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Do water saving technologies save water? Empirical evidence from North China ☆

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A B S T R A C T

This paper describes the extent of water saving technologies usage and evaluates their impacts on water use, water productivity, total irrigated sown area and crop mix in North China. A set of panel data collected at the househol.d and plot levels is used in empirical analysis. Water saving technologies are categorized into traditional technologies, household-based technologies and community-based technologies. By 2007, traditional technologies and household-based technologies are used in almost all sample villages. However, the shares of sown area on which water saving technologies are used are still fairly low. Econometric analysis using plot level fixed effects show that using water saving technologies can reduce crop water use and improve the productivity of water. The positive effects are generated mainly through the use of household-based or community-based technologies. The use of water saving technologies does not have statistically significant impacts on total irrigated sown area and crop mix.

Background

China's agriculture is increasingly threatened by the ever growing gap between the quantity of water demanded and the available water supply. Although China's government is still intent on maintaining a high level of food self-sufficiency, the share of water allocated to the agricultural sector has declined and is likely to continue to decline (Wang et al., 2013). Water is the most limiting factor in agricultural production, which puts a tremendous amount of pressure on national food security. More efficient irrigation is one of the tools most developed countries have relied on to alleviate the pressure of water shortages on agricultural production (World Bank, 2009). It may work for China too.

Although the research on water saving technologies has begun since the 1950s and some technologies have become common practices in agricultural production by the 1970s, China's government did not start to promote them nationwide until the 1990s (Jia and Jiang, 2000). The development and extension of water saving technologies first started with simple surface irrigation technologies such as furrow and boarder irrigation. More recent efforts are focused on modern irrigation technologies that can generate much larger water savings. Since 2000, water saving irrigation projects have been developed at a rapid pace. Both areas irrigated under water saving irrigation projects and their shares in China's total irrigated area

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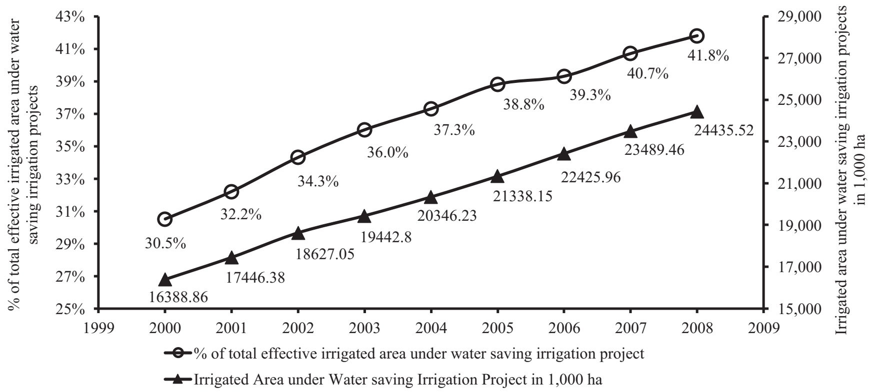

Fig. 1. Changes in irrigated area under water saving irrigation projects over years.
Source: Yearbook of China Water Resources, 2001–2009.

have been increasing at a steady rate (Fig. 1). The government continues its policy efforts and water investments. In 2009, the General Office of the State Council of China issued the document “National Water-saving Irrigation Planning,” which specified that by 2020 the area irrigated under water saving irrigation projects should reach 80% of the nation's effective irrigate area. The same document also stated that the government planned to invest a total amount of about 150 billion yuan in water saving irrigation projects during the twelfth “Five-year” plan period (2011–2015). In January 2011, the government's annual “No. 1 Document,” which reflects its top policy priorities, set the goal of achieving an irrigation efficiency of 0.55 by 2020. It also outlined the plan to expedite water conservancy development and reform and quadruple total investment in solving water problems to four trillion yuan in the next 10 years. Given the importance of finding a solution to the water shortage problem and the large sums the government spent on water saving irrigation projects, it is important to evaluate the effectiveness of water saving technologies.

There is an emerging literature investigating the effects of irrigation efficiency improvements. Both theoretical modeling (e.g., Huffaker, 2008) and studies that use programming models or simulations (e.g., Peterson and Ding, 2005; Ward and Pulido-Velazquez, 2008) show that more efficient irrigation may or may not reduce water use, depending on a variety of economic and hydrologic factors. Although more efficient irrigation technologies have the potential of reducing water use, they may also bring unintended consequences. Higher irrigation efficiency reduces the effective price of applied irrigation water and the savings provide additional irrigation capacity. Profit-maximizing producers may respond to this by expanding irrigated acreage or changing cropping mix. Thus conservation measures may cause more water to be diverted as a result of expansions at the extensive margins (Huffaker and Whittlesey, 1995; Ward and Pulido-Velazquez, 2008). In addition, not all water saving technologies can achieve their expected levels of water saving after adoption. The effectiveness of water saving technology also depends on factors such as farmers’ skills in implementing a technology and the production environment (e.g., soil characteristics). Without controlling for these factors, we cannot answer the question whether water saving technologies have worked outside experiment fields and gauge the magnitudes of water savings they have generated. Therefore, the effects of more efficient irrigation technologies remain an empirical question.

Despite the importance of the issue, partly due to lack of data, few studies are available to examine the question with observational data (in contrast to simulation models). Using field level data, Pfeiffer and Lin (2014) found in their econometric analysis that the conversion from center pivots to center pivots with low-pressure nozzles is accompanied by an increase in groundwater extraction. Wallander and Hand (2011) evaluated the impact of the Environmental Quality Incentives Program (EQIP), which provides subsidies for irrigation technology usage, on water use. Their analysis of the farm-level data from the Farm and Ranch Irrigation Survey showed that EQIP may have reduced water application rates per acre but increased total water use due to expansions in irrigation acreage.

Inside China, the literature on the impact of water saving technologies on water use is also limited. Most existing studies only used qualitative analysis (Zhang and Cai, 2001; Zhang et al., 2002; Deng et al., 2006). The few studies with quantitative analysis used data either from experiment fields or from only one or two pilot project sites (Wang and Li, 2005; Wang, 2007; Ding et al., 2009; Zhao and Wang, 2010). The analysis only compared water use before and after the use water saving technologies without controlling for any confounding factors (e.g., Hu et al., 2002; Liu and Kang, 2006). Very few studies have used data that cover large geographic areas to general broad policy implications.

The challenge of China's agricultural sector is to maintain crop production with a shrinking supply of irrigation water. Can water saving technologies be the solution? To answer this question, an in-depth understanding of the effects of water saving technologies on farmers’ water use is needed to guide policy efforts regarding water saving technologies. The objective of this study is to provide estimates of the impacts of different types of water saving technologies on water use. To achieve this objective, the authors have conducted a panel household survey in two of the most water scarce areas in north China: Yellow River Basin (YRB) and Hai River Basin (HRB). The sample areas of the survey cover Henan and Ningxia provinces in the YRB and Hebei province in the HRB. In all three sample provinces, agriculture takes up a large share of total water use. During the survey, 77 sample villages were randomly selected from the three sample provinces. The first round of the survey was conducted in 2001, which collected information on years 1995 and 2001. The second round of the survey collected information on year 2004. The third round collected information on year 2007. In the sample villages, the survey successfully tracked 118 households and 142 plots over the three panels of survey. The survey has collected detailed information on a wide range of water saving technologies that were used in the village, the characteristics of water resources and socio-economic characteristics of the villages and households. Farmers were also asked to report their input uses (e.g., water and fertilizer) in agricultural production at the plot level. Since climate conditions such as precipitation and temperature have a large influence on water use, climate data were obtained from China Meteorological Administration to supplement the survey data.

The detailed and large coverage of information collected in the survey enables us to control for factors that affect water use. More importantly, with a set of panel data, we can use household level or plot level fixed effects to control for any unobserved heterogeneity that may affect the choices of water saving technologies as well as to use instrumental variable estimation and thus address the potential endogeneity of water saving technologies. The rest of the paper first reports the descriptive findings on the spread of water saving technologies in rural China and compare crop water use, water productivity, irrigated sown area and crop mix under different groups of water saving technologies. The next section presents variable descriptions and the econometric method. The fourth section reports findings from regression results and the last section concludes. It should be noted that the term water-saving is used in a loose sense in that these technologies reduce the amount of applied water but do not necessarily generate real water saving (reduction in consumptive water use or evapotranspiration, Blanke et al., 2007).

