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Impact of the methods of groundwater access on irrigation and crop yield in the North China Plain

Does climate matter?

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Abstract

Purpose – The purpose of this paper is: to track the methods by which farmers access groundwater for irrigation in the North China Plain (NCP); to explore whether climate factors influence farmers' decisions on the methods of groundwater access for irrigation; and to examine whether the amount of groundwater use for irrigation and crop yield systematically differ across groups of farmers using various methods of groundwater access, and how climate factors affect them.

Design/methodology/approach – Descriptive statistical analysis and econometric models are used on household survey data collected over several years and county-level climate data.

Findings – Over the past few decades, a significant share of farmers have switched the methods of groundwater access from collective tubewells to own tubewells or groundwater markets. Farmers who bought water from groundwater markets applied less water to wheat plots than those who had their own tubewells. However, wheat yield was not negatively affected. Both average climate conditions and long-term variations were found to be related to farmers' choice of methods of groundwater access for irrigation. More frequent droughts and increasingly volatile temperatures both increased the likelihood of farmers gaining groundwater irrigation from markets.

Originality/value – The analysis results suggest farmers are using groundwater markets to help them adapt to climate change. Applying empirical analysis to identify the impact of the methods by which farmers access groundwater for irrigation on the amount of groundwater use and crop yield will help policy makers design reasonable adaptation policies for the NCP.

Keywords Climate, Crop yield, Amount of groundwater use, Groundwater markets, Methods of groundwater access, North China Plain

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1. Introduction

The North China Plain (NCP) is the largest agricultural production area in China. Its current grain production consists predominantly of a wheat-maize double cropping system (Wang *et al.*, 2008). About 56 percent of the nation's wheat and 27 percent of its maize are produced in the NCP (National Bureau of Statistics of China, 2013). The region is characterized by a semi-arid to semi-humid warm temperate climate, with an average annual temperature of 10-15°C and annual rainfall of 500-800 mm (Li *et al.*, 2015). More than 70 percent of precipitation occurs in summer (July-September) under the influence of the East Asia monsoon (Tao and Zhang, 2013; Wang *et al.*, 2008). Surface water used to be the main source of irrigation water for agriculture in the region; however, since the late 1960s, and especially since the 1990s, the surface water supply in this area has diminished dramatically (Wang *et al.*, 2005). Faced with limited surface water supplies and concentrated summer rainfall, the NCP began large-scale exploitation of groundwater in the late 1960s, and agricultural irrigation in the area now relies heavily on groundwater (Wang *et al.*, 2005, 2008; Zhang *et al.*, 2008).

However, the extensive use of groundwater for irrigated agriculture has resulted in rapid declines in groundwater resources and many environmental problems. The average rate of groundwater extraction in the NCP risen from 3.9 billion m^3 in the 1960s to nearly 23.7 billion m^3 in 2008 (Li *et al.*, 2013). Almost 80 percent of the groundwater withdrawn goes to agricultural production (Zhang *et al.*, 2013). Consequently, groundwater is being pumped at rates far greater than those at which aquifers can be naturally replenished (Famiglietti, 2014). This has resulted in rapid groundwater depletion at an annual rate of 2.2 ± 0.3 cm from 2003 to 2010, which is equivalent to a volume of $8.3 \pm 1.1\ km^3$ (Feng *et al.*, 2013). Moreover, the fast decline of the groundwater table has resulted in a series of environmental problems, such as land surface subsidence, seawater intrusion, streamflow depletion, wetlands degradation, and ecological damage (Famiglietti, 2014). Given the shrinking supply of groundwater and the government's intention to maintain or increase grain production, it is imperative to increase the efficiency of water use.

Some previous studies have examined how the methods by which farmers access groundwater influence the input efficiency of water in agricultural production (Manjunatha *et al.*, 2011; Zhang *et al.*, 2010). Based on the field survey, Zhang *et al.* (2010) found that there were three methods by which farmers access groundwater for irrigation: buying water from water markets, getting irrigation through collective tubewells or their own tubewells. Water markets, as user-driven or demand-side approaches, play an increasingly important role in reallocating water away from low-value irrigators to high-value ones (e.g. Bjornlund, 2006; Hadjigeorgalis, 2008; Wheeler *et al.*, 2009; Zhang *et al.*, 2010; Manjunatha *et al.*, 2011). Using the input-oriented approach of data envelopment analysis, Manjunatha *et al.* (2011) found that buyers in groundwater markets in India achieved higher water use efficiency. They also found the water use efficiency of traders was higher than non-traders. Zhang *et al.* (2010) found that farmers in the NCP accessing water through groundwater markets significantly reduced their water use relative to those pumping from their own tubewells. In addition, there were no measurable negative effects on crop yield or income.

A few recent studies in other countries have identified positive roles of water trading in mitigating the influence of climate change. For example, Wheeler *et al.* (2014) found that 86 percent of irrigators in southern Murray-Darling Basin used water trading to manage water on-farm and enjoyed a net benefit on average. Jiang and Grafton (2012) found that inter-regional water trading could help mitigate the on-farm impacts of climate change such as reduced surface water availability during droughts in Australia. Future water trading could also be crucial in facilitating or enabling new adaptation strategies in the face of climate change in Australia (Wheeler *et al.*, 2014).

Studies on groundwater markets in China are very limited, even scant on linking its adaptive role with climate change. The few existing studies mainly document the development of the groundwater market up to 2005, its socio-economic influence factors, and its comparative advantage on reducing irrigation water use (vs accessing irrigation through collective or own tubewells). However, these studies have not considered the influence of climate change either on farmers' irrigation decision (accessing irrigation by groundwater markets, collective or own tubewells), its influence on irrigation water use or crop yield.

Therefore, when we have included climate change into the consideration, answering the following questions have important policy implications: what are recent development status of groundwater markets in China? Whether climate factors influence farmers' decisions on through which method to access groundwater for irrigation? Under the background of climate change, whether the amount of groundwater use for irrigation and crop yield are systematically different across groups of farmers using various methods of groundwater access, and whether they are influenced by climate factors?

The overall goal of this paper is to answer the above questions. In order to realize the goal, we have purposed three specific objectives: the first objective is to understand the development status of the groundwater markets in recent years. The second objective is to examine whether climate factors influence farmers' decisions on through which method to access groundwater for irrigation. If they do, it may suggest that the groundwater market is employed by farmers as a strategy to adapt to climate change. The third objective is to examine whether the amount of groundwater use for irrigation and crop yield is systematically different across groups of farmers using various methods of groundwater access, and the influence of climate factors on them.

