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Water rights reform and water-saving irrigation: evidence from China

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ABSTRACT

As a market-based water resource management, the water rights reform (WRR) will allocate water rights to water users and allow water users to trade water rights, which can realize the reallocation across water users. In this context, the adoption of water-saving irrigation (WSI) is an important technical form to adapt to the reform. Based on this, this paper studies the impacts of the WRR on WSI using the difference-in-differences (DID) strategy. The results show that the WRR could increase the land area for WSI by an average of 13.63%. The WRR could promote the expansion of high-efficiency irrigation mainly because the WRR could promote the expansion of spray and drip irrigation areas, and micro-irrigation land areas, which are high-efficiency water-saving irrigation technologies. In addition, the WRR also could improve agricultural production by increasing agricultural water productivity and planting area (including the sown area of grain crops and cash crops), but the WRR does not reduce agricultural water extraction. Therefore, the WRR could increase agricultural production without increasing agricultural water extraction.

Key words: agricultural production, China, difference-in-differences, water rights reform, water-saving irrigation

HIGHLIGHTS

- The water rights reform could increase the land area for water-saving irrigation by an average of 13.63%.
- The water rights reform could promote the expansion of spray and drip irrigation areas, and micro-irrigation land areas.
- The water rights reform could improve agricultural production by increasing agricultural water productivity and planting area.
- The water rights reform could not reduce agricultural water extraction.

1. INTRODUCTION

A natural resource that is vital to human existence and economic growth is water. As economies grow, water scarcity eventually becomes a global issue. The primary cause of the water shortage is that human usage of water resources exceeds the supply of freshwater (Savenije 2000). This also reflects the contradiction between human use of water resources and the natural availability (Rijsberman 2006). The increase in food demand caused by global population growth will continue to increase the demand for water resources, resulting in more serious water scarcity. Water resource is also an important natural resource for food production (Mueller *et al.* 2012), and utilizing water resources wisely is one of the key elements in promoting the production of food (D'Odorico *et al.* 2018). In order to increase the yield of agriculture, agricultural production needs to shift from rain-fed agriculture to irrigated agriculture, which will also increase the demand for freshwater (Rosa *et al.* 2018). However, the popularization of irrigation may increase the demand for water resources, which may lead to an increase in water stress (Elliott *et al.* 2014). Facing water scarcity due to constraints in supplying enough fresh water, efficient water resource management is required to handle water issues (Mohseni *et al.* 2022). To deal with the contradiction between water stress and food production, adopting water-saving irrigation (WSI) technology has become one of the important measures to avoid the increase of water stress and promote the increase of food production.

Current research concentrates on a variety of influencing factors for the adoption of WSI. Factors influencing the adoption of WSI technologies include institutional factors (Liu *et al.* 2019; Hu *et al.* 2022), adoption of climate change (Mi *et al.* 2021; Surendran *et al.* 2021; Chen *et al.* 2022), household characteristics (Namara *et al.* 2007; Kumar 2012; Chandran & Surendran 2016). Because WSI devices are expensive, in order to promote the adoption of efficient water-saving technologies, the

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government will promote the adoption of WSI technologies through various subsidy policies (Liu *et al.* 2019; Hu *et al.* 2022). Due to the change and instability of rainfall caused by climate change, farmers will adopt high-efficiency technologies for irrigation to ensure production in agriculture (Mi *et al.* 2021; Surendran *et al.* 2021; Chen *et al.* 2022). For characteristics of households, Namara *et al.* (2007) and Kumar (2012) indicate that older irrigators with enough experience may adopt high-efficiency irrigation, while younger irrigators with new knowledge may adopt WSI for agricultural production (Chandran & Surendran 2016).

The current water resource management mode is gradually changing to marketization, especially the water rights reform (WRR), such as the groundwater market in India (Tamuli *et al.* 2022). As a part of the hydrological cycle, water resources are fluid and constantly updated, which limits the applicability of traditional legal methods to natural resources. Therefore, traditional water rights institutional arrangements are associated with land ownership institutional arrangements. Due to water scarcity and the escalating disparity between the supply and demand of water resources, the government gradually formed a reform of the separation of rights arrangements and land ownership, also known as modern WRR. The reform is an essential institutional arrangement to realize the efficient use of limited water resources under the condition of the market economy. This institutional arrangement can promote water rights to be transacted based on market principles so that scarce water resources will flow to high-efficiency uses, thereby achieving efficient use of water resources (Brown 2006). China is also facing the problem of water scarcity and the transformation of water resource management. The reform of China's water rights system mainly began to mature in 2014. First of all, the government allocates the amount of water that can be used in agriculture. This allocation amount is mainly the remaining water after deducting reasonable living, non-agricultural production, ecological environment water requirement and reserved water for natural flows from the distributable water. The savings of water resources that can be realized through water-saving technologies can be traded to obtain benefits. Thus, the WRR may be beneficial to adopt high-efficiency irrigation.

This study takes China's WRR as an example, with China's panel data from 2004 to 2019, and adopts a difference-in-differences (DID) model to empirically analyze the impact of WRR on the land area of WSI. The DID strategy is an econometric analysis method for studying pilot policy effects. Also, the WRR is a typical pilot policy, because only some areas have carried out this reform. So, it is suitable to use this method to estimate the impacts of the WRR on WSI. Also, using this method to estimate the impact of WRR on WSI areas can lead to more credible research conclusions. In addition, the impact on WSI areas is of great significance for ensuring agricultural production and promoting food security. Since the research in this article is based on the analysis of province data, it is difficult to clarify the microscopic mechanism of farmers' adoption of WSI technologies, which is worth exploring in future research.