Descriptive analysis of the use of water saving technologies and their impacts

The water saving technologies analyzed in this study are those implemented at the field level. In both field trips and survey data, a wide range of technologies has been observed. If each individual technology is analyzed, the analysis would be lengthy without much additional insights. In addition, some technologies are only used by a few households in the sample. There would not be enough degrees of freedom in econometric analysis to include other confounding factors. In the rest of this paper, based on several characteristics (magnitude of initial investment or fixed cost, whether a single household could use it on its own, and the time period the technology became widely used), the technologies observed in the survey sites are categorized into three types: traditional technologies, household-based technologies and community-based technologies.

Traditional technologies include border irrigation, furrow irrigation and field leveling. Farmers in our sample have had a long history of using these technologies. Some have started as early as the 1950s. These irrigation methods are not capital intensive. Because most Chinese farms are smaller than one acre, usually only a few days of labor are required to build the furrows or level the fields. Individual farm household can practice them independently. In contrast to traditional technologies, both household-based technologies and community-based technologies have become in use only after the 1980s. Household-based technologies include surface level plastic irrigation pipe. Drought resistant varieties, plastic sheeting and retaining stub/low till are also included. Although these are not irrigation technologies, they have the potential to save water. Similar to traditional technologies, household-based technologies do not require a large capital investment up front and can be used by individual households. Community-based technologies include underground pipe systems, lined canals, sprinkler systems and drip irrigation systems. Individual households usually cannot afford the large initial capital investment these technologies require. So they are often used at the village level or by groups of households instead of individual households.

The survey data show that there has been a wide spread of water saving technologies across sample areas. In 1995, 42% of the sample villages had used one or more water saving technologies (Table 1). By 2004, this share has jumped to 99%. This jump is driven by the increased use of traditional and household-based technologies. By 2007, the share of villages that have used traditional or household-based technologies have reached 99% and 96% respectively. This is in contrast to the much slower spread of the community-based technologies. Even in 2007, the share of villages that have used any of the community-based technologies was still only 55%.

Table 1
Percent of villages using water-saving technologies by type and by year (%).

Type of water saving technology	1995	2004	2007
Any technology	42	99	100
Traditional technologies	42	99	99
Household-based technologies	19	95	96
Community-based technologies	6	51	55

a. Traditional technologies include border and furrow irrigation and field leveling.
b. Household-based technologies include plastic sheeting, drought resistant varieties, retaining stub/low till and surface level plastic irrigation pipe.
c. Community-based technologies include underground pipe systems, lined canals, sprinkler systems and drip irrigation systems.

Table 2
Share of sown area using water-saving technologies by type and by year (%).

	1995	2004	2007	Overall[a]		
Traditional technologies	21	64	68	50		
	(27)	(31)	(30)	(41)	(B:21)[b]	(W:37)[b]
Household-based technologies	5	26	44	28		
	(23)	(29)	(39)	(34)	(B:25)	(W:28)
Community-based technologies	2	32	27	19		
	(18)	(42)	(39)	(34)	(B:26)	(W:26)

Standard deviations are reported in parentheses.

[a] The Overall column reports summary statistics of data pooled over years.

[b] In addition to report the overall standard deviation, standard deviations that measure between (B) and within (W) variations are also reported. Within variation is the variation across years. Between variation is the variation across villages.

Examining the share of sown area using water saving technologies paints a different picture. Even for traditional technologies, the share of sown area using any traditional technologies was as low as 21% in 1995 and rose to 68% in 2007 (Table 2). The extent of adoption is lower for household-based technologies, which were used on 44% of the sown area in 2007. It is even lower for community-based technologies, only reaching 27% of sown area. The Overall column in Table 2 reports summary statistics of data pooled over years. Overall standard deviations are also decomposed into between and within variations. Among households that used traditional technologies, the variation in the share of sown area within a village over time (within variations) was much larger than that across villages (between variations). Among households that used household-based and/or community-based technologies, between and within variations took up about the same share. In the first three columns that report statistics by year and by types of technologies, standard deviations measure variations across villages (between variations) for a given year. Among households that used traditional technologies, between variations stayed about the same level over years. Among households that used household-based and/or community-based technologies, between variations increased over years. These numbers clearly show that there is much room to extend any of the three types of water saving technologies. They also show that the use of water saving technologies was not universal within villages and is likely to be influenced by household level factors.

Two indicators are used to measure the effects of water saving technologies at the intensive margins. The first indicator is the crop-specific plot level irrigation water applied per unit of land. The unit is m^3/ha. The second indicator is the productivity of water (kg/m^3), defined as the amount of crop produced per unit of irrigation water applied (Molden et al., 2010). Since wheat and corn are the major crops produced in all three sample provinces, the analysis focuses on wheat and corn production. Because on most plots more than one type of technologies are practiced, we compare the differences between three main groups: plots that only used traditional technologies, plots that used both traditional and household-based technologies, plots that used all three types of technologies. The three groups comprise 89% of wheat plots and 92% of corn plots. The remaining plots include those that did not use any technology, those that only used household-based technologies, those that used both traditional and community-based technologies, and those that used both household and community-based technologies.

Descriptive analysis provides clear evidence that using household-based or community-based technologies may reduce crop level water use (Table 3). On average (over years and cross plots), only 4,664 m^3 of water is used to irrigate one hectare of wheat on plot that used both traditional and household-based technologies. This is a 9.8% reduction from plots that only used traditional technologies (5,175 m^3/ha). The difference is statistically significant at 5% level. Water use is further reduced to 3,530 m^3/ha if all three types of technologies are used on the plot, representing a 32% reduction from 5,175 m^3/ha. The difference is statistically significant at 1% level. The effect is stronger on corn plots. Corn plot that used both traditional and household-based technologies used 29.5% less water than plots that only used traditional technologies. The reduction is as large as 43% on plots that used all three types of technologies. Both differences are statistically significant at 1% level.

There is also evidence to support the positive effects of using household-based or community-based technologies on water productivity. In wheat production, plots that only used traditional technologies produced 1.07 kg per cubic meter of water applied (Table 3). The same amount of water produced 30% more wheat on plots that used both traditional and household-based technologies (1.41 kg/m^3). Almost 70% more wheat is produced on plots that used all three types of technologies (1.81 kg/m^3). The improvements of water productivity in wheat production are statistically significant at 1% level. Larger positive effects are observed on corn plots. Water productivity increases from 1.90 kg/m^3 to 2.5 kg/m^3 when plots switching from traditional technology only to the combination of traditional and household-based technologies. Water productivity further increased to 4.48 kg/m^3 when community-based technologies are also added in the combination.

Two indicators are used to measure the effects of water saving technologies at the extensive margins: total irrigated sown area and crop mix. On average, between 0.86 and 0.92 ha of sown area is irrigated (Table 3). The differences between households that use different types of technologies are not statistically different. In terms of crop mix, the shares of sown area that are allocated to wheat, corn or other grain crops do not seem to differ across households that use different types of technologies. Households that used both traditional and household-based technologies seem to grow less rice than households that used only traditional technologies (14% versus 19%). Households that used all three types of technologies

Table 3
Comparison of water use and crop allocation by types of water saving technology.

	(1)[a] Only used traditional technologies	(2) Used traditional and household-based technologies	(3) Used traditional, household and community-based technologies
Plot level crop water use per unit of land (m^3/ha)			
Wheat	5,175	4,664**	3,520***
	(127)[b]	(90)	(50)
Corn	5,674	3,999***	3,226***
	(99)	(70)	(35)
Plot level water productivity (kg/m^3)			
Wheat	1.07	1.41***	1.81***
Corn	1.90	2.50**	4.48***
Total irrigate sown area (ha)	0.89	0.86	0.92
	(280)[c]	(195)	(138)
% of sown area allocated to			
Wheat	37	38	35
Corn	31	36	33
Rice	19	14**	11***
Other grain crops[d]	3	3	4
Cash crops[e]	9	10	17***

* Indicates that differences in the means between column (1) and a column are statistically significant at 10% respectively.
** Indicates that differences in the means between column (1) and a column are statistically significant at 5% respectively.
*** Indicates that differences in the means between column (1) and a column are statistically significant at 1% respectively.
[a] Columns (1)–(3) represent three mutually exclusive groups of plots.
[b] Number of plots reported in parentheses.
[c] Number of households reported in parentheses.
[d] Other grain crops include millet, sorghum, soybean, sweet potato etc.
[e] Cash crops include cotton, peanuts, fruits, vegetables and trees.

also grew less rice (11%). Rice is only grown in two of the three sample provinces: Henan and Ningxia. By-province results show that only in Henan province do we observe the shrinking shares of rice when either household-based or community-based technologies are used. Households that used all three types of technologies also grew more cash crops than other households (17% versus 9% and 10%). By-province results show that this is mostly occurring in Hebei province.