The rest of this paper is organized as follows. Section 2 briefly introduces the data used in this study. Section 3 discusses the changes in the methods by which farmers access groundwater for irrigation and presents the results of the descriptive statistical analysis on the relationship between the methods of groundwater access and the amount of groundwater irrigation and crop yield. Section 4 constructs econometric models and section 5 presents the estimation results. Finally, Section 6 concludes the study with a discussion of several policy implications.

2. Data

All of the socio-economic data used in this study came from the China Water Institutions and Management survey (CWIM). The CWIM data were collected in four rounds in 2001, 2004, 2007, and 2011. The survey was carried out in the provinces of Hebei, Henan, and Ningxia. During the survey, a stratified random sampling strategy was used to select villages for the purpose of generating a representative sample. For example, villages in Hebei province were chosen from counties near the coast, near the mountains, and in between. In Henan province, villages were chosen from counties in irrigation districts at varying distances from the Yellow River (Zhang *et al.*, 2008). In each village, four farm households (in a few villages it was five or six households) were randomly selected and in each household two plots were selected for more careful investigation. In total, our sample covered 676 plots and 338 farm households in 80 villages in three provinces.

The same households were tracked over the four survey rounds. There was some attrition due to reasons such as migration and health. Overall, 225 households participated in all four rounds. In villages with household attrition, new households were randomly selected as replacements to make sure that at least four households were interviewed in each village. In the third round of the survey, eight new villages (and 32 new households) were added to the Hebei province sample and surveyed in the fourth round. The four-round CWIM survey covered a total of 518 households from 88 villages in three provinces.

Since groundwater irrigation is almost nonexistent in Ningxia, only data from Hebei and Henan were used in this paper. Both provinces are highly dependent on groundwater irrigation (Zhang *et al.*, 2008). Figure 1 shows the locations of Hebei and Henan in the NCP, with the locations of the sample villages marked by green triangles. Within the two provinces, only those households that used groundwater for irrigation were included. The final sample used in this paper included 261 households from 49 villages in Hebei and Henan provinces.

The survey included separate questionnaires for farmers and village leaders and covered a wide range of issues. Detailed information on how farmers accessed groundwater for irrigation and the amount applied were collected by crop and plot. Specifically, we asked three methods by which farmers accessed groundwater for irrigation (briefed as methods of groundwater access in the rest of the paper) for each plot: from groundwater markets, from collective tubewells or own tubewells. Several sets of questions were presented in order to obtain accurate measures of the amount of groundwater use for irrigation (briefed as amount of groundwater use in the rest of the paper) for each crop. First, farmers were directly asked the total amount of groundwater use for each crop during its growing season. Then they were asked to report the total number of irrigation sessions, the length of each session in hours, and the amount of groundwater use per hour. Information on the pump used for the tubewell from which farmers obtained water was also collected, including pump size and actual water yield per hour. This information allowed us to calculate the amount of groundwater use in multiple ways. If there were any discrepancies, they were resolved after a discussion with the farmers. The survey also collected information on household characteristics, such as the education level of the household head and any off-farm employment of household members, as well as plot characteristics such as plot size, soil type (loam, clay, or sandy soil), property rights, and distance from plot to home.

Interviews with village leaders were utilized to collect information on how prevalent groundwater markets are in the village. Village leaders were asked if there are tubewell owners that sell water to farm households that do not own a well. The survey tabulated the number of tubewells in villages from which water is sold by the well owner (Zhang *et al.*, 2008). Village leaders were also asked whether the upper level of the government has advocated the development of private tubewells in meetings or government directives and whether there is government support for investment in private tubewells, such as financial subsidies or bank loans. A summary of the statistical data can be found in Table AI.

The county-level climate data used in this study were provided by the National Meteorological Information Center in China. The basic climate data were based on actual measurements from 753 national meteorological stations located throughout China (Wang *et al.*, 2009). Temperature and precipitation data for each month were