2. METHODS AND DATA SOURCES

2.1. Methods

Since WRR is a pilot policy in China, the policy can be regarded as a quasi-natural experiment. The DID is a policy evaluation method used to estimate the impact of pilot policies, so this article mainly uses the empirical strategy of DID for estimation. The adoption of the method requires parallel trend testing, so this article will further use the event study method to test it to ensure the credibility of the estimation results.

According to Cao & Chen (2022), this paper employs a DID strategy to estimate the impact of the WRR on the land area for WSI. The specific specification can be expressed as follows:

$$Area_{it} = \beta Reform_i \times Post_t + \delta_i + \sigma_t + \lambda X_{it} + \varepsilon_{it} \tag{1}$$

where the i and t denote province and year. The $Area_{it}$ denotes land area for WSI. The $Post_t$ denotes the time period whether it is after the reform. The δ_i and σ_t denotes effects of province and year. The X_{it} denotes control variables and the λ is the corresponding parameter. The ε_{it} denotes other factors which may affect the dependent variable. The β is the parameter of interest. The expected sign is positive of the β, which indicates that the WRR can increase the expansion of the land area for high-efficiency irrigation.

To further analyze the pre-trend of the land area for WSI, we will further use the event study to estimate the dynamic effects, which can further clarify the details of DID estimations. According to Jia (2014), the specification is:

$$Area_{it} = \sum_{\tau \in \{-10,\ldots,-2,0,1,\ldots,5\}} \beta_\tau Reform_i \times Post_t^\tau + \delta_i + \sigma_t + \lambda X_{it} + \varepsilon_{it} \quad (2)$$

where the $Post_t^\tau$ denotes the time span in year t compared to the reform year of 2014. The β_τ denotes the effects of the reform during different time spans. The previous year, 2013, is used as a comparing year. If the baseline model is credible, whether to participate in the reform will not affect the dependent variable before the reform year in 2014, but after the reform year in 2014, whether to participate in the reform will significantly affect the dependent variable in some years.

2.2. Data sources

The variables used in the analysis is described in Table 1. In this study, the dependent variable is the land area for WSI, which represents the land area which is irrigated with WSI technologies. The WRR took place in 2014. The Chinese government selected seven provinces as a pilot: Gansu, Ningxia, Inner Mongolia, Hunan, Hubei, Jiangxi, and Guangdong. The specific distribution is shown in Figure 1. 22.58% of provinces have implemented WRR in China as a national policy. The control variables mainly include precipitation, land potential and slope, the data of which come from the Resource Environment Science and Data Center. In order to further consider the impact of other factors, the data used also include irrigated land area and cultivated land area. In order to further clarify which types of WSI technologies have been promoted by WRR, the variables in this study also include spray and drip irrigation areas, micro-irrigation areas, low-pressure tube irrigation areas and other water-saving areas. For further analysis, we also obtain other variables, including agricultural water use, agricultural water productivity, gross domestic product, sown area, grain area and cash crop area. Also, the data excluding the control variables come from the National Bureau of Statistics of China. The data are used from 31 provinces between 2004 and 2019, thus there is 496 observations in this study.

Table 1 | Summary statistics for variables

Variables	**Mean**	**S.D.**	**Min**	**Max**	***N***
WSI area (1,000 ha)	913.4039	901.7165	9.0200	4,247.8301	496
Reform (0/1)	0.2258	0.4185	0.0000	1.0000	496
Precipitation (mm)	899.9490	531.3017	36.6000	2,628.2000	496
Land potentiality (t/hectare)	2.3880	1.8269	0.0042	6.4313	496
Slope (1 means standard hill slope)	1.1710	1.2910	0.0044	5.4142	496
Irrigation land area (1,000 hectares)	2,007.5994	1,556.4453	103.9200	6,208.2300	496
Cultivated land area (1,000 hectares)	4,222.7641	3,109.8181	187.6000	15,865.9004	496
Spray and drip irrigation area (1,000 hectares)	108.3414	218.2628	0.0000	1,661.1700	496
Micro-irrigation area (1,000 hectares)	108.1100	427.0874	0.0000	3,681.5400	496
Low-pressure tube irrigation area (1,000 hectares)	241.2342	480.8185	0.0000	2,816.3701	496
Other water-saving area (1,000 hectares)	455.7183	436.7873	0.0000	2,519.5801	496
Agricultural water use (0.1 billion m^3)	120.3244	102.2094	3.7000	561.7000	496
Agricultural water productivity (CNY/ m^3)	9.4456	5.8019	0.9297	32.9724	496
Gross domestic product (0.1 billion CNY)	958.2938	713.9312	43.3300	3,194.7668	496
Sown area (1,000 hectares)	5,205.7254	3,696.4746	88.6000	14,783.4004	496
Grain area (1,000 hectares)	3,109.5121	2,497.0928	46.5153	11,219.5498	496
Cash crop area (1,000 hectares)	2,096.2133	2,240.6406	42.0847	13,352.1992	496