Econometric analysis

The equation used to evaluate the impact of water saving technologies on crop water use per unit of land is as follows[1]:

$$\ln\ W_{ikmt} = \boldsymbol{\alpha}_{ikm} + \mathbf{T}_{ikmt}\boldsymbol{\beta} + \mathbf{X}_{ikmt}\boldsymbol{\delta} + \mathbf{C}_t\boldsymbol{\gamma} + \varepsilon_{ikmt} \tag{1}$$

In Eq. (1), the dependent variable is the log of W_{ikmt}, which is amount of water per unit of land the kth household applied on the i^{th} plot to irrigate crop m in period t. Three periods are included (years 2001, 2004 and 2007). On the right hand side, the key variables of interest are contained in the vector $\mathbf{T}_{ikmt}$. Two specifications of $\mathbf{T}_{ikmt}$ are used. In specification 1, two dummy variables are included. The first dummy variable equals one if household-based technologies were used on a plot. The second dummy variable equals one if community-based technologies were used on a plot. Since more than one type of technology can be used on the same plot, the two dummies do not represent two mutually exclusive groups. In specification 2, three dummy variables are included to represent four groups of plots that are mutually exclusive. The first dummy equals one if both traditional and household-based technologies were used. The second dummy variable equals one if all three types of technologies were used. The third dummy variable equals one for plots that only used household-based technologies, or used both traditional and community-based technologies, or used both household and community-based

[1] Theoretically, the direction of the impact of water saving technologies at the intensive margins is ambiguous. In his benchmark analysis, Huffaker (2008) models a profit-maximizing farmer that irrigates a single crop and shows that in response to subsidized investment in on-farm irrigation efficiency, the demand for applied water increases when higher irrigation efficiency boosts the marginal productivity of water. This is expressed as $\partial^2 Y/(\partial W_A\ \partial I) > 0$, where Y denotes crop yield, W_A is the amount of applied irrigation water and I is irrigation efficiency. However, if $\partial^2 Y/(\partial W_A\ \partial I) < 0$, the demand for applied water reduces.

Practically, higher irrigation efficiency often boosts the marginal productivity of water. However, even in the more likely case when $\partial W_A/\partial I < 0$, the direction of the impact on the consumptive water use (W_C) is ambiguous. The relationship $W_C = IW_A$ implies that $\partial W_C/\partial I = W_A\ [1(\partial W_A/\partial I)(I/W_A)]$. If $(\partial W_A/\partial I)(I/W_A) > -1$, $\partial W_C/\partial I > 0$. That is, if the demand for applied water is inelastic in response to an improvement in irrigation efficiency, consumptive water use may increase.

Empirically, it is also important to examine the impacts of water saving technologies at the intensive margins. In rural China, farmers' plots are not necessarily located next to each. Since plots are spread out spatially, the decisions of using water saving technology as well as how much water to apply are made at the plot level, subject to constraints set by household level factors such as land, labor and capital. Usually only one crop is grown in a plot. Analyzing crop level water use is therefore important in the specific context of rural China.

technologies. The base group is plots that did not use any technology or only used traditional technologies.

A set of variables are included in $\mathbf{X}_{ikmt}$ to control for factors that may influence water use. Economic theory predicts that the use of irrigation water in agricultural production is influenced by the prices of output (crop price), the price of water and the prices of other inputs. Including wheat and corn prices in the regressions, however, caused collinearity problem. This is probably because crop prices do not vary much across places in rural China. Crop prices are thus excluded in the regression. The price of water differs depending on the source of irrigation water. Like their counterparts in many other countries, farmers in rural China pay for surface water irrigation on a per unit of land basis. So there is no volumetric charge for surface water within a village. In contrast, when using groundwater for irrigation, almost all farmers paid for groundwater according to the number of hours the pumps were operated to irrigate their plot. Therefore, the cost of water is closely related to the energy cost needed to lift water out of wells. The log of electricity price multiplied by the depth to groundwater in wells is included in the regression to control for the price of water. A dummy variable is also included to indicate if the plot was irrigated by surface water and thus no volumetric price is available.[2] The price of fertilizer and wage rate are included. The size of plot is included since it is likely to influence water use. Other plot characteristics such as soil type and distance to farmers' house are not included. These variables are time invariant and would be dropped in the regression if included due to the estimation method we have employed. The size of plot does vary over time because famers often split a plot into multiple parcels or combine several neighboring plots into one. Since irrigation requires labor, percent of family labor that worked off-farm is included to control for the available labor on farm. This variable may also influence water use by changing the importance of agriculture in household income. Again household size and the total number of family labor are not included because they are time invariant. Cultivated land per capita in hectare is included to control for the constraint on total amount of land farmers face in agricultural production. To measure the endowment of water resources in the village, a variable is included to measure whether water in a village is scarce. The water scarcity variable is a dummy variable constructed using answers from village leaders to questions regarding the degree of water scarcity in the village. If the leaders reported that "water is severely scarce" or "water is scarce and is one of the limiting factors in agricultural production," then the water scarcity dummy variable equals one. If the leaders reported that "water is not scarce (in the long-term or in the short-term)," then the dummy variable equals zero.

The vector, $\mathbf{C}_t$, includes county-level annual total precipitation and average temperatures. The vectors, $\boldsymbol{\beta}$, $\boldsymbol{\delta}$ and $\boldsymbol{\gamma}$, are the parameters to be estimated. The term, ε_{ikmt}, is the error term in the regression. Two year dummies are included, one for year 2004 and one for year 2007.

One econometric issue in estimating Eq. (1) is the potential endogeneity of the water saving technology variables in $\mathbf{T}_{ikmt}$. Many factors that influence water use may also affect the use of water saving technologies. One such factor is farmers' farming skill, which affects water use as well as the likelihood of using water-saving technology. If some of these factors are not controlled for in the regression, this will bias the estimated coefficients on the technology variables.

Since the survey data we collected are panel in nature, plot level fixed effects can be used to control for any unobserved time-invariant household or plot characteristics in estimating Eq. (1). The use of plot level fixed effects is denoted by the term, $\boldsymbol{\alpha}_{ikm}$, in Eq. (1). It captures any time-invariant plot level characteristics. A short explanation of the plot level fixed effects model is as follows. Lagging Eq. (1) by one time period generates Eq. (1a):

$$\ln\ W_{ikm,t-1} = \boldsymbol{\alpha}_{ikm} + \mathbf{T}_{ikm,t-1}\boldsymbol{\beta} + \mathbf{X}_{ikm,t-1}\boldsymbol{\delta} + \mathbf{C}_{t-1}\boldsymbol{\gamma} + \varepsilon_{ikm,t-1} \tag{1a}$$

Notice the lagged term of $\boldsymbol{\alpha}_{ikm}$ is itself because it is time invariant. Subtracting Eq. (1a) from (1) generates Eq. (1b):

$$(\ln\ W_{ikmt} - \ln\ W_{ikm,t-1}) = (\mathbf{T}_{ikmt} - \mathbf{T}_{ikm,t-1})\boldsymbol{\beta} + (\mathbf{X}_{ikmt} - \mathbf{X}_{ikm,t-1})\boldsymbol{\delta} + (\mathbf{C}_t - \mathbf{C}_{t-1})\boldsymbol{\gamma} + (\varepsilon_{ikmt} - \varepsilon_{ikm,t-1}) \tag{1b}$$

The term $\boldsymbol{\alpha}_{ikm}$ disappears in Eq. (1b). Estimating Eq. (1b) thus generates consistent estimates of all parameters in Eq. (1) such as $\boldsymbol{\beta}$, $\boldsymbol{\delta}$, and $\boldsymbol{\gamma}$ without the need to include all possible observed and unobserved time-invariant factors at the plot level. Because of this, we believe that the estimated coefficients on the key technology variables are not subject to endogeneity bias. One drawback of plot level fixed effects, however, is that the influence of any time-invariant characteristics cannot be analyzed although we have such information in the survey, such as soil type, the distance from the plot to the house of a household, the size of the household, the education level of the household head.