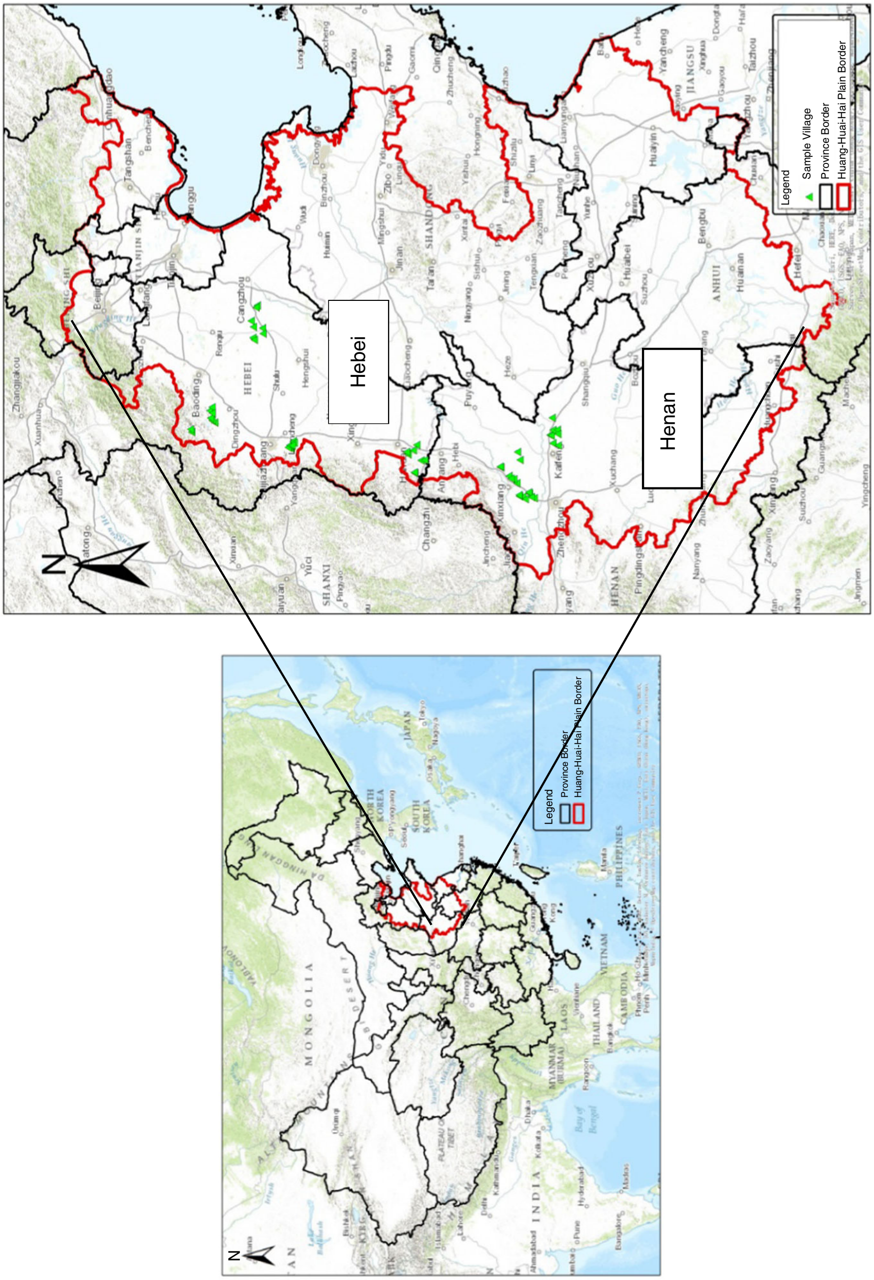

Figure 1.
Location of
study area and
sample villages

collected from 1960 to 2012. Because not each county has a meteorological station, spatial interpolation was used to generate the temperature and precipitation data for each sample county. Using climate data from meteorological stations and soil data from the Institute of Soil Science at the Chinese Academy of Sciences, a monthly Palmer Drought Severity Index (PDSI) was calculated based on the way developed by Liu *et al.* (2004). Spatial interpolation was also used to generate a PDSI at the county level. Spatial interpolation involves predicting the values of a primary variable at points within the same regions of sampled locations and has been developed for and applied in various disciplines (Li and Heap, 2014).

Following an approach found in the literature (e.g. Barnwal and Kotani, 2010), we gathered the following two major climate variables at the county level: monthly mean temperature and monthly total precipitation. Since the growth of winter wheat is mainly influenced by its growing season's temperature, we estimated the monthly mean temperature during growing season. The growing season for winter wheat in the sample areas is from October of the previous year to June of the current year. Because precipitation outside the growing season can influence crop growth through soil moisture accumulation, a period exceeding the length of the growing season was used to calculate total precipitation. We estimated the total precipitation from last July to current June, it can be treated as annual total precipitation. Based on these two variables, we also estimated the standard deviation of both monthly mean temperature and annual total precipitation over the past 30 years (from 1980 to 2010), and percentage of months with extreme or severe droughts in the current year. When the PDSI value of the month was below or equal to −3, we define that this month experienced extreme or severe droughts.

3. Methods of groundwater access, amount of groundwater use, and crop yield

Before China's economic reform that began in late 1970s, almost all plots in rural villages were irrigated by water from collectively owned and managed tubewells. Village leaders made decisions on when and how much water to be delivered to households in the command areas of collective tubewells. Often village leaders hired a water manager and paid them a fixed amount to carry out the day-to-day irrigation duties. With the increase in private tubewells, groundwater markets have developed rapidly in the NCP over the past two decades. Groundwater markets were found in only 2.7 percent of sample villages in the NCP in 1990 (Table I, column 1, row 1), but by 2011 they had spread to 68.1 percent of villages (row 6). Within the villages, market participation also increased to a large degree, both in terms of the number of

Table I. Development of groundwater markets at the village level in the NCP

	Proportion of villages with groundwater markets (%)	Proportion of private tubewell owners selling water (%)	Proportion of irrigated sown areas serviced by groundwater markets (%)
1990	2.7	0.1	0.1
1995	5.4	0.3	0.3
2001	33.3	9.9	6.7
2004	43.9	33.0	22.3
2007	67.4	52.1	31.5
2011	68.1	47.3	40.6

Source: Authors' survey

participants and farm acreage. The proportion of tubewells from which owners sell water has increased significantly, from 0.1 percent in 1990 to 47.3 percent in 2011 (column 2, rows 1 and 6). The proportion of irrigated sown area in villages serviced by groundwater markets has increased sharply. In 1990, only 0.1 percent of the total area was irrigated through water trade on the groundwater markets (column 3, row 1); by 2011, this number had increased to 40.6 percent (row 6).

With the development of groundwater markets, farmers have changed the methods of groundwater access. The CWIM survey data showed that 72.2 percent of households accessed water from collective tubewells in 2001 (Table II, column 2, row 1). By 2011, this proportion decreased to 57.2 percent (row 4). On the contrary, the proportion of households buying water through markets increased from 11.9 percent in 2001 to 24.8 percent in 2011 (column 1, rows 1 and 4). At the same time, the proportion of households gaining water from their own tubewells rose from 19.0 to 27.6 percent during the same period (column 3, rows 1 and 4). The same trend was observed when examining plot-level data. For example, the proportion of wheat plots irrigated using water from collective tubewells dropped from 72.0 percent in 2001 to 57.5 percent in 2011 (column 2, rows 5-8). This drop marked an increase in plots being irrigated with water bought from groundwater markets (from 11.6 percent to 19.3 percent; column 1, rows 5-8) as well as more plots being irrigated with water pumped from farmers' own tubewells (from 16.4 to 23.2 percent; column 3, rows 5-8).

Descriptive statistics indicated that farmers' choices about methods of groundwater access may be related with the degree of the development of groundwater markets at the village level. In Table III, villages were divided into four groups based on the proportion of tubewells in the village whose water was sold. Consistent with our expectation, the proportion of wheat plots irrigated using water from own tubewells was higher when larger proportions of tubewell owners sold water in the village. In villages where no tubewell owners sold water, the proportion of wheat plots irrigated by own tubewells was only 10 percent (column 4, row 1), which was much lower than the proportion in the villages where tubewell owners sold water (rows 2-4). Moreover, the difference was statistically significant (rows 5-7). Similarly, a positive relationship can be observed between the proportion of wheat plots irrigated using water from groundwater markets and the proportion of tubewell owners selling water in the village (column 2). Interestingly, in villages where between 50 and 100 percent of tubewell owners sold water, the proportion of wheat plots irrigated using water from groundwater markets

	From groundwater markets	From collective tubewells	From own tubewells
Proportion of households (%)			
2001	11.9	72.2	19.0
2004	17.8	66.1	23.7
2007	28.9	58.5	19.0
2011	24.8	57.2	27.6
Proportion of wheat plots (%)			
2001	11.6	72.0	16.4
2004	15.8	62.7	21.5
2007	21.6	62.8	15.6
2011	19.3	57.5	23.2

Source: Authors' survey

Table II.
The methods by which farmers accessed groundwater for irrigation in the NCP

Table III. Relationship between the development of groundwater markets at the village level and the methods by which farmers accessed groundwater for irrigation