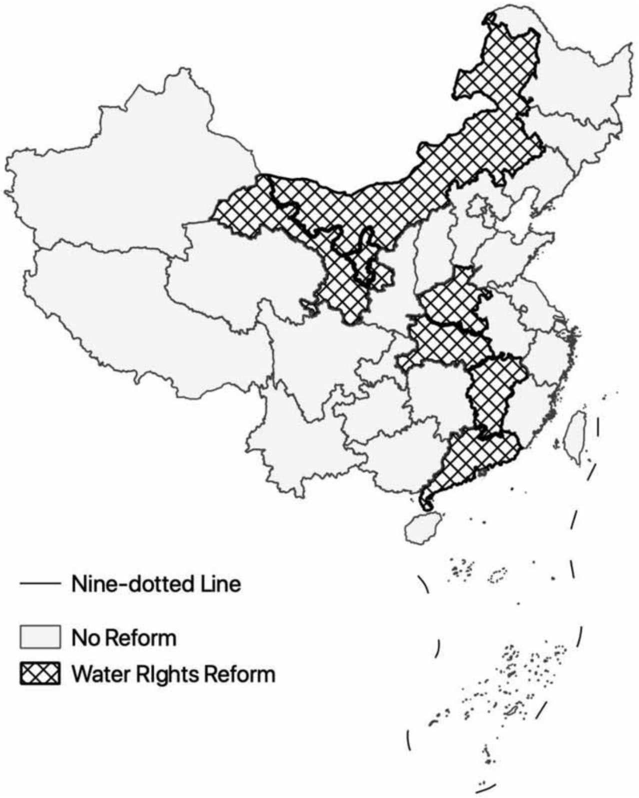

Figure 1 | The WRR in China.

3. RESULTS

3.1. Baseline results

Table 2 shows the estimation results of the baseline specification. In addition to the fixed effects, there are no control variables in column 1 at all, columns 2–4 include a natural water-related variable (precipitation), a land-related variable (land

Table 2 | Baseline estimation

	Dependent variable: Ln WSI area				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × Post	0.1369***	0.1366***	0.1364***	0.1374***	0.1363***
	(0.0397)	(0.0397)	(0.0397)	(0.0383)	(0.0392)
Constant	6.5321***	6.5422***	6.6326***	6.4168***	6.4032***
	(0.0333)	(0.0509)	(0.0683)	(0.0512)	(0.1357)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	496	496	496	496	496
R^2	0.5160	0.5161	0.5320	0.5671	0.5696

Notes: Standard errors in parentheses. $^{***}p < 0.01$.

potential), and a geography variable (slope) respectively, and column 5 is a specification with full variables mentioned above. Column 1 shows that the WRR can increase the land area for WSI at a significance level of 1%. Specifically, the WRR can expand the land area for high-efficiency irrigation by an average of 13.69%. Columns 2–4 are all consistent with the previously mentioned results in column 1, and the relationship is all significant at the 1% level. According to the estimation results including all the control variables, compared with other provinces, the land area for WSI can be increased by an average of 13.63% in the provinces with WRR, which is a relatively large increase. Therefore, the WRR can promote the expansion of land area for WSI, and the increase is relatively large.

To ensure the credibility of the estimated results, the event study method is used in Table 3 to estimate the dynamic effects of the WRR on the land area for WSI. It should be noted that in different time periods, the impact of the WRR on the land area for WSI is the result of a comparison with the previous year before the reform. Column 1 indicates that participation in the WRR starts to affect the land area for WSI significantly at the level of 10% in the second year. The estimates in columns 2–3 are consistent with the estimates in column 1. The results in column 4 show that participation in the WRR started to affect the WSI area significantly at the 10% level in the fourth year after the policy took place. The results can be expressed in Figure 2. Participation in the reform does not significantly affect the land area for WSI before the policy occurs, however, its impact starts to become significant after the policy occurs. Therefore, the baseline results have a certain degree of credibility, which also shows that the WRR can effectively promote the expansion of land area for WSI.

3.2. Robust analysis

The impact of WRR on WSI areas has been analyzed previously. In order to ensure the robustness of the estimation results, re-estimation will be carried out considering alternative outcome measures, confounding policies, and subsample.

3.2.1. Re-estimation with alternative outcome measures

The benchmark model analyzes the influence of the WRR on the absolute quantity of land area for WSI, which is further estimated by replacing alternative variables to ensure robustness. In the following, we will further consider the size of the irrigated land area and the cultivated land area, and use the relative size of the land area for WSI to the irrigated area and the cultivated area.

Table 4 shows the results of the re-estimation using the WSI rate relative to the irrigated area. Column 1 shows that the WRR can significantly increase the rate of WSI. Specifically, the WRR can increase the rate of WSI by an average of 13.18%. The results in columns 2–4 show that the WRR can still increase the rate of WSI significantly, and the estimated results are consistent with the results in column 1. Column 5 is the estimation result including full variables. Compared with other provinces, the WSI rate of the provinces with WRR can increase by 13.03% on average. To further ensure the credibility of the estimation results, the event study method is used, and Figure 3 shows the estimation results. The results show that before the policy occurs, participation in WRR does not affect the rate of WSI, and it is only significant at the 10% level in the fourth year after the WRR. Therefore, after being re-estimated by replacing the dependent variable with the rate of WSI relative to the irrigated area, the estimated results are still robust.

Table 5 shows the results of the re-estimation using the WSI rate relative to the cultivated area. The column 1 shows that the WRR can significantly increase the rate of WSI. Specifically, the WRR can increase the rate of WSI by an average of 11.18%. The results in columns 2–4 show that the WRR can still increase the rate of WSI significantly, and the estimated results are consistent with the results in column 1. Column 5 is the estimation result including full variables. Compared with other provinces, the rate of WSI in the provinces with WRR can increase by 11.34% on average. To further ensure the credibility of the estimation results, the event study method is used, and Figure 4 shows the estimation results. The results show that before the policy occurs, participation in WRR does not affect the rate of WSI, and it is only significant at the 10% level in the third year after the WRR. Therefore, after being re-estimated by replacing the dependent variable with the WSI rate relative to the cultivated area, the estimated results are still robust.