There is attrition of sample plots in the survey. There are two sources of the attrition. First, there is attrition of households. From 2004 to 2007 and from 2007 to 2011, the attrition rate of sample households is about 20%. The attrition is mostly due to households taking on off-farm work. The variable, % of family labor that worked off-farm, contained in $\mathbf{X}_{ikmt}$, in helps control for this type of attrition. Second, for households that stayed in the sample, only about half of their plots can

[2] The choice of using groundwater or surface water for irrigation is endogenous if it is correlated with factors that influence the use of water saving technologies as well as the dependent variables (crop water use or water productivity) and if these factors are not controlled for in the regression. In our survey, we asked which source of water (surface water or groundwater) farmers preferred. Surface water is clearly the preferred source of irrigation water. For example, in the 2008 round of survey, 90% of farmers reported they preferred surface water. The top reason was that surface water was significantly cheaper than groundwater. So the majority of the farmers would prefer surface water if it were available. The availability of surface water is determined by the presence of canals and the availability of water from the irrigation districts, both of which are out of the control of individual households. Therefore, the choice of using surface water is largely exogenous. For the remaining 10% of the farmers that preferred groundwater, the top reason was that the quality of groundwater in their areas was better than that of surface water. The quality of groundwater, however, is controlled for in the regression through the use of plot level fixed effects since it is time invariant.

be matched. Some reasons farmers given for the attrition include: exchange of plots with other farmers in the village, rent out plots, given to sons or daughters, confiscated for highway construction. Descriptive analysis using the first round of data (year 2001) did not reveal any statistically significant differences in crop level water uses and the use of water saving technologies between plots that remained in the sample and plots that dropped out of the sample. A test of attrition suggested by Verbeek and Nijman (1992) is conducted. The result indicates that the attrition is not systematic (that is, not related to the error term in any of the regressions). Thus the attrition will not result in sample selection problems.

The estimating equation for factors that influence water productivity is:

$$\ln\ Q_{ikmt} = \boldsymbol{\alpha}'_{ikm} + \mathbf{T}_{ikmt}\boldsymbol{\beta}' + \mathbf{Z}_{ikmt}\boldsymbol{\delta}' + \mathbf{C}_t\boldsymbol{\gamma}' + \upsilon_{ikmt} \tag{2}$$

where Q_{ikmt} is the productivity of water in producing crop m on plot i of household k in period t. It is calculated as yield (kg/ha) divided by crop water use per unit of land (kg/m^3). So the unit of Q_{ikmt} is kg/m^3. Eq. (2) is similar to Eq. (1) in that the same sets of variables are included in $\mathbf{T}_{ikmt}$ and $\mathbf{C}_t$. The only difference is that the vector $\mathbf{Z}_{ikmt}$ contains one more variable than $\mathbf{X}_{ikmt}$ Eq. (1): the yield loss due to disasters such as wind or pest. The vectors, $\boldsymbol{\beta}'$, $\boldsymbol{\delta}'$ and $\boldsymbol{\gamma}'$, are the parameters to be estimated. The term, υ_{ikmt}, is the error term in the regression. Plot level fixed effects model is also used to estimate Eq. (2). Eqs. (1) and (2) are estimated for wheat and corn plots. To increase the efficiency of estimations, observations on wheat and corn plots are pooled to run a single regression in which all estimated coefficients are allowed to be different between wheat and corn. The pooled estimation also allows us to test whether estimated coefficients are different between wheat and corn equations. Diagnostic tests show that none of the specifications suffer from multicollinearity. The test for serial correlation suggested by Wooldridge (2002) and Drukker (2003) is conducted. The result fails to reject the null hypotheses that there is no serial correlation in the model. As a robustness check, in a separate set of regression (not reported for the sake of brevity), household level fixed effects, instead of plot level fixed effects, are also used. The signs, levels of statistical significance and magnitudes of estimates coefficients are largely consistent between plot level fixed effects models and household level fixed effects models.

Since water use decision is often made at the farm level, examining farm level total water use would provide a complete picture of the impacts of using water saving technologies. Since we did not collect water use information on crops that only took a small share of the sown area such as fruits and vegetables, we do not have farm level total water use. However, the analysis of adjustments farmers may make at the extensive margins (e.g., change in crop mix and expansion of irrigated area) can shed lights on the impact of water saving technologies on farm level total water use. In this set of regression analysis, we first estimate Eq. (3) defined as:

$$S_{kmt} = \boldsymbol{\alpha}''_{km} + \mathbf{T}_{kt}\boldsymbol{\beta}'' + \mathbf{H}_{kt}\boldsymbol{\delta}'' + \mathbf{C}_t\boldsymbol{\gamma}'' + \omega_{kmt} \tag{3}$$

where S_{kmt} is the share of sown area allocated to crop m by household k in period t. Wheat, corn, rice and cash crops are considered. Variables in $\mathbf{T}_{kt}$ are similar to those in $\mathbf{T}_{ikmt}$ from Eqs. (1) and (2) but are defined at the household level. The vector $\mathbf{C}_t$ is defined the same way as before. A set of household characteristics are included in $\mathbf{H}_{kt}$ that may influence households' responses at the extensive margins. Two variables characterize water supply of a household: depth to groundwater in meters in the village and share of household land irrigated by groundwater. The price of fertilizer and wage rate are included. The characteristics of household land are measured by total land holding, total number of plots and cultivated land per capita. Household size and percent of family labor that worked off-farm are also included.

The following two equations are also estimated:

$$IS_{kmt} = \boldsymbol{\alpha}'''_{km} + \mathbf{T}_{kt}\boldsymbol{\beta}''' + \mathbf{H}_{kt}\boldsymbol{\delta}''' + \mathbf{C}_t\boldsymbol{\gamma}''' + \eta_{kmt} \tag{4}$$

$$Y_{kt} = \boldsymbol{\alpha}''''_{k} + \mathbf{T}_{kt}\boldsymbol{\beta}''' + \mathbf{H}_{kt}\boldsymbol{\delta}''' + \mathbf{C}_t\boldsymbol{\gamma}''' + \psi_{kt} \tag{5}$$

where IS_{kmt} is the percent of crop m's sown area that is irrigated, conditional on crop m being planted by household k. Rice is not included because it is 100% irrigated. The variable Y_{kt} measures total irrigated sown area of household k.

To address the potential endogeneity of water saving technology variables in $\mathbf{T}_{kt}$, instrumental variables (IV) are used together with household fixed effects to estimate Eqs. (3)–(5). We instrument for water saving technology variables using the following IVs: a set of dummy variables that equal one if there were policy efforts by upper level government to encourage the use of water saving technology (e.g., whether the upper level government organized meetings or issued directives, whether the government provided fiscal subsidies for investment in water saving technology variables), a dummy variable that equals one if both traditional and household-based technologies are used in the village, a dummy variable that equals one if all three types of technologies are used in the village, a dummy variable that equals one if a village falls in the other group (only used household-based technologies, or used both traditional and community-based technologies, or used both household and community-based technologies). All of these variables are correlated with households' choices of water saving technologies, but they are not likely to be directly correlated with the dependent variables (irrigated sown area, crop mix and percent of sown area irrigated by crop). So they could potentially serve as IVs. For the village-level technology variables, the lagged version is used in an alternative specification to instrument for household technology variables, but the results do not differ much. To increase the efficiency of estimation, regressions in Eq. (3) are estimated as a system of equations. Regressions in Eq. (5) are also estimated as a system of equations. In the next section, we report the estimation results using the balanced panel. Eqs. (3)–(5) are also estimated using the unbalanced panel where data are

Table 4
Impacts of water saving technologies (WST) on crop water use per unit of land using plot level fixed effects.