Proportion of tubewell owners selling water in the village		(1) Number of wheat plots	Proportion of wheat plots with different methods of groundwater access for irrigation (%) (2) From groundwater markets	(3) From collective tubewells	(4) From own tubewells
0%	(1)	383	0	90	10
0-50% (average 18%)	(2)	133	15	54	31
50-100% (average 75%)	(3)	124	48	26	26
100%	(4)	132	40	32	28
t-test					
t-statistic	(2)-(1)		4.83***	7.82***	4.86***
t-statistic	(3)-(1)		10.74***	15.19***	3.75***
t-statistic	(4)-(1)		9.37***	13.40***	4.30***

Notes: Significance of *t*-statistics: $^{***}p < 0.01$
Source: Authors' survey

was highest (48 percent), and it was even higher than those villages in which all tubewell owners sold water (40 percent). The survey data revealed that the number of tubewells per capita was lowest among the group of villages in which between 50 and 100 percent of tubewell owners sold water. Therefore, one possible explanation is that in such villages more households may have to gain irrigation water through groundwater markets. There was a strong and negative correlation between the proportion of farmers' wheat plots irrigated using water from collective tubewells and the proportion of tubewell owners selling water in the village (column 3).

The field surveys also revealed that farmers' methods of groundwater access at the plot level was associated with government support for private tubewells. Private tubewells have been encouraged by the upper-level government since the start of China's economic reforms in the early 1980s. During the fieldwork we found that in some villages the government provided fiscal subsidies or low-interest bank loans for investing in private tubewells. In addition, the local Bureau of Water Resources advocated the construction of private tubewells in some villages by organizing meetings and issuing policy directives. Survey data supported that more farmers irrigated their wheat plots using water from own tubewells when there was government support for private tubewells in the village (Table IV). In all, 49 percent of wheat plots were irrigated using

Table IV. Government support for private tubewells and the methods by which farmers accessed groundwater for irrigation at the plot level

Government support for private tubewells	Number of wheat plots	Proportion of wheat plots with different methods of groundwater access for irrigation (%) From groundwater markets	From collective tubewells	From own tubewells
Yes	153	27	24	49
No	619	15	74	11
t-statistic		3.28***	12.91***	8.74***

Notes: Significance of *t*-statistics: $^{***}p < 0.01$
Source: Authors' survey

farmers' own tubewells in villages where the upper-level government supported private tubewells, which was much higher than in villages without support policy (11 percent – column 4). The *t*-test result showed that the difference was statistically significant (row 3). Likewise, compared with the villages without government support, the proportion of plots irrigated using water from groundwater markets was higher significantly (27 percent) in villages where government support was available (column 2). However, descriptive analysis indicated that if government support was available in a village, the proportion of plots irrigated using collective tubewells was lower than in villages without such support (column 3). For example, in villages where the upper-level government supported private tubewells, 24 percent of wheat plots were irrigated using collective tubewells (column 3, row 1). In contrast, the proportion was 74 percent in villages without government support (row 2). The value of *t*-statistic was 12.91 and showed that their difference was significant at the 1 percent level (row 3).

According to the analysis of the survey data, farmers' methods of groundwater access might have effects on the amount of groundwater use for crops. As shown in Table V, groundwater markets could reduce famers' amount of groundwater use for wheat. For example, if farmers bought groundwater from markets to irrigate their wheat, the amount of groundwater use was 3,248 m^3 (column 1, row 1), which was 3.1 percent lower than the amount of those gaining groundwater irrigation from own tubewells (3,351 m^3 – row 3). However, the *t*-test result showed that the difference was not significant (row 5). Analysis results indicated that farmers that bought water from markets also used 7.5 percent less water than those relying on collective tubewells (3,513 m^3 – row 2). The value of the *t*-statistic was 2.02 and the difference was significant at the 5 percent level (row 4). In addition, farmers that irrigated their wheat plots using water from collective tubewells used 4.8 percent more water than those using own tubewells though the statistical test was not significant (row 6).

Although water buyer used less groundwater for irrigation than tubewell owners, their wheat yield was not significantly affected (Table V, column 2). Compared to farmers that irrigated wheat with water from their own tubewells (5,534 kg/ha – row 3), farmers actually had slightly higher yield (5,557 kg/ha – row 1) when they used water markets (a 0.4 percent increase). However, the difference was not statistically significant based on the result of the *t*-test (row 5). Yield of wheat plots irrigated by groundwater from collective tubewells, was significantly higher than that of plots irrigated by groundwater from water markets or from own tubewells.

		Amount of groundwater use for wheat (m^3/ha)	Wheat yield (kg/ha)
Methods of groundwater access			
From groundwater markets	(1)	3,248	5,557
From collective tubewells	(2)	3,513	5,822
From own tubewells	(3)	3,351	5,534
t-test			
t-statistic	(1)-(2)	2.02**	2.13**
t-statistic	(1)-(3)	0.58	0.15
t-statistic	(2)-(3)	1.03	2.50***

Notes: Significance of *t*-statistics: $^{**}p < 0.05$; $^{***}p < 0.01$
Source: Authors' survey

Table V. The methods by which farmers accessed groundwater for irrigation, amount of groundwater use for wheat and wheat yield

4. Econometric models

Although the descriptive analysis offered some insights on how water markets might affect the amount of groundwater use and crop yield, it did not control for the influence of other important factors such as climate variables. In the next step, a set of econometric models was used to identify the impact of farmers' methods of groundwater access on the amount of groundwater use and wheat yield. The models employed a number of control variables that were also used in other studies (e.g. Wheeler *et al.*, 2008, 2009, 2010; Zhang *et al.*, 2010). The first econometric model took the following form:

$$Log\left(W_{ijkct}\right) = \alpha + \boldsymbol{T}_{ct}\boldsymbol{\theta} + \beta_1 G_{ijkct} + \beta_2 C_{ijkct} + \boldsymbol{Z}_{ijkct}\boldsymbol{\gamma} + \mu P + \delta D + \varepsilon_{ijkct} \quad (1)$$

where W_{ijkct} is the log form of amount of groundwater use (m^3/ha) on plot i by household j in village k of county c in year t. The key variables of interest were G_{ijkct} and C_{ijkct}, measuring the methods of groundwater access from groundwater markets ($1 = $ yes, $0 = $ no), or from collective tubewells ($1 = $ yes, $0 = $ no). The comparing basis is from own tubewells. Gaining groundwater irrigation from own tubewells constituted the base group (when both G_{ijkct} and C_{ijkct} equaled 0).

