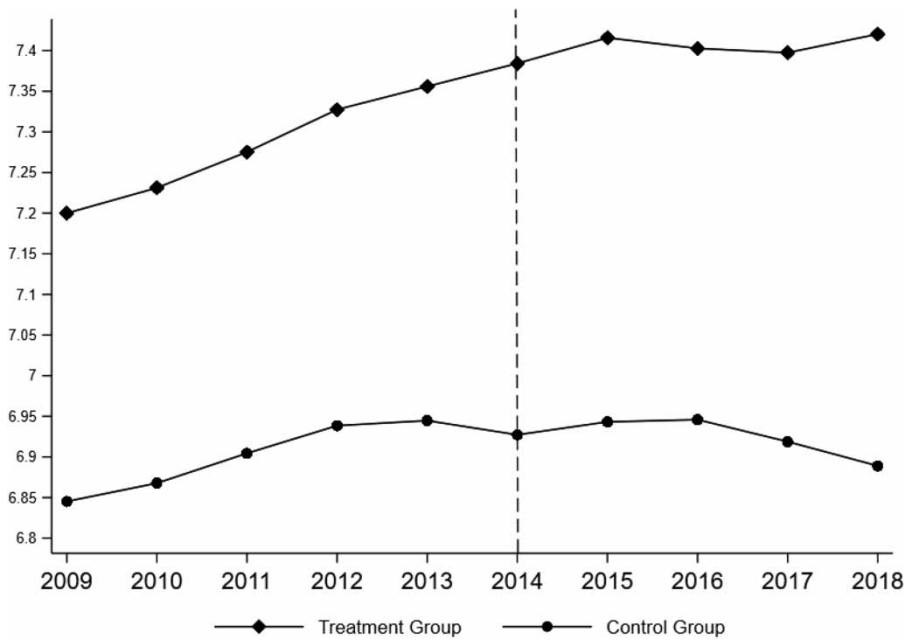


Fig. 3. | Parallel trend test of total yield of three main grains.

4.2.2. Common trend test

In order to further verify whether the hypothetical conditions of parallel trends are true, we use the data from the early implementation of the WRTTP to test the common trend. In 2009, 2010, 2011, 2012, and 2013, the trend values were assigned to 1, 2, 3, 4, and 5 to construct a time trend variable (*Trend*) to analyze the linear time trend of pilot and non-pilot provinces (municipalities). If there is no systematic difference between the time trends of pilot and non-pilot provinces (municipalities) between 2009 and 2013, *Treat* should have statistically insignificant coefficients. Table 4 lists the results of the common trend. The coefficient of *Treat* is not significant, indicating that there are similar time trends between the pilot and non-pilot provinces (municipalities). Therefore, our research does not violate the parallel trend assumption of the DID method. Our results are robust.

5. MECHANISM AND DYNAMIC EFFECT ANALYSIS

5.1. Water rights trading pilot policy, water-saving irrigation technology, and food security

The baseline result and a series of robustness checks confirm that the WRTTP has a significant role in helping ensure food security. How is this effect realized? This requires further exploration of its mechanism. Therefore,

Table 4. | Common trend test.

Variable	Total yield		Yield per unit area		Yield per capita Grain yield per capita
	Total grain yield	Total yield of three main grains	Grain yield per unit area	Yield per unit area of three main grains	
Treat ₁	0.007 (0.006)	0.009 (0.008)	0.003 (0.005)	0.002 (0.005)	0.005 (0.007)
Industrial structure	-0.923 (0.643)	-2.088** (0.804)	-1.164** (0.537)	-0.821 (0.508)	-0.188 (0.916)
Machinery	-0.006 (0.039)	0.009 (0.043)	-0.007 (0.028)	-0.029 (0.033)	-0.061 (0.067)
Pesticide	0.149** (0.063)	0.208*** (0.072)	0.185*** (0.047)	0.150*** (0.056)	0.236*** (0.072)
Disaster	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Irrigation	0.603** (0.263)	0.685** (0.265)	0.199** (0.097)	0.094 (0.114)	0.747** (0.292)
Fixed assets	0.025 (0.025)	-0.011 (0.023)	0.061*** (0.020)	0.014 (0.017)	-0.026 (0.023)
Labor	0.199 (0.193)	0.346* (0.201)	-0.073 (0.129)	-0.002 (0.157)	0.128 (0.282)
Infrastructure	0.066 (0.131)	0.047 (0.170)	0.091 (0.112)	0.155 (0.131)	0.121 (0.151)
_cons	6.176*** (1.312)	4.922*** (1.397)	3.096*** (0.959)	2.527** (1.179)	5.708*** (1.968)
Year FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
N	144	144	144	144	144
R ²	0.999	0.999	0.975	0.961	0.997