Dependent variable: Log of water use (m^3/ha)	(1) Wheat	(2) Corn	(3) Wheat	(4) Corn
WST Specification 1				
Used household-based technologies	−0.123	−0.218*		
	(0.0922)	(0.0964)		
Used community-based technologies	−0.425**	−0.398**		
	(0.136)	(0.148)		
WST Specification 2				
Used traditional and household-based technologies			−0.124	−0.261*
			(0.102)	(0.101)
Used traditional and household-based and community-based technologies			−0.525**	−0.578**
			(0.187)	(0.169)
All other groups			−0.198	−0.436***
			(0.166)	(0.236)
Log of (electricity price*depth to groundwater)	−0.0427	−0.0984	−0.0330	−0.0855
	(0.0586)	(0.0613)	(0.0585)	(0.0629)
Dummy = 1 if the plot was irrigated by surface water	−0.278	−0.270	−0.253	−0.238
	(0.209)	(0.267)	(0.211)	(0.281)
Log of average fertilizer price in yuan/kg	0.0523***	−0.0183	0.0512***	−0.0192
	(0.0308)	(0.0308)	(0.0306)	(0.0306)
Log of hourly wage rate	0.0376	−0.00606	0.0346	−0.0133
	(0.0497)	(0.0622)	(0.0517)	(0.0640)
Plot size in hectare	−1.098	−1.848***	−1.183	−1.840***
	(0.859)	(1.044)	(0.819)	(1.022)
% of family labor that worked off-farm	−0.00103	0.0000475	−0.000871	−0.000138
	(0.00119)	(0.00155)	(0.00120)	(0.00156)
Cultivated land per capita in hectare	−0.357	−0.166	−0.418	−0.214
	(0.435)	(0.414)	(0.443)	(0.427)
Water resource in the village is scarce	−0.0621	−0.204*	−0.0746	−0.215*
	(0.0679)	(0.0821)	(0.0677)	(0.0825)
Annual precipitation in mm	−0.000578			−0.00221**
−0.000507				
−0.00210**		(0.000425)	(0.000544)	(0.000434)
(0.000549)				
Annual average temperature °C	−0.0109			−0.0843***
−0.00375				−0.0772
	(0.0356)	(0.0504)	(0.0336)	(0.0486)
Year 2004	−0.183*	−0.0904	−0.197*	−0.0911
	(0.0787)	(0.104)	(0.0804)	(0.107)
Year 2007	−0.0828	−0.00767	−0.0774	−0.00476
	(0.0801)	(0.0952)	(0.0790)	(0.0949)
Constant	−1.052	9.931**	−1.099	9.932**
	(0.829)	(0.816)	(0.803)	(0.794)
Observations	519		519	
Adjusted R-squared	0.279		0.276	

Note: Robust standard errors reported in parentheses.
* Significant at 5%, respectively.
** Significant at 1%, respectively.
*** Significant at 10%, respectively.

treated as repeated cross sections and village level fixed effects are used. Both the magnitudes and the levels of statistical significance of estimated coefficients are similar across these two approaches.

Results

Consistent with findings from descriptive analyses, results from econometric analysis show that using water saving technologies can lead to reduction in crop water use (Table 4). The estimated coefficients on most technology variables are negative and statistically significant in both specifications. Because the dependent variable takes the log form, the estimated coefficients measure the percentage differences in water use per unit of land. Since the technology variables are dummy variables, the *exact* percentage difference is calculated as $\exp^{\beta}-1$, where β is the parameter on the dummy variable (Halvorsen and Palmquist, 1980). We focus on specification 2 to interpret results since groups in specification 2 are mutually exclusive. The percentage differences calculated using Table 4 columns 3 and 4 results are reported in Table 7 columns 1 and

2. The base group is plots that only used traditional technologies. Water use per unit of land on wheat plots that used both traditional and household-based technologies is not statistically different from the base group. Water use per unit of land on wheat plots that used traditional, household-based and community-based technologies is 40.8% ($\exp^{-0.525} - 1$) lower than on plots that only used traditional technologies. The percentage difference is statistically significant at 1% level. The effects are stronger on corn plots. Corn plots that used both traditional and household-based technologies used 23% less water than plots that only used traditional technologies. The reduction is as large as 44% on plots that used all three types of technologies compared to the base group. Both differences are statistically significant.

Two F tests, one for wheat plots, and one for corn plots, are conducted to check if estimated coefficients on the variables "Used traditional and household-based technologies" and "Used traditional and household-based and community-based technologies" are statistically different. The test results reveal that for both wheat and corn plots, plots that used all three types of technologies used less water per unit of land than plots that used both traditional and household-based technologies. The differences are statistically different. Two F tests, one for the variable "Used traditional and household-based technologies" and the second for the variable "Used traditional and household-based and community-based technologies," are conducted to see if they differ between wheat and corn equations. The test results indicate that the percentage reductions generated by using either household-based technologies or both household-based and community-based technologies are not statistically different between wheat and corn plots. In short, estimation results in Table 4 show that combing traditional technologies with household-based technologies can lead to reduction in water use. Adding community-based technologies can further reduce water use. The effects do not seem to differ between wheat and corn.

Tables 5 and 6 examine the potential impacts of using water saving technologies at the extensive margins. Tests indicate that instruments are valid and none of the models is not weakly identified. Results show the shares of sown area allocated to

Table 5
Impacts of water saving technologies (WST) on crop mix using household level fixed effects and IV estimation.

Dependent variables	% of sown area allocated to			
	(1) Wheat	(2) Corn	(3) Rice	(4) Cash Crops[a]
Used traditional and household-based technologies	−7.431	19.78	−17.71	4.559
	(13.12)	(16.74)	(14.43)	(12.16)
Used traditional and household-based and community-based technologies	21.32	−14.98	4.976	−12.83
	(24.74)	(31.58)	(27.22)	(22.94)
All other groups	−11.01	20.10	−11.09	4.758
	(19.94)	(25.45)	(21.94)	(18.49)
Depth to groundwater in m	10.13	7.406	−2.866	−5.144
	(10.33)	(13.18)	(11.37)	(9.577)
Share of household land irrigated by groundwater	2.512	1.956	5.362	−8.179*
	(3.482)	(4.443)	(3.830)	(3.228)
Log of average fertilizer price in yuan/kg	−1.122	0.00409	−0.0253	3.088
	(2.066)	(2.637)	(2.273)	(1.916)
Log of hourly wage rate	1.424**	−0.591	−1.047*	−0.791***
	(0.455)	(0.580)	(0.500)	(0.422)
Total household land holding in hectare	−3.100	−2.725	4.044	2.220
	(3.305)	(4.218)	(3.636)	(3.064)
Total number of plots in household	0.0538	−0.202	−0.0785	−0.0311
	(0.455)	(0.580)	(0.500)	(0.422)
Total number of people in household	−0.333	−0.138	−0.109	0.144
	(0.876)	(1.119)	(0.964)	(0.812)
% of family labor that worked off-farm	−0.0594	0.0669	0.0187	−0.00630
	(0.0570)	(0.0728)	(0.0628)	(0.0529)
Cultivated land per capita in hectare	1.436	0.388	−3.552	−0.268
	(9.621)	(12.28)	(10.58)	(8.919)
Annual precipitation in mm				−0.0202***
−0.0117	0.00251			0.0114
	(0.0105)	(0.0134)	(0.0116)	(0.00975)
Annual average temperature °C	13.88**	4.920	−10.11	−9.044
	(6.007)	(7.666)	(6.609)	(5.569)
Year 2004	8.671*	−5.966	3.559	−2.382
	(3.719)	(4.746)	(4.091)	(3.447)
Year 2007	−6.030	2.535	9.826*	−0.164
	(4.525)	(5.775)	(4.978)	(4.195)
Constant	−150.6***	−11.09	85.96***	75.13*
	(85.95)	(101.9)	(51.39)	(36.50)
Observations	735			

* Significant at 5%, respectively.
** Significant at 1%, respectively.
*** Significant at 10%, respectively.
[a] Cash crops include cotton, peanuts, fruits, vegetables and trees.

Table 6
Impacts of water saving technologies (WST) on irrigated area and % irrigated using household level fixed effects and IV estimation.