The impact of climate variables was also a focus of this study. The vector $\boldsymbol{T}_{ct}$ included seven climate variables. The first two variables were monthly mean temperature during the growing season and annual total precipitation in county c in harvesting year t. The construction of these two variables is described in Section 2. Following some existing studies (e.g. Blanc, 2012), the quadratic terms of mean temperature and total precipitation were included in Equation (1) to account for any non-linear effects of climate factors on the amount of groundwater use. Two variables were used to capture the volatility in climate factors: the standard variation of mean temperature during the crop growing season in county c over the past 30 years, and the standard variation in annual total precipitation over the past 30 years. To capture the effect of extreme weather events, the percentage of months with extreme or severe droughts was included.

The vector $\mathbf{Z}_{ijkct}$ contained a set of other factors that affect the amount of groundwater use. The first group of variables controlled for household characteristics, including age and education of the household head and labor use (percentage of household labor time spending on off-farm work). The second group of variables controlled for plot characteristics, including plot area, soil type (sand, clay, or loam), land property rights (contracted land, rent-in land from other households, or rent-in land from a collective), and distance of the plot from the home. The cost of water, P, was also controlled for. P was the price farmers paid to sellers on groundwater markets. D was a dummy variable that equaled 1 if sample plots came from Henan province (fixed effects at the provincial level). This variable captured the effects of any province-specific factors that do not change over time. Year dummies were not included in the model because they were highly collinear with the climate variables. α, $\boldsymbol{\theta}$, β_1, β_2, $\boldsymbol{\gamma}$, μ, and δ were the parameters to be estimated. ε_{ijkct} was the error term that captured the uncertainty faced by farmers and satisfied $E(\varepsilon) = 0$.

The main econometric challenge when estimating Equation (1) was the potential endogeneity of the variables that measured the methods of groundwater access (G_{ijkct} and C_{ijkct}). Reverse causality could have arisen if farmers chose their methods of groundwater access based on the expected amount of groundwater use, which was highly correlated with the observed amount of groundwater use, the dependent variable in Equation (1). To address the endogeneity problem and obtain consistent estimates of parameters, the instrumental variable (*IV*) approach was used. Prior to estimating Equation (1), we estimated the following two equations:

$$G_{ijkct} = \alpha' + \boldsymbol{T}_{ct}\boldsymbol{\theta}' + \boldsymbol{IV}_{ijk}\boldsymbol{\beta} + \boldsymbol{Z}_{ijkct}\boldsymbol{\gamma}' + \mu P + \delta' D + v_{ijkct} \tag{2}$$

$$C_{ijkct} = \alpha'' + \boldsymbol{T}_{ct}\boldsymbol{\theta}'' + \boldsymbol{IV}_{ijk}\boldsymbol{\beta}'' + \boldsymbol{Z}_{ijkct}\boldsymbol{\gamma}'' + \mu P + \delta'' D + \omega_{ijkct} \tag{3}$$

Equations (2) and (3) controlled for the same set of exogenous variables as in Equation (1). Two *IVs* were included in the vector $\boldsymbol{IV}_{ijk}$: the proportion of tubewell owners selling water in the village and a dummy variable that indicated if upper-level officials supported or advocated private tubewell investment through financial subsidies, low-interest bank loans, meetings, or government directories. The proportion of tubewell owners selling water in the village reflected how prevalent groundwater markets are at the village level. The descriptive analysis in Table III shows that it was correlated with farmers' decisions on through which method to access groundwater for irrigation. The descriptive analysis in Table IV shows that government support for private tubewell investment was correlated with farmers' methods of groundwater access. There is no reason to believe either of the two *IV*s at the village level had any independent effect on the amount of groundwater use at the plot level, except through their correlation with farmers' methods of groundwater access. In implementing the *IV* approach, the predicted values of G_{ijkct} and C_{ijkct} from Equations (2) and (3) replaced G_{ijkct} and C_{ijkct} in Equation (1) to obtain consistently estimated coefficients, G_{ijkct} and C_{ijkct} were still used to calculate the standard errors and *t*-statistics.

Since the only channel through the methods of groundwater access would affect crop yield is irrigation, following the strategy used in Zhang *et al.* (2010), we analyzed the effect of farmers' methods of groundwater access on crop yield through the amount of groundwater use. The following econometric model was estimated:

$$Log\left(Y_{ijkct}\right) = \alpha''' + \boldsymbol{T}_{ct}\boldsymbol{\theta}''' + \beta'' log\left(\hat{W}_{ijkct}\right) + \boldsymbol{X}_{ijkct}\boldsymbol{\lambda} + \boldsymbol{Z}_{ijkct}\boldsymbol{\gamma}''' + \delta''' D + \psi_{ijkct} \tag{4}$$

where Y_{ijkct} represents the log form of wheat yield (kg/ha). The key variable of interest, $\hat{W}_{ijkct}$, was the predicted amount of groundwater use from Equation (1). The vector, $\boldsymbol{X}_{ijkct}$, represented other production inputs including labor use (measured in man days per ha), fertilizer (kg/ha), and expenditures on other inputs per ha, they were transferred into log form. Using the Agricultural Productive Materials Price Index (National Bureau of Statistics of China, 2014), total expenditure on other inputs such as seeds, pesticide, plastic film, machinery, and custom services were inflation adjusted to 2001 monetary terms. The same set of climate variables ($\boldsymbol{T}_{ct}$) and other control variables (D and $\boldsymbol{Z}_{ijkct}$) used in Equation (1) were used in Equation (4).

5. Econometric estimation results

5.1 Factors that influence the methods of groundwater access

The estimation results of Equations (2) and (3) showed that both *IVs* were correlated with farmers' choice of methods of groundwater access (Table VI). The regression coefficient of the variable measuring the proportion of tubewell owners selling water in the village was positive and statistically significant in the regression for accessing from groundwater market (briefed as market access model) (column 1), but negative and statistically significant in the regression for accessing from collective tubewells (briefed

Table VI. Regression results on the determinants of the methods by which farmers accessed groundwater for irrigation, and its impacts on the amount of groundwater use and wheat yield