Note: ***, **, and * indicate significance at the levels of 1, 5, and 10%, respectively. The standard errors adjusted by province-year clustering are in brackets.

this section further discusses the mechanism of the policy on helping ensure food security from the perspective of water-saving irrigation technology.

Using water-saving irrigation technology can improve agricultural water efficiency. More importantly, water-saving irrigation technology enhances grain productivity by the integration of water and fertilizer and reduces water evaporation to increase the farmers' willingness to grow grain (Habteyes & Ward, 2020) and help ensure food security. The policy implemented in 2014 not only clarifies the water rights of industry and agriculture and establishes water trading markets, but also realizes the rational allocation of water resources to optimize the structure of agricultural water use and promotes agricultural water conservation. At the same time, the policy puts forward new requirements to ensure food security under water constraints. To this end, the following model is constructed:

$$Y_{it} = \alpha_0 + \alpha_1 \text{Treat}_{it} + \alpha_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

$$Y_{it} = \alpha_0 + \alpha_1 \text{Technology}_{it} + \alpha_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (3)$$

$$\text{Technology}_{it} = \alpha_0 + \alpha_1 \text{Treat}_{it} + \alpha_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (4)$$

$$Y_{it} = \alpha_0 + \alpha_1 \text{Treat}_{it} + \alpha_2 \text{Technology}_{it} + \alpha_3 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (5)$$

Among them, Technology_{it} represents water-saving irrigation technology, which is measured by the ratio of water-saving irrigation area to cultivated area of each province (municipality). Y_{it} represents the total grain yield and grain yield per capita. The definition of other variables is consistent with formula (1). We also control the characteristic variables of provinces (municipalities).

Table 5 shows the results of the mechanism the policy works. Column (1) presents the impact of the policy on water-saving irrigation technology. The coefficient of estimator *Treat* is significantly positive at the 5% level, indicating that the policy can promote water-saving irrigation technology increased by 8.8%. Column (2) further reports the results of the technology and total grain yield. The study found that the coefficient of the technology is significantly positive at the 5% level, indicating that the technology has increased the total grain yield by 9%. The adoption of the technology is conducive to helping ensure food security. Column (3) indicates that the policy can increase total grain yield. It can be seen from the results in column (4) that the coefficient of the DID method estimator *Treat* is significantly reduced. Therefore, the first three columns in Table 5 show that the policy can increase grain production to help ensure food security by improving the adoption of water-saving irrigation technology. Our hypothesis 2 has been initially verified.

At the same time, we explore the impact of the policy on grain yield per capita by improving water-saving irrigation technology. The results are listed in Table 6. The coefficient of the explanatory variable in column (2) is significantly positive at the 1% level, indicating that the technology can significantly increase grain yield per capita. Column (4) reports the results of formula (5). The coefficient of the estimator *Treat* is significantly reduced, indicating that the policy increases the grain yield per capita by improving the adoption of the technology. This also further validates our hypothesis 2. That is, WRTTP can improve the adoption of water-saving irrigation technology to help ensure food security.

5.2. Dynamic effects

In order to examine the dynamic effects of the WRTTP on helping to ensure food security, the impact of the policy is broken down into years to observe the changing trend of food production. The results are shown in Table 7. The coefficient of $\text{Treat} \times \text{year}_1$ represents the impact on grain yield in the first year after the policy implementation. The coefficient of $\text{Treat} \times \text{year}_2$ represents the impact on grain yield in the second year. The

Table 5. | Water rights trading pilot policy, agricultural water-saving irrigation technology, and total grain yield.