3.2.2. Re-estimation after considering contemporaneous water-related policy

A potential problem with the above estimates is that the impact of the WRR on the land area for WSI may come from other policies occurring at the same time. In China, the policy that is close to the WRR and may also affect the land area for WSI is the Agricultural Water-Saving Outline proposed in 2012. This policy is implemented to save agricultural irrigation water, mainly through subsidies to promote the land area for WSI. In order to avoid the estimation bias caused by the policy,

Table 3 | Flexible estimation

	Dependent variable: ln WSI area				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × 2004	0.0374	0.0376	0.0509	−0.0060	−0.0190
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2005	0.0071	0.0074	0.0156	−0.0180	−0.0234
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2006	0.0260	0.0262	0.0334	0.0020	−0.0054
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2007	0.0380	0.0376	0.0453	0.0132	0.0054
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2008	0.0499	0.0499	0.0547	0.0316	0.0233
	(0.1095)	(0.1096)	(0.1097)	(0.1056)	(0.1083)
Reform × 2009	0.0722	0.0717	0.0756	0.0580	0.0519
	(0.1095)	(0.1098)	(0.1097)	(0.1056)	(0.1084)
Reform × 2010	0.0940	0.0946	0.0954	0.0854	0.0769
	(0.1095)	(0.1099)	(0.1097)	(0.1056)	(0.1084)
Reform × 2011	0.1356	0.1352	0.1366	0.1262	0.1179
	(0.1095)	(0.1098)	(0.1097)	(0.1056)	(0.1083)
Reform × 2012	0.1338	0.1340	0.1350	0.1240	0.1147
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2014	0.0943	0.0945	0.0941	0.0939	0.0919
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2015	0.1707	0.1710	0.1758	0.1505	0.1399
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2016	0.1870*	0.1868*	0.1928*	0.1639	0.1536
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2017	0.2050*	0.2047*	0.2105*	0.1843*	0.1761
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2018	0.2414**	0.2410**	0.2460**	0.2212**	0.2108*
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Reform × 2019	0.2797**	0.2794**	0.2847***	0.2605**	0.2531**
	(0.1095)	(0.1097)	(0.1097)	(0.1056)	(0.1083)
Constant	6.4999***	6.5034***	6.5966***	6.3852***	6.3412***
	(0.0407)	(0.0569)	(0.0730)	(0.0567)	(0.1418)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	496	496	496	496	496
R^2	0.5235	0.5236	0.5394	0.5749	0.5769

Notes: Standard errors in parentheses. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

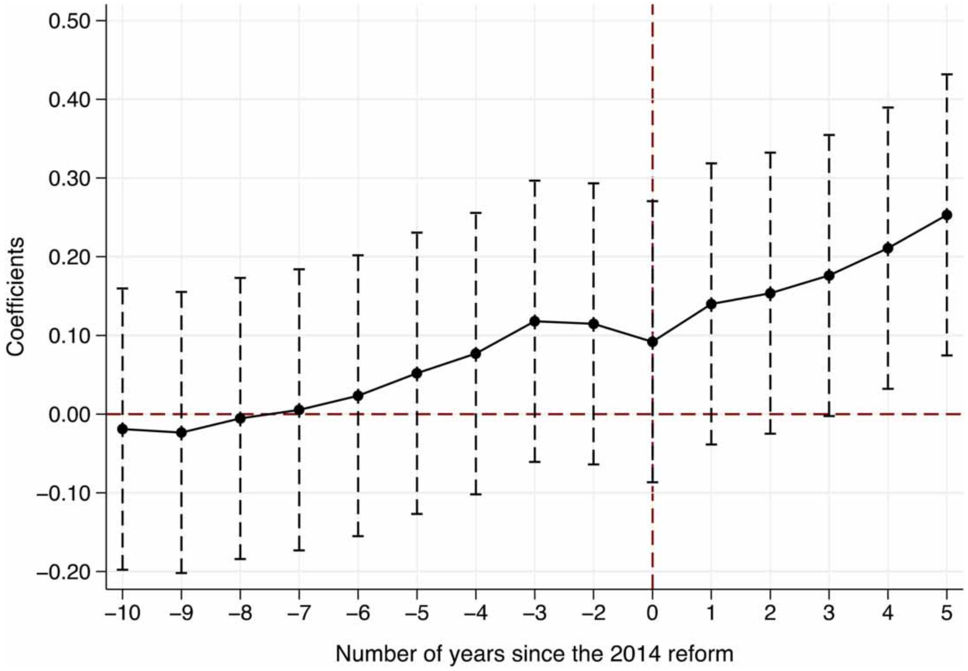

Figure 2 | Flexible estimation in baseline estimation.

according to Xu & Yang (2022), we try to avoid the impact of the contemporaneous policy by controlling the interaction between suitable arable land area and whether the policy occurs.