Dependent variables	(1) Access from groundwater markets (1 = yes; 0 = no)^a	(2) Access from collective tubewells (1 = yes; 0 = no)^a	(3) Amount of groundwater use (m^3/ha, log)	(4) Wheat yield (ka/ha, log)
Climate variables				
Temperature^b	0.8182 (3.54)***	−0.6745 (2.53)**	1.5614 (12.08)***	−0.0756 (0.45)
Temperature squared	−0.0345 (3.30)***	0.0284 (2.34)**	−0.0749 (11.47)***	0.0051 (0.64)
Precipitation^c	0.0040 (2.97)***	−0.0060 (3.59)***	0.0068 (2.99)***	0.0014 (1.47)
Precipitation squared	−0.000003 (3.02)***	0.000004 (3.33)***	−0.000005 (3.34)***	−0.0000 (1.54)
Percentage of months with extreme or severe drought	0.0062 (2.09)**	−0.0139 (4.44)***	0.0068 (2.99)***	0.0014 (1.47)
SD of temperature	0.5124 (3.85)***	−0.3560 (2.42)**	0.6032 (4.07)***	−0.4066 (3.52)***
SD of precipitation	−0.0003 (0.16)	−0.0032 (1.54)	−0.0170 (7.19)***	−0.0080 (5.30)***
Instrument variables				
Proportion of tubewell owners selling water in the village (%)	0.0046 (11.46)***	−0.0053 (11.43)***		
Government support for private tubewells (1 = yes; 0 = no)	−0.0226 (0.57)	−0.2770 (5.97)***		
Methods of groundwater access				
From groundwater markets (1 = yes; 0 = no)			−0.6093 (2.71)***	
From collective tubewells (1 = yes; 0 = no)			−0.2305 (1.48)	
Cost of water (yuan/m^3)	0.0249 (0.94)	−0.0828 (2.59)***	−0.0970 (2.95)***	
Production inputs				
Amount of groundwater use (m^3/ha, log)				−0.0637 (1.32)
Labor use (days/ha, log)				−0.0575 (6.09)***
Fertilizer use (kg/ha, log)				0.0114 (0.84)
Other inputs (yuan/ha, log)				0.0089 (0.42)

(continued)

Table VI.

Dependent variables	(1) Access from groundwater markets (1 = yes; 0 = no)[a]	(2) Access from collective tubewells (1 = yes; 0 = no)[a]	(3) Amount of groundwater use (m^3/ha, log)	(4) Wheat yield (ka/ha, log)
Plot characteristics				
Area of plot (ha)	−0.2387 (2.43)**	−0.1754 (1.31)	−0.3142 (1.49)	−0.0757 (1.10)
Loam soil (1 = yes; 0 = no)	−0.0855 (2.63)***	0.0294 (0.72)	0.0198 (0.37)	0.0648 (3.03)***
Clay soil (1 = yes; 0 = no)	−0.0090 (0.29)	−0.0049 (0.14)	0.0045 (0.11)	0.0635 (3.25)***
Rent-in land from other households (1 = yes; 0 = no)	0.1377 (1.06)	−0.1084 (1.09)	0.0604 (0.36)	−0.0558 (0.70)
Rent-in land from a collective (1 = yes; 0 = no)	0.0087 (0.12)	0.0829 (0.82)	0.0788 (0.75)	−0.0658 (0.98)
Distance to home (km)	0.0193 (1.12)	−0.0405 (2.80)***	0.0114 (0.39)	−0.0187 (1.34)
Household characteristics				
Age of household head	−0.0021 (1.81)*	0.0008 (0.53)	−0.0051 (2.52)**	0.0011 (1.36)
Education of household head	−0.0068 (1.60)	0.0066 (1.24)	−0.0104 (1.57)	0.0087 (2.68)***
Percentage of household labor time spending on off-farm work	0.0005 (0.74)	0.0019 (2.41)**	−0.0006 (0.53)	0.0017 (3.43)***
Province dummy (1 = Henan;0 = Hebei)	−0.2160 (4.86)***	0.2270 (4.10)***	0.1567 (1.94)*	0.1263 (3.91)***
Constant	−6.1053 (4.26)***	7.3604 (4.33)***	0.0000	9.9916 (9.98)***
Observations	772	772	772	772
R^2	0.3389	0.4077	0.1349	0.2696

Notes: Absolute value of *t*-statistics in parentheses. [a]Columns (1) and (2) are the first stage regressions in the IV estimation. Column (3) is the second stage; [b]temperature is the monthly mean temperature during growing season from previous October to current June; [c]precipitation is annual total precipitation from last July to current June. *,**,***Significant at 10, 5, 1, percent, respectively as collective tubewells access model) (column 2). This finding is consistent with the expectation that, all other things being constant, farmers in villages with more extensive groundwater markets are more likely to buy water to irrigate their crops. However, if having extensive groundwater markets, the possibility to have the service of collective tubewells will be lower, and farmers also are less likely to access groundwater through collective tubewells. The coefficient of the dummy variable of government support for private tubewells was negative and statistically significant in collective tubewells access model (column 2), implying when government supported the development of private tubewells, due to increasing private tubewells, the possibilities for farmers to access groundwater through collective tubewells will be significantly reduced.

Climate factors also influenced the methods of groundwater access. The results revealed an inverted-*U*-shaped relationship between temperature and the decision to buy water from markets (Table VI, column 1). The turning point, where the positive relationship changed into a negative one, was 11.86°C (estimated coefficient on temperature/(2 × estimated coefficient on temperature squared)), which was close to the maximum monthly average temperature at the study site (12.96°C). This means for most temperature levels at the study site, a higher temperature increases the likelihood of buying water from markets. One possible reason is that when temperature is higher than 11.86°C, water supply capacity of own tubewells will be reduced and not enough for satisfying irrigation demand, and farmers have to depend on markets to gain irrigation. However, the relationship between temperature and the decision to access water from collective tubewells presented to be *U*-shaped relationship and the turning point was 11.88°C (Table VI, column 2). This not hard to be understood, increasing the likelihood of buying water from markets will reduce the likelihood of access groundwater from collective tubewells.

Total precipitation also had an inverted-*U*-shaped relationship with the decision to buy water from markets, but a *U*-shaped relationship with the decision to access water from collective tubewells (Table VI, columns 1 and 2). The turning points were 667 mm in the estimation results of market access model, and 750 mm in the collective tubewells access model, which were close to the mean of total precipitation. This indicated that as the precipitation got closer to the upper end of the water required for winter wheat (about 773 mm; Sun *et al.*, 2013), due to decline of irrigation demand, farmers were more likely to gain groundwater irrigation from collective tubewells, not from water markets or own tubewells. One possible explanation is that when having more precipitation, groundwater supply from collective tubewells can ensure irrigation demand in large degree and farmers do not need to buy water from markets. The important reason is that farmers need to pay more money for gaining groundwater irrigation from markets (Zhang *et al.*, 2010). In addition, due to higher investment cost, farmers also do not need to dig tubewells by themselves when they have available water from collective tubewells.

Another interesting finding was that the methods of groundwater access was also influenced by extreme drought events. The estimated coefficient of percentage of months with extreme or severe droughts was positive and statistically significant in the market access model, and negative and statistically significant in the collective tubewells access model (Table VI, columns 1 and 2). So, farmers were more likely to access groundwater from markets in severe drought years, and water market is one effective adaptative strategy for farmers to mitigate the negative impacts of extreme drought events. This is consistent with findings from studies on water markets in other regions, such as California (Howitt *et al.*, 2014) and Australia (Loch *et al.*, 2012).