Variable	Technology	Total grain yield	Total grain yield	Total grain yield
Treat	0.088** (0.043)		0.068*** (0.024)	0.061** (0.024)
Technology		0.090** (0.037)		0.078** (0.038)
Industrial structure	4.929*** (0.979)	-1.843*** (0.579)	-1.532*** (0.534)	-1.919*** (0.556)
Machinery	-0.110 (0.080)	0.022 (0.039)	0.033 (0.041)	0.042 (0.043)
Pesticide	-0.035 (0.081)	-0.244** (0.096)	-0.244*** (0.093)	-0.241** (0.094)
Disaster	-0.000 (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Irrigation	0.780*** (0.196)	1.398*** (0.180)	1.464*** (0.182)	1.403*** (0.178)
Fixed assets	0.012 (0.026)	0.049*** (0.018)	0.052*** (0.018)	0.051*** (0.018)
Labor	-0.446** (0.218)	0.156 (0.134)	0.117 (0.128)	0.152 (0.131)
Infrastructure	-0.944*** (0.270)	0.364*** (0.121)	0.233** (0.111)	0.307*** (0.117)
_cons	1.411 (1.684)	4.415*** (1.197)	4.502*** (1.147)	4.392*** (1.170)
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
N	285	285	285	285
R ²	0.966	0.995	0.996	0.996

Note: ***, and ** indicate significance at the levels of 1%, and 5%, respectively. The standard errors adjusted by province-year clustering are in brackets.

rest can be done in the same manner. The results reveal that the policy has a positive effect on helping ensure food security in the first year and the effect increased after the third year. The promotion effect reached the maximum in the fourth year. Overall, after the policy implementation, food production has been greatly positively affected, indicating that the policy will have a long-term effect on helping ensure food security.

6. CONCLUSIONS AND IMPLICATIONS

With the development of the international economy and the changing global social and political environment, food security has increasingly become an important issue concerning global food production and consumption patterns. Based on Chinese provincial panel data from 2009 to 2018, we use the DID method to evaluate the impact of China's WRTTP on helping ensure food security and its mechanism. It is found that the policy has a significant promoting effect on food production. After the implementation of the WRTTP, the total grain yield and yield per unit area in the pilot provinces (municipalities) increased, and the per capita share of grain also increased significantly. Furthermore, this effect began to increase after the third year of the policy implementation

Table 6. | Water rights trading pilot policy, agricultural water-saving irrigation technology, and grain yield per capita.

Variable	Technology	Grain yield per capita	Grain yield per capita	Grain yield per capita
Treat	0.088** (0.043)		0.077*** (0.026)	0.067** (0.026)
Technology		0.125*** (0.041)		0.113*** (0.042)
Industrial structure	4.929*** (0.979)	-1.990*** (0.646)	-1.518** (0.599)	-2.073*** (0.622)
Machinery	-0.110 (0.080)	-0.002 (0.044)	0.007 (0.047)	0.019 (0.048)
Pesticide	-0.035 (0.081)	-0.206** (0.100)	-0.207** (0.096)	-0.203** (0.096)
Disaster	-0.000 (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Irrigation	0.780*** (0.196)	1.637*** (0.190)	1.730*** (0.193)	1.642*** (0.188)
Fixed assets	0.012 (0.026)	0.042** (0.019)	0.046** (0.019)	0.045** (0.019)
Labor	-0.446** (0.218)	0.043 (0.169)	-0.012 (0.161)	0.039 (0.167)
Infrastructure	-0.944*** (0.270)	0.379*** (0.134)	0.210* (0.123)	0.316** (0.129)
_cons	1.411 (1.684)	4.006*** (1.384)	4.139*** (1.314)	3.980*** (1.356)
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
N	285	285	285	285
R ²	0.966	0.995	0.996	0.996

Note: ***, **, and * indicate significance at the levels of 1, 5, and 10%, respectively. The standard errors adjusted by province-year clustering are in brackets.

and reaches the maximum in the fourth year after its implementation. After further analysis of the mechanism, we reveal that the policy can help to achieve a sufficient supply of grain and help guarantee food security by improving the adoption of agricultural water-saving irrigation technology. After a series of robustness checks, the conclusion remains robust. Our conclusions can be used as a reference for other developing countries to alleviate conflicts between food production and agricultural water use.