Table 6 shows the results of estimating the impact of the WRR on the land area for WSI. Column 1 shows that the WRR can increase the land area for WSI by an average of 10.40%, and the estimated coefficient is significant at the 1% level. The estimated results of columns 2–4 are not much different from those of column 1, so after including control variables, consistent estimated results can still be obtained. Column 5 includes the full variables, and the estimation results show that the WRR can promote the expansion of WSI areas significantly. Specifically, compared with other provinces, the land area for WSI in provinces participating in WRR can increase by an average of 10.41%. From the estimation results in columns 1–5, it can be found that the contemporaneous policy increase the land area for WSI significantly. After considering the contemporaneous

Table 4 | Estimation with WSI rate compared to irrigation land area

	Ln (WSI area/irrigation land area)				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × Post	0.1318***	0.1313***	0.1330***	0.1294***	0.1303***
	(0.0427)	(0.0428)	(0.0432)	(0.0418)	(0.0428)
Constant	−0.7211***	−0.7048***	−0.6796***	−0.7904***	−0.8421***
	(0.0359)	(0.0548)	(0.0743)	(0.0560)	(0.1481)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	496	496	496	496	496
R^2	0.3655	0.3658	0.3746	0.4156	0.4204

Notes: Standard errors in parentheses. $***p < 0.01$.

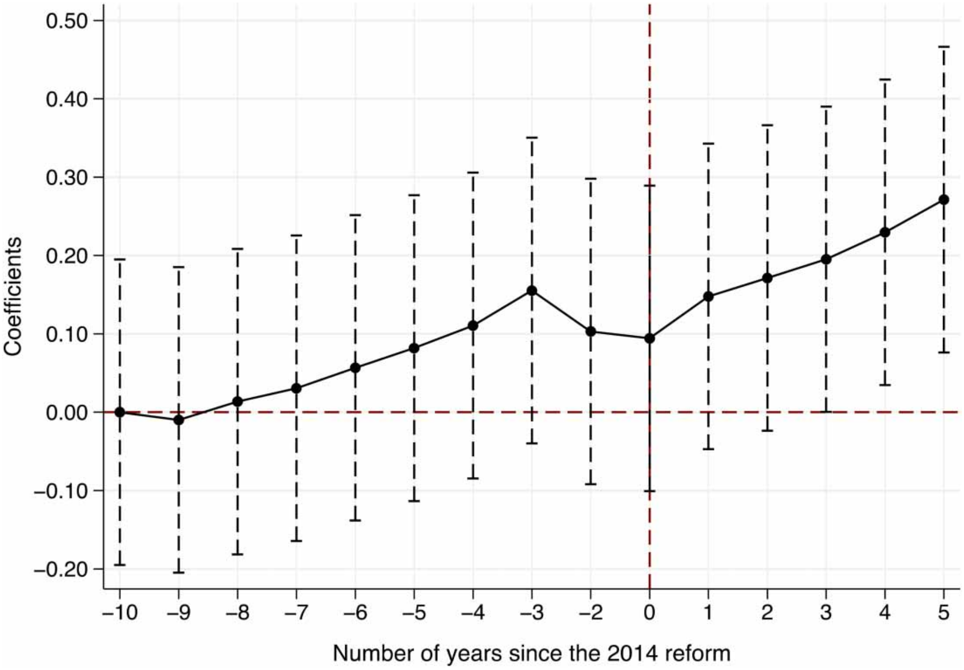

Figure 3 | Flexible estimation with WSI rate compared to irrigation land area.

policy, the estimated coefficient has decreased compared with the baseline model. The possible reason is that the increase in land area for WSI is partly due to the impact of contemporaneous policy. Using the specification that includes all control variables, it is estimated by the event study method. The results are shown in Figure 5. It can be found that whether to participate in WRR does not affect the land area for WSI before the policy occurs, but in the third year after the policy occurs, whether to participate in WRR starts to affect the land area for WSI significantly. Therefore, after considering contemporaneous policy, the estimated results are still robust.

3.2.3. Re-estimation with a subsample

To avoid the bias caused by sample selection, the following re-estimation is performed by deleting the sub-samples of the special municipalities, including, Tianjin, Beijing, Chongqing and Shanghai. Table 7 shows the re-estimation after deleting

Table 5 | Estimation with WSI rate compared to cultivated land area

	Ln (WSI area/cultivated land area)				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × Post	0.1118***	0.1122***	0.1143***	0.1083***	0.1134***
	(0.0378)	(0.0378)	(0.0381)	(0.0369)	(0.0376)
Constant	−1.4095***	−1.4245***	−1.3785***	−1.4865***	−1.6316***
	(0.0318)	(0.0484)	(0.0656)	(0.0494)	(0.1300)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	496	496	496	496	496
R^2	0.4676	0.4678	0.4771	0.5124	0.5209

Notes: Standard errors in parentheses. $***p < 0.01$.