There was also evidence that volatility in climate affected the methods of groundwater access. The estimated coefficient of the variable of the standard deviation of temperature was positive and statistically significant in the market access model, but negative and statistically significant in the collective tubewells access model (Table VI, columns 1 and 2). This indicated that in areas with more historical fluctuations in temperature, farmers were more likely to buy water to irrigate their plots instead of using own tubewells. It probably implied that farmers expected more volatility in the future and believed that the water trade between individual farmers was more flexible than digging own tubewells for dealing with climate volatility. However, farmers more likely replied on own tubewells to deal with the fluctuations in temperature than that on collective tubewells. The estimated coefficient of the variable of the standard deviation of total precipitation was not statistically significant in two models. One explanation may be that most precipitation occurs from July to September and wheat is grown outside this period; thus, wheat production may be less exposed to variations in precipitation.

The results for the other variables were also of interest. The estimated coefficient of plot size was negative and statistically significant in the market access model (Table VI, column 1). Farmers with larger plots are more likely to have their own tubewells (the base group). This is probably because farmers with larger plots were more likely to have the financial capacity to invest in tubewells. Farmers were less likely to buy water to irrigate plots with loam soil relative to sandy soil (the base group), probably because loam soil has a better water holding capacity. Plots that were further away from home were more likely to be irrigated by water either bought from groundwater markets or from own tubewells. This may be because it was more difficult for farmers to make sure water was delivered from collective wells at the needed quantity or time. Older farmers were less likely to participate in the groundwater market. Households that spent more time on off-farm work were more likely to rely on collective wells. This is probably because off-farm work competed with groundwater irrigation for available family labor. So, farmers were less likely to spend time on sinking their own wells and maintaining them. Another explanation is that farming was a relatively small part of the total income of those households that spent more time on off-farm work, so they were less likely to invest in sinking a tubewell.

5.2 Impact of the methods of groundwater access on the amount of groundwater use and crop yield

The results of estimating Equation (1) using the *IV* approach showed that the amount of groundwater use was lower for wheat plots gained groundwater irrigation from groundwater markets compared with those from own tubewells. The estimated coefficient of the dummy variable indicating groundwater access from water markets was negative and statistically significant at the 1 percent percent level (Table VI, column 3). Because the dependent variable took the log form, the estimated coefficients measured percentage differences. Since the groundwater access variables were dummy variables, the exact percentage difference was calculated as $\exp^{\beta} - 1$, where β is the parameter of the dummy variable (Halvorsen and Palmquist, 1980). Farmers who bought water from markets applied about 46 percent less groundwater than tubewell owners. The coefficient of the variable indicating the use of water from collective tubewells, although negative, was not significant (column 3). Thus, our analysis suggested the amount of groundwater use by tubewell owners and those of farmers relying on collective tubewells were not statistically different. These results are consistent with the findings of Zhang *et al.* (2010). The lower amount of groundwater use from groundwater markets were partly related to the higher water costs they faced (Zhang *et al.*, 2010). Descriptive analysis showed that farmers who bought water paid 0.41 yuan/m^3 for groundwater, 22 percent higher than the cost tubewell owners incurred. However, even after the cost of water was controlled for, water buyers still used less water than tubewell owners. The difference was statistically significant.

Although the amount of groundwater use for wheat was lower for farmers who bought water from groundwater markets, our analysis suggested that wheat yield was not negatively affected. While the coefficient of the amount of groundwater use was not statistically significant (Table VI, column 4), it indicated that less irrigation is not likely to affect wheat yield. One possible explanation is that water buyers had more incentives to reduce inefficient water use. During the field survey, we found farmers buying water wasted less water than those relying on collective tubewells or pumping from their own tubewells. Groundwater markets may also enable farmers to adjust their amount of groundwater use contingent on weather conditions. In an alternative specification of Equation (1) in which climate variables were interacted with the groundwater access dummy variables (see Table AII), only the interaction terms between climate variables and the water buying dummy variable were statistically significant. For example, the estimated coefficient of percentage of months with droughts interacted with the dummy variable, indicating that buying water was positive and statistically significant. So, farmers who bought water from groundwater markets were able to apply more water in drought years. The estimated coefficient of percentage of months with droughts interacted with the dummy variable, indicating that gaining water from collective tubewells was not statistically significant. Therefore, this group of famers was not able to increase their amount of groundwater use in drought conditions. Famers who bought water also applied more of it as the precipitation level decreased. In contrast, the amount of groundwater use of farmers who gained water from collective tubewells did not vary with the precipitation level. These findings indicated that the flexibility of groundwater markets enabled farmers to adjust their amount of groundwater use and thus increase irrigation productivity.

The amount of groundwater use was also influenced by climate variables (Table VI, column 3). The estimation results revealed an inverted-*U*-shaped relationship between the amount of groundwater use on wheat plots and temperature. An inverted-*U*-shaped relationship also existed between the amount of groundwater use and precipitation. A possible explanation may be found in the climate patterns and water scarcity of the sample areas. Lack of rain in winter and severe spring droughts dominate the wheat growing season (Zhang *et al.*, 2013). Farmers apply more irrigation to compensate for higher rates of evaporation due to the increasing temperature, up to a peak temperature point. In addition, the groundwater table is often lowest during the wheat growing season. Before the rainy season begins, a modest increase in precipitation recharges aquifers. The resulting rising water table in turn leads farmers to irrigate more. Variables that measured long-term variations in climate also played a role. The estimated coefficient of the standard deviation of temperature was positive and that of precipitation was negative; both were statistically significant. Farmers' expectation of more variations in temperature will lead them to apply more water, probably to hedge against low temperatures (protection against frost) or high temperatures (protection against heat stress). Expectation of higher volatility in precipitation reduces the amount of groundwater use. Given the generally low levels of precipitation in the study area, higher volatility is more likely caused by unexpected intense rainfall.

Therefore, farmers may reduce amount of groundwater use to reduce the risk of flooding crops in the event of unexpected high levels of precipitation.

Climate variables had the expected effects on wheat yield (Table VI, column 4). After production inputs had been controlled for, the variables that measured mean temperature and total precipitation did not affect wheat yield. This is because farmers used production inputs such as irrigation water to offset/supplement the effects of weather fluctuations. The estimation results revealed a negative and statistically significant relationship between wheat yield and the standard deviations of temperature and precipitation. This implied that wheat yield have been negatively affected by larger climate variations over the years. The estimated coefficient of percentage of months with extreme or severe droughts was positive but not statistically significant.