Dependent variables	(1) Total irrigated sown area (ha)	% of sown area that is irrigated			
		(2) Total	(2) Wheat	(3) Corn	(4) Cash Crops[a]
Used traditional and household-based technologies	0.228	0.560	−0.530	8.954	−11.60
	(0.288)	(14.49)	(6.270)	(30.63)	(31.62)
Used traditional and household-based and community-based technologies	0.357	21.15	3.223	46.28	34.98
	(0.581)	(29.92)	(13.10)	(35.99)	(61.16)
All other groups	0.223	−13.73	0.818	−10.01	37.01
	(0.494)	(21.10)	(5.151)	(46.72)	(60.62)
Depth to groundwater in m	0.344	1.596	15.17*	2.401	55.92
	(0.237)	(12.71)	(7.377)	(22.11)	(68.43)
Share of household land irrigated by groundwater	0.0587	0.656	4.696	7.049	0.352
	(0.0725)	(5.524)	(5.564)	(11.00)	(11.95)
Log of average fertilizer price in yuan/kg	0.0150	2.484	−2.336	4.085	−1.047
	(0.0443)	(2.411)	(1.561)	(5.320)	(9.313)
Log of hourly wage rate	−0.00636	−0.402	−0.0816	0.561	−3.440**
	(0.0102)	(0.641)	(0.363)	(1.087)	(1.887)
Total household land holding in hectare	0.202	1.732	0.591	1.075	−0.810
	(0.166)	(3.059)	(1.188)	(4.961)	(9.920)
Total number of plots in household	0.0539***	−0.536	−0.0337	−0.906	−2.807
	(0.0146)	(0.478)	(0.155)	(1.039)	(2.363)
Total number of people in household	−0.00163	−1.146	0.173	−2.090	−1.229
	(0.0220)	(1.013)	(0.409)	(2.496)	(3.016)
% of family labor that worked off-farm	−0.00102	0.0290	0.0266	0.0692	−0.183
	(0.00135)	(0.0674)	(0.0474)	(0.115)	(0.336)
Cultivated land per capita in hectare	−0.0975	−3.636	−2.814	−4.038	8.999
	(0.239)	(10.69)	(3.118)	(18.34)	(36.50)
Annual precipitation in mm	−0.000189		−0.0247*		−0.00419
−0.0500*	−0.103***				
	(0.000233)	(0.0109)	(0.00862)	(0.0245)	(0.0383)
Annual average temperature °C	0.0701	6.775	−5.630*	8.449	11.74
	(0.148)	(6.438)	(2.844)	(17.96)	(36.06)
year 2004	−0.0448	2.807	0.0577	1.955	19.09
	(0.0817)	(4.394)	(1.564)	(8.669)	(20.41)
Year 2007	−0.0475	4.388	0.400	5.561	15.35
	(0.102)	(4.924)	(2.635)	(8.865)	(18.81)
Observations	735	718	643	604	325

* Significant at 5%, respectively.
** Significant at 10%, respectively.
*** Significant at 1%, respectively.
[a] Cash crops include cotton, peanuts, fruits, vegetables and trees.

wheat, corn, rice or cash crops do not vary systematically with the type of water saving technologies. None of the estimated coefficients on the technology variables is statistically significant (Table 5). The negative correlation between the share of rice and the use of household-based and/or community-based technologies observed in descriptive analysis (Table 3) disappears. The negative correlation may arise due to the positive correlation between the extent of water scarcity a household faces and the use of water saving technologies and its negative correlation with the share of rice acreage. Once we control for water scarcity using the depth to groundwater and household level fixed effects, the spurious relationship disappears. Results in Table 6 indicate that the use of water saving technologies does not have statistically significant impacts on either the irrigated sown area or the share of a crop's sown area that is irrigated. In short, we do not find much impact at the extensive margins. One likely explanation is that the farm size is small in nature. Most farms in our sample are less than one acre in size. In rural China, farm land is allocated to farmers by the state. During our sample period, farmers do not have complete property rights to farm land. They cannot legally sell or buy farm land. Therefore farmers have limited means to increase their farm size or expand irrigated acreage. Furthermore, agriculture in North China is much more heavily irrigated than other places in the world (Huang et al., 2007). So farmers have limited capacity to expand irrigated acreage. Other factors such as the lack of infrastructure, market access and production technology may explain why we do not see a significant shift to higher value cash crops. The crop mix in our sample did not change significantly over years. In the survey periods, wheat and corn remain the major crops in the study area. This may also explain most estimated coefficients are not statistically significant in Tables 5 and 6.

All the findings above are in terms of applied irrigation water. Reductions in applied water do not necessarily mean real water savings. A portion of irrigation water returns to the stream or the aquifer through runoff or return flow (percolation), which can be used by downstream users or pumped out in the future (Ward and Pulido-Velazquez, 2008; Ward et al., 2006; Cai et al., 2003). More efficient irrigation technologies (e.g., sprinkler irrigation) reduce return flows from irrigation. The

Table 7
Back-of-envelope calculations of impacts on consumptive water use.

	Estimated %Δ in the amount applied water using Table 4 columns 3 and 4 results, ($\exp^{\beta}-1$)		Threshold level of post-adoption irrigation efficiency[a]	
	(1) Wheat	(2) Corn	(3) Wheat	(4) Corn
Used traditional and household-based technologies	−11.7%	−23.0%	0.57	0.65
Used traditional and household-based and community-based technologies	−40.8%	−43.9%	0.85	0.89

[a] The threshold level of post-adoption irrigation efficiency is when consumption water use remains the same before and after the use of household-based or community-based technologies. The irrigation efficiency is assumed to be 0.5 for the base group, which includes plots that only use traditional technologies.

reduction in applied water associated with more efficient irrigation technologies may only come from a reduction in return flows. The higher is the improvement in irrigation efficiency, the larger is the gap between the reduction in applied water and the change in consumptive water use because more of the reduction comes from changes in return flows. To correctly measure the actual water savings, changes in consumptive water use should be measured. However, collecting information on consumptive use at the plot level is prohibitively expensive. To our knowledge, this is not done in any studies.

To gauge the impact of water conservation practices on consumptive water use, we use back-of-envelope calculations. Assume the irrigation efficiency is 0.5 on plots that use only traditional technologies, which means about 50% of the applied irrigation water is consumptive water use. This is the commonly used estimate of the current level of irrigation efficiency in China (Wang and Zhao, 2008).[3] With this assumption and estimated percentage changes reported in Table 4, we can calculate the threshold level of post-adoption irrigation efficiency above which the consumptive use is actually not changed and thus no real water savings are achieved.[4] When farmers combines household-based technologies with traditional technologies, if the irrigation efficiency increases from 0.5 to 0.57 in wheat production, the reduction in the amount of water applied is likely to come only from the reduction in return flow and thus consumptive water use remains the same (Table 7). If the irrigation efficiency improved beyond 0.57, consumptive water use would be higher with the addition of household-based technologies. The threshold level is 0.65 in corn production. When farmers add both household-based and community-based technologies, because larger reductions in the amount of applied water are achieved, the threshold levels of irrigation efficiency increase to 0.85 for wheat and 0.89 for corn. Estimates of irrigation efficiencies are available only for regions outside China such as the US (e.g., Howell, 2003). The most recent estimate in China comes from the press release held by Ministry of Water Resources of China in April 14, 2015 (People's Daily, 2015). The number given is that irrigation efficiency is 0.52 in water saving project area. Given this, the field level irrigation efficiency in rural China is likely to be below the threshold levels estimated for household-based and community-based technologies. This means the reductions in applied water use are likely to have achieved reductions in consumptive water use.

There is also evidence of the positive effects of household-based or community-based technologies on the productivity of water (Table 8). In both specifications, the estimated coefficients on the dummy variables that indicate the use of household-based or community-based technologies are positive and most are statistically significant. The results from estimating specification 2 (columns 3 and 4) are translated into percentage differences in Table 9 (columns 1 and 2). The numbers show

[3] In the Chinese literature, two approaches have been used to estimate irrigation efficiencies in China. The first approach employs statistical analysis of survey data. Most researchers use Stochastic Frontier Analysis (SFA), which gives the ratio of the minimum amount of an input required to achieve a given yield to the actual amount of the input used. This ratio is defined as irrigation efficiency. For example, Wang and Zhao (2008) apply SFA to a set of province level panel data from 1997 to 2006 and find the average irrigation efficiency is 0.49. The second approach uses direct measurement from fields. In 2006, the Ministry of Water Resources in China organized a nationwide effort to measure irrigation water use efficiency (MWR, 2006). In addition to measuring the volume of applied water, consumptive water use is obtained by measuring the changes in soil moisture before and after irrigation at the field level. Sample fields are selected to reflect typical plot size, irrigation method, source of irrigation water (surface water or groundwater) and crop mix in the irrigation districts. When such measures are not available, consumptive use is imputed using the amount of water applied, crop grown on the field and weather information. Irrigation efficiencies at the province and national levels are the weighted average of field level measures with the weight being total volume of water applied. Results show that the average irrigation efficiency in rural China is about 0.47 (Gao, 2008). The irrigation efficiency is relatively high in areas irrigated by groundwater (about 0.6) and lower in surface water areas (lower than 0.4).