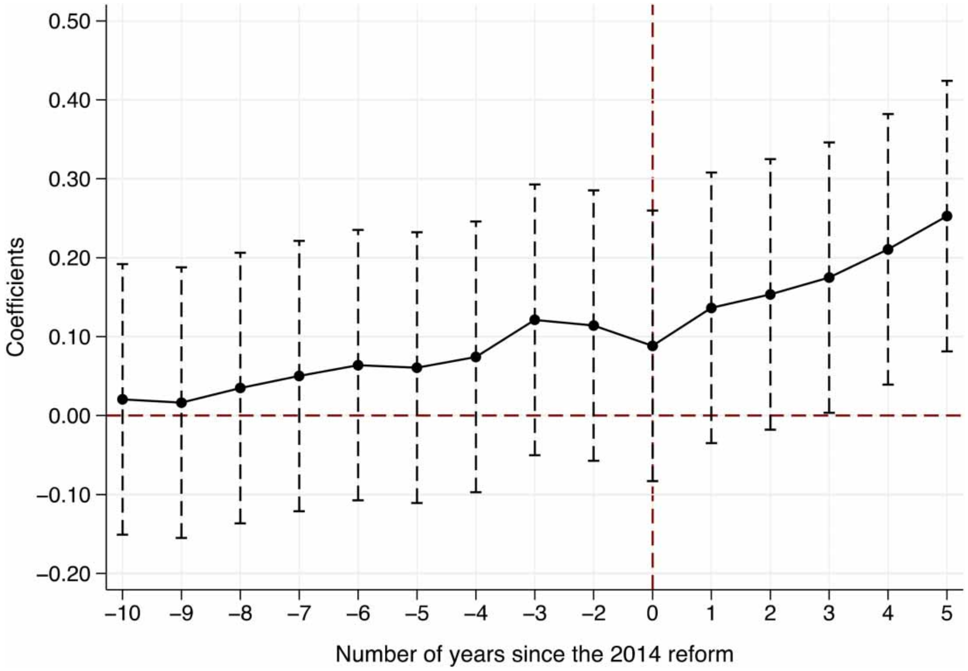

Figure 4 | Flexible estimation with WSI rate compared to cultivated land area.

the special municipalities as mega cities. Column 1 shows that under subsample regression, the WRR can still significantly increase the land area for WSI at the level of 5%. Specifically, the WRR can increase the land area for WSI by an average of 9.87%. The findings of columns 2–4 are not much different from those in column 1, and they are all significant. The estimated results in column 5 show that, compared with other provinces, the land area for WSI of the provinces with WRR can increase by 9.01% on average, and the estimated coefficient has decreased compared with the baseline model. The possible reason is that, in the mega cities, the increase in the land area for WSI brought about by the WRR will be greater than in other

Table 6 | Estimation addressing contemporaneous policy: agricultural water-saving outline

	Dependent variable: ln WSI area				
	(1)	(2)	(3)	(4)	(5)
Reform × Post	0.1040***	0.1036***	0.1036***	0.1025***	0.1041***
	(0.0391)	(0.0392)	(0.0392)	(0.0373)	(0.0381)
Ln Land × Post 2012	0.0724***	0.0724***	0.0721***	0.0821***	0.0851***
	(0.0142)	(0.0142)	(0.0141)	(0.0137)	(0.0141)
Constant	5.7260***	5.7365***	5.8289***	5.4868***	5.3884***
	(0.1609)	(0.1652)	(0.1711)	(0.1631)	(0.2132)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	496	496	496	496	496
R^2	0.5427	0.5428	0.5585	0.6002	0.6040

Notes: Standard errors in parentheses. $^{***}p < 0.01$.

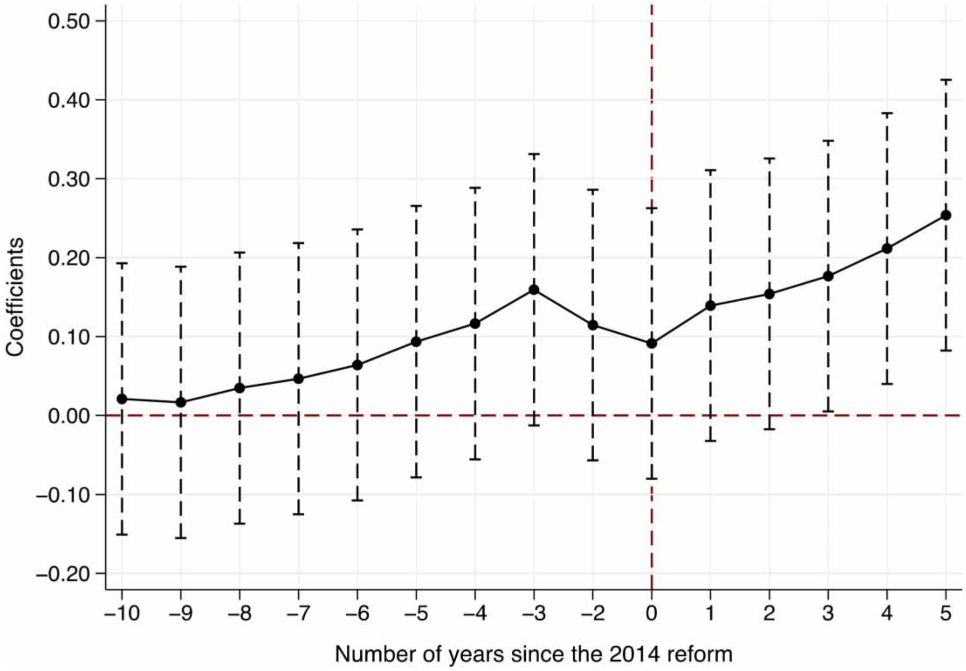

Figure 5 | Flexible estimation addressing contemporaneous policy.

Table 7 | Estimation with subsample: excluding municipality directly under the central government

	Dependent variable: ln WSI area				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × Post	0.0987**	0.0981**	0.0988**	0.0912**	0.0901**
	(0.0388)	(0.0389)	(0.0388)	(0.0374)	(0.0383)
Constant	6.7192***	6.7416***	6.7759***	6.6347***	6.6273***
	(0.0344)	(0.0516)	(0.0662)	(0.0539)	(0.1333)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	No	Yes	No	No	Yes
Land potentiality	No	No	Yes	No	Yes
Slope	No	No	No	Yes	Yes
Observation	432	432	432	432	432
R^2	0.5821	0.5825	0.5977	0.6337	0.6360

Notes: Standard errors in parentheses. $^{**}p < 0.05$, $^{***}p < 0.01$.

regions. Using the specification that includes all control variables, it is estimated by the event study method, which is shown in Figure 6. It can be found that whether to participate in WRR does not affect the land area for WSI before the policy occurs, but in the fourth year after the policy occurs, whether to participate in WRR starts to affect the land area for WSI significantly. Therefore, after considering subsample regression, the estimated results are still robust.