6. Conclusion

Groundwater markets have developed rapidly in the NCP over the past two decades. This development has changed farmers' methods of groundwater access. More and more farmers who used to rely on collective tubewells have turned to groundwater markets or their own tubewells. Our estimation results showed that farmers who bought water from groundwater markets applied less water to wheat plots than those who had their own tubewells. However, wheat yield was not negatively affected.

Against the background of inevitable climate change in the NCP, our study suggests farmers are using groundwater markets as a way to help them adapt to climate change. Over the past 60 years, the annual mean temperature in the NCP has increased at a rate of 0.3°C per decade, while the annual precipitation rate has declined at a rate of −2.8 to −34.3 mm per decade (Wang *et al.*, 2015). Moreover, droughts are occurring more frequently (China Meteorological News, 2013). In the future, it is projected that the annual average temperature will rise by 0.23 to 0.44°C every ten years, and the overall trend of precipitation is increasing, with large fluctuations expected in the NCP throughout the twenty-first century (China Meteorological News, 2013). Our econometric estimation results showed that both average climate conditions (mean temperature and total precipitation) and long-term variations were related to farmers' choice of the methods of groundwater access. More frequent droughts and increasingly volatile temperatures both increased the likelihood of farmers gaining groundwater irrigation from markets. There was also evidence that groundwater markets provided farmers with more flexibility in adjusting their amount of groundwater use based on weather conditions.

Our findings have important implications for the NCP, where climate change and water management are arguably two of the most important policy challenges. Our results suggest that as an instrument of adaptation to climate change, groundwater markets, and tubewell privatization are more effective for groundwater management than collective tubewells. To improve farmers' ability to adapt to climate change, government support considering the local characteristics is essential in the NCP. In the areas where most tubewells are collectively owned and managed, fiscal subsidies and low-interest loans for private tubewell investment should be provided. However, in areas where tubewell privatization has reached a certain level, the development of groundwater markets should be promoted. For example, there needs to be more investment in irrigation infrastructure for water delivery to facilitate water trading.

Our study has some limitations. The first limitation is on our survey sample. In each village, we only had four sample households and in each household, we only selected two plots to collect relevant information. In the future, if we can expand our household and plot samples, the understanding of methods of groundwater access will be further improved. Second, in addition to groundwater use and crop yield, it is necessary to further explore the impacts of methods of groundwater access on groundwater table, cropping pattern, farmer income, and other relevant issues. Finally, the impacts of climate change are long term, so it is valuable to conduct follow-up investigation and analysis in the future.

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Appendix

	Mean	SD	Min.	Max.
Dependent variables				
Amount of groundwater use (m^3/ha)	3,436.61	1,547.52	590.00	8,500.00
Wheat yield per hectare (kg/ha)	5,721.20	1,229.42	1,500.00	8,250.00
Buying water from groundwater markets (1 = yes; 0 = no)	0.17	0.38	0.00	1.00
Using water from collective tubewells (1 = yes; 0 = no)	0.64	0.48	0.00	1.00
Independent variables				
Climate variables				
Temperature (°C)	10.99	1.27	7.88	12.96
Precipitation (mm)	638.43	123.34	455.65	885.36
SD of temperature	0.71	0.13	0.58	1.11
SD of precipitation	114.67	11.08	96.05	131.43
Percentage of months with extreme or severe droughts	2.68	5.85	0.00	25.00
Instrument variables				
Proportion of tubewell owners selling water in the village (%)	32.09	41.02	0.00	100.00
Government support for private tubewells (1 = yes; 0 = no)	0.20	0.40	0.00	1.00
Production inputs				
Labor use per hectare (days/ha)	92.00	91.19	7.80	555.00
Fertilizer use per hectare (kg/ha)	381.18	164.42	0.00	1,636.25
Value of other inputs per hectare (yuan/ha)	1,715.09	811.40	366.50	7,077.49
Plot basic characteristics				
Area of plot (ha)	0.18	0.13	0.01	0.80
Loam soil (1 = yes; 0 = no)	0.25	0.43	0.00	1.00
Clay soil (1 = yes; 0 = no)	0.48	0.50	0.00	1.00
Rent-in land from other households (1 = yes; 0 = no)	0.01	0.09	0.00	1.00
Rent-in land from a collective (1 = yes; 0 = no)	0.02	0.15	0.00	1.00
Distance to home (km)	0.78	0.78	0.00	15.00
Household characteristics				
Age of household head (years)	49.35	10.21	25.00	77.00
Education of household head (years)	6.99	2.94	0.00	15.00
Percentage of household labor time spending on off-farm work	19.66	17.10	0.00	76.67

Note: $n = 772$

Table AI.
Descriptive statistics of variables

Table AII. Impact of the methods by which farmers access groundwater for irrigation on amount of groundwater use for wheat

	Amount of groundwater use (m3/ha, log)
Climate variable and farmers' methods of groundwater access	
Buying water from markets × temperature	−8.5874 (2.64)***
Buying water from markets × temperature squared	0.4486 (1.52)
Buying water from markets × precipitation	0.1488 (1.13)
Buying water from markets × precipitation squared	−0.0001 (1.86)*
Buying water from markets × % of months with extreme or severe drought	0.1333 (1.98)**
Using water from collective tubewells × temperature	0.0000 (0.00)
Using water from collective tubewells × temperature squared	−0.1065 (0.14)
Using water from collective tubewells × precipitation	0.0303 (0.35)
Using water from collective tubewells × precipitation squared	−0.0000 (0.33)
Using water from collective tubewells × percentage of months with extreme or severe droughts	−0.1867 (0.63)
Additional climate variables	
SD of temperature	1.3439 (0.29)
SD of precipitation	0.0328 (0.44)
Plot characteristics	
Area of plot (ha)	0.7324 (0.71)
Loam soil (1 = yes; 0 = no)	−0.1613 (0.20)
Clay soil (1 = yes; 0 = no)	−0.1208 (0.16)
Rent-in land from other households (1 = yes; 0 = no)	−1.0454 (0.34)
Rent-in land from a collective (1 = yes; 0 = no)	1.1474 (0.91)
Distance to home (km)	0.0442 (0.31)
Household characteristics	
Age of household head	0.0379 (0.82)
Education of household head	0.0229 (0.15)
Percentage of household labor time spending on off-farm work	−0.0001 (0.01)
Province dummy = 1 if Henan province	0.6116 (0.05)
Observations	772

Notes: Absolute value of *t*-statistics in parentheses. *,**,***Significant at 10, 5, 1 percent, respectively

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