First, this study confirms that the WRTPP is conducive to helping ensure food security, which enriches the existing research on the factors influencing food security and has important theoretical significance. Existing empirical studies have found that food security is related to many factors, such as water resources (Gohar & Ward, 2010; Hanjra & Qureshi, 2010), land resources (Qi *et al.*, 2018), climate change (Atuoye *et al.*, 2020), and government intervention (Farrukh *et al.*, 2020). However, compared with existing evidence on the impact of other factors on food security, the role of the WRTPP in contributing to help ensure food security still needs further exploration. As a complement, our results demonstrate that the WRTPP can improve grain yields to help ensure food security.

Additionally, this study confirms that the WRTPP can help promote the realization of food security by improving the utilization rate of water-saving irrigation technology. Existing research has shown that the implementation

Table 7. | Dynamic effect.

Variable	Total grain yield	Grain yield per capita
Treat×year ₁	0.038 (0.028)	0.046 (0.029)
Treat×year ₂	0.075 (0.047)	0.082 (0.051)
Treat×year ₃	0.082* (0.048)	0.090* (0.052)
Treat×year ₄	0.090* (0.051)	0.100* (0.056)
Control variables	Yes	Yes
_cons	4.601*** (1.188)	4.244*** (1.350)
Year FE	Yes	Yes
Province FE	Yes	Yes
N	285	285
R ²	0.995	0.989

Note: ***, and * indicate significance at the levels of 1%, and 10%, respectively. The standard errors adjusted by province-year clustering are in brackets.

of agricultural water rights can guarantee sufficient supplies to meet the water quota of crops and thus increase crop yields (Li & Guo, 2014). However, few studies have discussed how the WRTPP encourages farmers to adopt water-saving irrigation technology, thereby increasing food production. Thus, from the perspective of water-saving irrigation technology, we have reached this conclusion.

This study provides useful policy implications for effectively solving the contradiction between water resource shortages and food production, namely the need to formulate a scientific and reasonable water right policy, to help promote food security. First, the findings have demonstrated that the WRTPP can help promote food security to a great degree, which fully affirms the development direction of the policy and provides implications for evaluating its effects. Therefore, one policy implication of the study's finding is to suggest that it will be beneficial to further promote these experiences throughout the country and expand the implementation scope of the policy in China. Secondly, the results also indicate that the WRTPP can help guarantee food security by improving the adoption of agricultural water-saving irrigation technology. Therefore, the government must act to protect farmers' water rights, scientifically determine agricultural water consumption and water prices, improve agricultural water-saving facilities, effectively guide farmers to actively adopt water-saving irrigation technology, and ensure the realization of food security through the improvement of technology. Finally, the incentive mode and supporting policies for efficient water-saving irrigation technology should be formulated. Policies should aim to broaden farmers' access to credit information and promote the linkage mechanism between agricultural insurance and loans, which can stimulate farmers' adoption of water-saving irrigation technology to help ensure food security.

However, there are some limitations of this study. Due to the limitation of data availability, food security is merely measured by total grain yield, grain yield per unit area, and grain yield per capita rather than the FAO's comprehensive definition. Furthermore, this paper only investigates the impact of the WRTPP to promote the adoption of water-saving technologies among farmers, the mechanism of WRTPP on helping ensure food security from multiple perspectives can be examined in future research.

FUNDING

The work was supported by the ‘Major Projects of the Humanities and Social Sciences Base of the Ministry of Education (17JJD790015)’; ‘National Natural Science Foundation of China (72103115)’; ‘Humanities and Social Science Research General Project of the Ministry of Education (21XJC790008)’; ‘China Postdoctoral Science Foundation (2020T130393)’.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 20 February 2021; accepted in revised form 21 September 2021. Available online 4 October 2021