4. DISCUSSION

The previous section has analyzed the impact of WRR on the overall WSI area, but it is not clear which types of water-saving technologies have increased. Based on this, it is further discussed below which types of WSI technologies have been adopted.

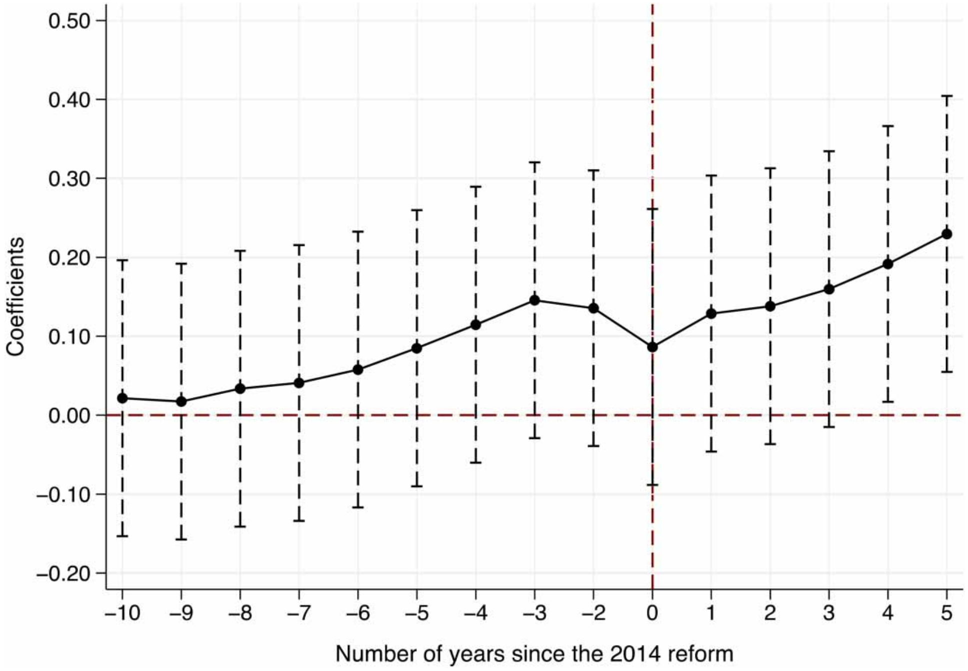

Figure 6 | Flexible estimation addressing subsample.

Since WSI technology plays an important role in agricultural production, the impact of WRR on agricultural production is further discussed below. Since this article is based on the analysis of provincial panel data, it is difficult to conduct further analysis of the internal mechanism of individual farmers adopting WSI technology, which needs to be further examined by other micro-level studies.

4.1. The effect of WRR on WSI technologies

The results are consistent with the previous research by Mu *et al.* (2022), Zhang *et al.* (2021) and Fang & Zhang (2020). Mu *et al.* (2022) indicate that the WRR can effectively improve WSI technology. Fang & Zhang (2020) suggest that farmers tend to actively promote irrigation technology and reduce agricultural water use after the WRR. Zhang *et al.* (2021) also indicate that the main channels of water-saving effects from the policy are the promotion of agricultural technology innovation and the water rights transfer to high water-consuming industries. Based on this, what kind of WSI area will increase the most after the WRR deserves further discussion. Based on this, the impact of the WRR on WSI technologies will be further analyzed below. The Table 8 shows the results estimating the effect of the WRR on various kinds of WSI technologies.

As a comparison group, column 1 shows that the WRR can increase the land area for WSI by 13.63% on average, and it is significant at the level of 1%. The dependent variable in column 2 is the logarithmic form of the spray and drip irrigation area. Column 2 shows that the WRR can increase the spray and drip irrigation area by 43.11% on average, and it is also significant at the level of 1%. The dependent variable in column 3 is the logarithmic form of the micro-irrigation area. Column 3 shows that the WRR can increase the micro-irrigation area by 67.30% on average, and it is also significant at the level of 1%. The dependent variable in column 4 is the logarithmic form of the low-pressure tube irrigation area. Column 4 shows that the WRR can increase the low-pressure tube irrigation area by an average of 13.72%, but the estimated result is not significant. The dependent variable in column 5 is the logarithmic form of other WSI areas, including other non-mainstream WSI technologies. Column 5 shows that the WRR can reduce other WSI area by 2.98% on average, but the estimated result is not significant. To sum up, the WRR has mainly promoted the increase of spray and drip irrigation areas, and micro-irrigation land area, which are high-efficiency technologies for irrigation.