[4] Suppose W_{1A} and W_{2A} are the amounts of applied irrigation water before and after the adoption of a technology. W_{1C} and W_{2C} are the amounts of consumptive water use before and after the adoption of a technology. They are related as $W_{1C}=I_1{}^{*}W_{1A}$ and $W_{2C}=I_2{}^{*}W_{2A}$, where I_1 and I_2 are the irrigation efficiencies before and after the adoption of a technology. The econometric analysis generates estimates of the percentage change in W_{1A}, denoted as $\%\Delta=(W_{2A}-W_{1A})/W_{1A}$. Using these relationships, it can be shown that $W_{2C}=W_{1C}$ means $I_2=I_1/(\%\Delta+1)$, which gives us the threshold level of I_2 when the consumptive water use is the same before and after the adoption of a technology.

Table 8
Impacts of water saving technologies on water productivity in crop production using plot level fixed effects.

Dependent variable: Crop produced per unit of water (kg/m^3)	(1) Wheat	(2) Corn	(3) Wheat	(4) Corn
WST Specification 1				
Used household-based technologies	0.233*	0.153		
	(0.0898)	(0.0991)		
Used community-based technologies	0.546**	0.599**		
	(0.142)	(0.146)		
WST Specification 2				
Used traditional and household-based technologies			0.245*	0.162
			(0.100)	(0.108)
Used traditional and household-based and community-based technologies			0.772**	0.764**
			(0.197)	(0.176)
All other groups			0.409*	0.198
			(0.187)	(0.236)
Log of (electricity price*depth to groundwater)	0.0475	0.139*	0.0340	0.121***
	(0.0599)	(0.0658)	(0.0573)	(0.0660)
Dummy = 1 if the plot was irrigated by surface water	0.302	0.321	0.272	0.279
	(0.217)	(0.294)	(0.217)	(0.308)
Log of average fertilizer price in yuan/kg	−0.0624*	0.0319		−0.0605***
0.0313				
	(0.0315)	(0.0250)	(0.0315)	(0.0244)
Log of hourly wage rate	−0.00560	0.0366	−0.00334	0.0367
	(0.0472)	(0.0589)	(0.0504)	(0.0631)
Plot size in hectare	1.437***	1.737	1.536*	1.880***
	(0.815)	(1.144)	(0.769)	(1.078)
% yield loss due to disasters such as wind or pest	−0.00369	0.00142	−0.00346	0.00225
	(0.00263)	(0.00248)	(0.00259)	(0.00253)
% of family labor that worked off-farm	0.00107	0.00104	0.000937	0.000790
	(0.00124)	(0.00138)	(0.00125)	(0.00138)
Cultivated land per capita in hectare	0.880*	0.624	0.959*	0.805
	(0.391)	(0.477)	(0.405)	(0.495)
Water resource in the village is scarce	0.0892	0.290**	0.109	0.313**
	(0.0672)	(0.0853)	(0.0662)	(0.0866)
Annual precipitation in mm				0.000808***
0.00185**	0.000657			0.00172**
	(0.000466)	(0.000536)	(0.000482)	(0.000554)
Annual average temperature °C	−0.0129	0.0373	−0.0246	0.0277
	(0.0341)	(0.0562)	(0.0337)	(0.0557)
Year 2004	0.210*	0.148	0.227**	0.165***
	(0.0827)	(0.0970)	(0.0849)	(0.0996)
Year 2007	0.0889	0.0439	0.0810	0.00907
	(0.0810)	(0.103)	(0.0770)	(0.106)
Constant	0.0967	−0.518	0.136	−0.475
	(0.821)	(0.835)	(0.798)	(0.820)
Observations	519	519		
Adjusted R-squared	0.346	0.345		

Note: Robust standard errors reported in parentheses.
* Significant at 5%, respectively.
** Significant at 1%, respectively.
*** Significant at 10%, respectively.

Table 9
Back-of-envelope calculations of impacts on the productive of consumptive water use.

	Estimated %Δ in productive of applied water using Table 8 columns 3 and 4 results, ($\exp^{\beta}-1$)		Threshold level of post-adoption irrigation efficiency[a]	
	(1) Wheat	(2) Corn	(3) Wheat	(4) Corn
Used traditional and household-based technologies	27.8%	17.6%	0.64	0.59
Used traditional and household-based and community-based technologies	116.4%	114.7%	1.0	1.0

[a] The threshold level of post-adoption irrigation efficiency is when the productivity of consumption water use remains the same before and after the use of household-based or community-based technologies. The irrigation efficiency is assumed to be 0.5 for the base group, which includes plots that only use traditional technologies.

that wheat produced per unit of water increases by 27.8% when household-based technologies are used in addition to traditional technologies in wheat production. The increment is as much as 116.4% if both community-based and household-based technologies are used in addition to traditional technologies. The magnitudes of increment are similar on corn plots. F tests indicate the estimated coefficients are not statistically different between wheat and corn equations. F tests indicate that the estimated coefficients on the variables "Used traditional and household-based technologies" and "Used traditional and household-based and community-based technologies" are statistically different in both wheat and corn equations. Therefore adding community-based technologies on plots that used both traditional and household-based technologies also leads to improvements in the productivity of water. These large effects clearly show that community-based technologies generate the largest benefit in terms of water productivity.

We can use similar back-of-envelope calculations to get a sense of the impacts on the productive of water if consumptive water is measured. The same relationship can be used to derive the threshold levels of post-adoption irrigation efficiency above which the productivity of consumptive water use would remain the same before and after technologies are used (Table 9, columns 3 and 4). The magnitudes of the threshold levels indicate that the use of household-based or community-based technologies in rural China is not likely to lift irrigation efficiencies above those levels. Therefore, our results also support that the use of household-based or community-based technologies improve the productivity of consumptive water use.

The estimation results on other variables are reasonable. In the water use regressions (Table 4), the estimated coefficient on annual average precipitation is negative and statistically significant in corn. This is expected because higher levels of precipitation reduce the amount of irrigation water required for crop growth. This coefficient is not statistically significant in wheat production. This is probably because in contrast to corn, the growing season of wheat is outside the rainy season. So the level of precipitation has less influence on water use in wheat production. There is some evidence that larger plots use less water per unit of land. The estimated coefficient is negative and statistically significant for corn plots. As expected, in villages with more scarce water resource, water use is significantly lower. The estimated coefficient on the variable "Log of (electricity price*depth to groundwater)" is negative but not statistically significant. This is mostly because more than half of the plots only use surface water. When we only use groundwater plots in the regression, the estimated coefficients become statistically significant.

In the regressions on water productivity (Table 8), results show that water productivity tends to be higher on larger plots and in villages with more scarce water resources. The estimated coefficient on the variable "Log of (electricity price*depth to groundwater)" is positive and statistically significant in corn equation, indicating that a higher price of water pushes farmers to improve the productivity of water. The estimated coefficient on annual average precipitation is also positive and statistically significant in both corn and wheat production (row 16). Farmers apply less irrigation water when there is more rainfall. Since the amount of applied irrigation water is the denominator of the dependent variable, more rainfall is likely to increase crop produced per unit of applied water. In an alternative specification, annual precipitation is replaced by growing season precipitation and non-growing season precipitation. The estimated coefficients on growing season precipitation are positive and statistically significant in both corn and wheat production. The estimated coefficient on non-growing season precipitation is also positive and statistically significant in corn production. This may be because higher levels soil moisture in areas with higher levels of precipitation help improving the productivity of water in crop growth.

To enrich the analysis of household-based or community-based technologies, we have also done some back-of-envelope cost-benefit calculations for household-based technologies commonly used in the sample area. Table A1 reports the benefits of adding household-based technologies to traditional technologies. It should be noted that the benefits are underestimated.[5] Table A2 reports technology specific costs as reported by farmers during our survey. The comparison of Tables A1 and A2 shows that the benefits in terms of water savings and yield gains generated by household-based technologies are likely to be less than the costs of using these technologies. This may explain why the share of sown area that uses household-based technologies is still less than half by 2007. However, if the government were to raise the price of groundwater and move the pricing of surface water towards volumetric pricing, the benefits would increase.