4.2. The impact of WRR on agricultural production

Gao *et al.* (2014) showed that WSI is an important technology to promote agricultural production. Rosa *et al.* (2018) indicate that a shift from rain-fed agriculture to irrigated agriculture will increase the yield of agriculture. The reform of the water

Table 8 | The effect of WRR on WSI technologies

	Dependent variable: ln land area of WSI technologies				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Reform × Post	0.1363***	0.4311***	0.6730***	0.1372	−0.0298
	(0.0392)	(0.1165)	(0.1337)	(0.1341)	(0.0949)
Constant	6.4032***	3.7672***	5.2826***	4.6137***	5.1023***
	(0.1357)	(0.4029)	(0.4623)	(0.4637)	(0.3281)
Province	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Precipitation	Yes	Yes	Yes	Yes	Yes
Land potentiality	Yes	Yes	Yes	Yes	Yes
Slope	Yes	Yes	Yes	Yes	Yes
Observation	496	496	496	496	496
R^2	0.5696	0.2929	0.7211	0.5050	0.1526

Notes: The dependent is logarithmic form of WSI land area in column 1. The dependent is logarithmic form of spray and drip irrigation land area in column 2. The dependent is logarithmic form of micro-irrigation land area in column 3. The dependent is logarithmic form of low-pressure tube irrigation land area in column 4. The dependent is logarithmic form of other WSI land area in column 5. Standard errors in parentheses. $^{***}p < 0.01$.

rights system can promote the popularization of WSI technology, so whether it is beneficial to agricultural production deserves further discussion. The WRR can further guarantee agricultural production after promoting the expansion of the land area for WSI. However, whether the WRR can significantly promote agricultural production needs further testing with empirical data. Table 9 shows the results of estimating the effect of the WRR on agricultural production. Note that all the dependent variables of the model are in logarithmic form.

Column 1 indicates that the WRR can increase water use in agriculture by about 0.39%, but the estimated coefficient is not significant. Column 2 clarifies the impact of the WRR on the agricultural water use productivity (agricultural value added per unit of water used). The WRR can increase water productivity in agriculture at a significant level of 5%. Specifically, compared with other provinces, the agricultural water productivity of provinces with WRR can increase by an average of 5.66%. Although the impact of the WRR on agricultural water use is not significant, the WRR can promote the added

Table 9 | The effect of WRR on agricultural production variables

	Dependent variable: ln agricultural production variables					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Reform × Post	0.0039	0.0566**	0.0605***	0.0747***	0.0957***	0.1410***
	(0.0258)	(0.0228)	(0.0195)	(0.0245)	(0.0301)	(0.0389)
Constant	4.2840***	2.5333***	6.8173***	8.0188***	7.3587***	7.0225***
	(0.0892)	(0.0787)	(0.0674)	(0.0848)	(0.1042)	(0.1344)
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Precipitation	Yes	Yes	Yes	Yes	Yes	Yes
Land potentiality	Yes	Yes	Yes	Yes	Yes	Yes
Slope	Yes	Yes	Yes	Yes	Yes	Yes
Observation	496	496	496	496	496	496
R^2	0.0669	0.8123	0.8465	0.1318	0.1228	0.2944

Notes: The dependent is logarithmic form of agricultural water use in column 1. The dependent is logarithmic form of agricultural water productivity in column 2. The dependent is logarithmic form of agricultural value added in column 3. The dependent is logarithmic form of sown land area in column 4. The dependent is logarithmic form of sown grain land area in column 5. The dependent is logarithmic form of sown cash crop land area in column 6. Standard errors in parentheses. $^{**}p < 0.05$, $^{***}p < 0.01$.

value that can be realized per unit of water resources used in agricultural production. Column 3 estimates the impact of the WRR on agricultural value added. Column 3 shows that the WRR can significantly increase the added value of agriculture, specifically, the WRR can increase the added value of agriculture by an average of 6.05%. The promotion effect of the WRR on the added value of agriculture and the estimated results in columns 1–2 can be mutually confirmed. Column 4 clarifies the impact of the WRR on the sown area of crops. Column 4 shows that the WRR can increase the sown area of crops at a significant level of 1%, and its increasing effect can reach 7.47%. This shows that the possible reason why the WRR promotes the increase of agricultural added value is due to the expansion of crop sown area. Columns 5–6 clarify the impact of the WRR on the sown area of grain crops and the sown area of cash crops, respectively. Columns 5–6 show that the WRR not only promotes the expansion of the sown area of grain crops at the 1% significant level, but also significantly increases the sown area of cash crops. Specifically, the WRR increases the sown area of grain crops by 9.57% and the sown area of cash crops by 14.10%. This shows that the WRR has increased the sown area of cash crops more than the sown area of food crops, which indicates that the WRR is more beneficial to cash crops than grain crops.

5. CONCLUSION

This study takes China's WRR as an example, with China's panel data from 2004 to 2019, and adopts a DID model to empirically analyze the impact of WRR on the land area for WSI. The estimated results indicate that the WRR can increase the land area for WSI at a significant level of 1%. Specifically, compared with other provinces, the land area for WSI could increase by an average of 13.63% in the provinces with WRR, which is a relatively large increase. The event study indicates that participation in WRR does not significantly affect the land area for WSI before the policy occurs, and its impact starts to become significant in the fourth year after the policy occurs. The robust results could be obtained when alternative outcome measures are used, a contemporaneous policy is considered, and subsample regression is applied. Furthermore, the WRR could promote the expansion of spray and drip irrigation areas and micro-irrigation land areas, which are high-efficiency irrigation technologies. Specifically, the WRR could increase the spray and drip irrigation area by 43.11% on average and the WRR could increase the micro-irrigation area by 67.30% on average. In addition, the WRR also could improve agricultural production by increasing agricultural water productivity and planting area (including the sown area of grain crops and cash crops), but it has not reduced agricultural water extraction. Therefore, the WRR could increase agricultural production without increasing agricultural water extraction.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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