There is evidence that community-based technologies generate positive returns. Table A3 reports the benefits of adding community-based technologies to traditional and household-based technologies. Our survey did not collect the operation and maintenance costs of community-based technologies. Cost information is obtained from secondary sources. Table A4 reports the cost-benefit analysis reproduced from Ma and Qiao (2009), which analyzes one irrigation district in one of our sample provinces, Hebei province. The figures from Ma and Qiao (2009) are within the same order of magnitudes of those in Zou et al. (2013), who have conducted a meta-analysis of studies on China and published on peer reviewed journals. The monetary values of water saved and yield gains calculated using our survey data and regression results (Table A3) are smaller than the figures in Ma and Qiao (2009), (Table A4). But the numbers are comparable. Ma and Qiao (2009) include additional benefits such as the value of land saved and labor saved. The cost-benefit analysis conducted by Ma and Qiao (2009) indicates that for both lined canals and underground pipes, the benefit outweigh the cost. This is consistent with other studies in the Chinese literature (e.g., Zou et al., 2013).

[5] First, the cost of groundwater is mostly the energy cost of pumping water out. It does not include the scarcity value of water. Water saved could flow back to the aquifers or be pumped out by other users, which generate values for other users or the environment. Second, reduced pumping also reduces the amount of labor required for irrigation. This part is not included due to lack of data. Third, technologies such as surface level plastic irrigation pipe also saves land needed for conveying water. The value of saved land is not included due to lack of data.

Conclusions

This paper describes the extent of water saving technologies usage and evaluates the impacts of using various types of technologies on water use and crop allocations in the YRB and HRB. We examine three groups of technologies. Traditional technologies such as border irrigation and furrow irrigation have been in use since the 1950s. Household-based technologies such as surface level plastic irrigation pipe, drought resistant varieties and plastic sheeting have become in use only after the 1980s. Community-based technologies such as underground pipes and lined canals are capital intensive and often used at the village level or by groups of households. Our results show that using water saving technologies can reduce crop water use and improve the productivity of water. Results do not show any statistically significant impacts on crop mix, irrigated sown area or the share of a crop's sown area that is irrigated. Therefore, our sample households do not seem to make these extensive margin adjustments that may result in an increase in total household level water use. The overall effects of using water saving technologies on water use are dominated by the impacts at the intensive margins, which result in less water applied by farmers to irrigate their crops. The positive effects are generated mainly through the use of household-based or community-based technologies.

Currently the percent of sown area on which water saving technologies are used is still fairly low. Since our results show that using these technologies can reduce crop water use without negatively affecting crop production, the government should continue its efforts to promote and extend water saving technologies. Our findings indicate that the efforts should be focused on household-based and community-based technologies. The government should design policies that take into account the characteristics of local water resources and the environment of agricultural production when extending the use of water saving technologies to more farmers.

This study is a significant addition to the small literature of impact evaluations of water saving technologies. There is much more research to be conducted on this subject. Although community-based technologies entail much larger water savings than other technologies, they are usually much more expensive. So their net benefits are not necessarily higher. Only a cost-benefit analysis can answer the question which type of technology is most cost effective in saving water. Our data only allow us to do a simple cost-benefit analysis. With more data that may become available in the future, a more thorough cost-benefit analysis can address this question. Like other studies, this study suffers from the lack of information on consumptive water use. Back-of-envelope calculations indicate that at the current levels of irrigation efficiencies in China, reductions in the amounts of water applied on fields are likely to have resulted in reductions in consumptive water use in rural China. Further increase in irrigation efficiency may increase consumptive water use. This may be desirable given the potential yield increases. Other policies such as increasing the price of irrigation water to move the pricing of water closer to its scarcity value should also be implemented to improve the economic efficiency of water allocation. Our estimates are very crude and are educated guesses at best. Future research on field level irrigation efficiencies associated with various water saving technologies would provide better estimates. We have grouped technologies due to limited sample size. Larger data sets should be collected in the future research to allow analysis of individual technologies.

It should also be noted that due to data limitation, our analysis does not capture other changes farmers may have made in response to higher irrigation efficiency. One such response is the use of different/improved varieties that can now be cultivated as a result of higher irrigation efficiency. It is important to document such responses in future data collection efforts and quantify both the direct and the indirect impacts of using water saving technologies on water use. For example, if using different/improved varieties is prevalent among farmers after improvement in irrigation efficiency, extension efforts on promoting water saving technologies should also provide farmers with production knowledge on those varieties as well as information on how to get access to them. Last but not least, results in this study do not have the final say on the impact of water saving technologies. In the changing landscape of rural China, it is important to update the analysis to reflect any changes in policies or in the production environment. For example, if farmers were given the complete property rights to farm land and thus the freedom to buy/sell land, farmers could respond to higher irrigation efficiency by expanding irrigated acreage. Then using water saving technologies might increase farm level water use.

Appendix A. Back-of-envelope cost-benefit analysis

In Tables A1 and A3, since surface water is paid on per unit of land basis, a reduction in the amount of applied water will not reduce water fee. Only plots that use groundwater are included in the calculations of the monetary values of water savings (Tables A2 and A3).

Technology-specific costs are calculated. Only those technologies that are commonly used in the sample areas are included. Since the benefits are calculated using plots that grow mostly wheat and corn, we only include three household-based technologies that apply to these two crops in Table A2: surface pipes, drought resistant varieties and retain stub/low till. Most households use two or three of these technologies. Table A4 only reports the two most common community-based technologies: lined canals and underground pipes. In our sample, less than 1% of villages used sprinkler or drip irrigation. Across years, among villages that used community-based technologies, 64% use lined canals, 25% used underground pipes and 8% used both. This share is similar cross years. In 2007, 58% use lined canals, 27% used underground pipes and 13% used both technologies.

Table A1
Annual benefits of adding household-based technologies to traditional technologies.[a]

	Mean	Median	Standard Error
Monetary value of water saved ($/ha)[b]	39	30	41
Monetary value of yield gain ($/ha)[c]	61	69	37
SubTotal	99	103	72

[a] All monetary terms are converted to 2007 US dollars using the exchange rate $1 = 7.58 yuan.
[b] Monetary value of water saved is calculated as amount of water saved in wheat and corn production multiplied by cost of water. Estimates of water savings are from Table 4.
[c] Monetary value of yield gain is calculated as amount of yield increase for wheat and corn multiplied by prices of corresponding crops. Estimates of yield gain are obtained from regressions with crop yields as the dependent variables. Independent variables are the same as the regressions in columns 3 and 4 of Table 8 in the revised manuscript.

Table A2
Annual cost of some household-based technologies.[a]

	Mean	Median	Standard Deviation
Surface level plastic irrigation pipe ($/ha)[b]	52	46	44
Drought resistant varieties ($/ha)	168	148	112
Retain stub/low till ($/ha)	52	40	63

[a] Costs of equipment, materials and labor are included. All monetary terms are converted to 2007 US dollars using the exchange rate $1 = 7.58 yuan. Plastic sheeting is not included because it is usually used on cotton fields, not on wheat and corn fields.
[b] Annual cost is reported assuming 4 years of service life.

Table A3
Annual benefits of adding community-based technologies to traditional and household-based technologies.[a]

	Mean	Median	Standard Error
Monetary value of water saved ($/ha)[b]	51	38	41
Monetary value of yield gain ($/ha)[c]	135	129	37
SubTotal	186	157	72

[a] All monetary terms are converted to 2007 US dollars using the exchange rate $1 = 7.58 yuan.
[b] Monetary value of water saved is calculated as amount of water saved in wheat and corn production multiplied by cost of water. Estimates of water savings are obtained using the difference between the estimated coefficients on the "Used traditional and household-based technologies" and the "Used traditional and household-based and community-based technologies" variables in Table 4.
[c] Monetary value of yield gain is calculated as amount of yield increase for wheat and corn multiplied by prices of corresponding crops. Estimates of yield gain are obtained from regressions with crop yields as the dependent variables. Independent variables are the same as the regressions in columns 3 and 4 of Table 8 in the revised manuscript.

Table A4
Cost-benefit analysis of two community-based technologies (Unit: $/ha).[a]
Source: Ma and Qiao (2009).

	(1) Annual benefit					(2) Annual O&M cost	(3)[b] Net present value of net benefits	(4) Total initial investment
	(1a) Water saved	(1b) Yield gain	(1c) Land saved	(1d) Energy saved	(1e) Labor saved			
Underground Pipes	87	253	59	36	20	151	2,270	534
Lined Canals	71	127	30	30	20	165	844	792

[a] All monetary terms are converted to 2007 US dollars using the exchange rate $1 = 7.58 yuan.
[b] Net benefit = Annual benefit − Annual O&M cost, where O&M stands for operation and maintenance. In calculation of the net present value, 20 years of service life is used and a discount rate of 12% is used.

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