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Impact of agricultural water reallocation on crop yield and revenue: a case study in China

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Abstract

Our study area in the People's Victory Canal Irrigation District of Henan Province in China has been transferring agricultural water to the city for municipal use. This study starts with an examination of the impacts of irrigation frequency, irrigation water sources, and irrigation water supply performance on crop yield and net crop revenue, using data from a survey of 182 households in the study area. Thereafter, it analyzes the impact of agricultural water reallocation (AWR) on crop yield and revenue. The study ends with an estimation of the compensation for affected farmers and a discussion of the compensation methods. Regression results indicate that irrigation frequency shows a significantly positive impact on crop yield and net crop revenue. The change of irrigation water source from canal water to well water and local small river water decreases the integrated crop yield of wheat and rice by 9% and 12%, and decreases the net integrated crop revenue by 16% and 19%, respectively. AWR decreases the integrated crop yield of wheat and rice by at least 2%, and decreases the net integrated crop revenue by at least 3.5%. Estimated compensation for affected farmers is between 78.72 and 97.85 USD/ha.

Keywords: Compensation; Henan Province; Irrigation frequency; Irrigation water source; People's Victory Canal Irrigation District

1. Introduction

Increasing tendency to reallocate water from agriculture to industrial and domestic needs is inevitable along with the accelerating process of industrialization and urbanization in most developing countries

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(Gohari *et al.*, 2013). Many irrigation districts in China, such as Hengjing Irrigation District in Zhejiang Province (Chen, 2008), People's Victory Canal Irrigation District (PVCID), Luhun Irrigation District, and Baisha Irrigation District in Henan Province (Dai *et al.*, 2015), have reallocated water from agriculture to meet industrial and domestic use. However, despite its benefits, agricultural water reallocation (AWR) may have an adverse impact on crop yield and revenue (Rosegrant & Ringler, 2000; Chen, 2008). Understanding the impact of agriculture water reallocation on crop yield and revenue is important in analyzing the compensation for farmers affected by AWR.

AWR initially affects the delivery reliability of irrigation water (Heaney *et al.*, 2006; Hu, 2007). Dai *et al.* (2015) found that the quantity, timeliness, and reliability of canal water supply in the PVCID are affected by AWR. Thereafter, the irrigation behavior of farmers changes because of AWR. For example, farmers may change irrigation water sources, reduce the use of unreliable water sources, or discard irrigation if the performance of irrigation water supply deteriorates. Some researchers found that an increasing area of cropland changed irrigation source from canal water to well water (Celio & Giordano, 2007; Dai *et al.*, 2015), local small river water (Dai *et al.*, 2015), and small pool water (Roost *et al.*, 2008) under the impact of AWR. In understanding the impact of AWR on crop yield and revenue, identifying the impact of farmers' irrigation behavior change on crop yield and revenue is crucial.

Some studies examined the impact of irrigation on crop production and revenue. Huang *et al.* (2006) demonstrated strong relations between irrigation and crop yield and revenue. Zhou *et al.* (2009) showed that irrigated croplands increased maize yield and net revenue by 21% and 32%, respectively, compared to non-irrigated cropland. Groundwater irrigation had higher elasticity on crop yield than surface water (Zhou *et al.*, 2009). Nevertheless, most of the studies only compared the difference of crop yield and revenue between irrigated and non-irrigated croplands. The impacts of irrigation frequency, irrigation water sources, and irrigation water supply performance on crop yield and revenue are seldom studied. The loss of crop yield and revenue from AWR is not fully examined.

The current study aims to analyze the impacts of irrigation frequency, irrigation water sources, and irrigation water supply performance on crop yield and revenue and to estimate the contribution of AWR to the loss of crop yield and revenue based on household research.

2. Sampling design and data

2.1. Sampling design

Our study area is the PVCID, a 99,000 ha irrigation district located in Henan Province in China (Figure 1) (Dai *et al.*, 2015). This district has been irrigated since 1952 using the Yellow River water. The PVCID has transferred agricultural water to Xinxiang City for municipal uses since 1970. Farmers only owned the rights to use irrigation water and were not compensated for the transfer of agricultural water. The main water source of the PVCID is water from the Yellow River; well water and local small river water are also used for irrigation especially in the downstream. Farmlands are mainly irrigated by surface irrigation systems in the study area. With an average rainfall of 620 mm/year, the district is dominated by the continental temperate monsoon climate (Dai *et al.*, 2015). The PVCID is a suitable study area because the Administration Bureau of the PVCID has data on water diversion and irrigation since 1952. Such data allow us to analyze the impact of AWR on the performance of canal water

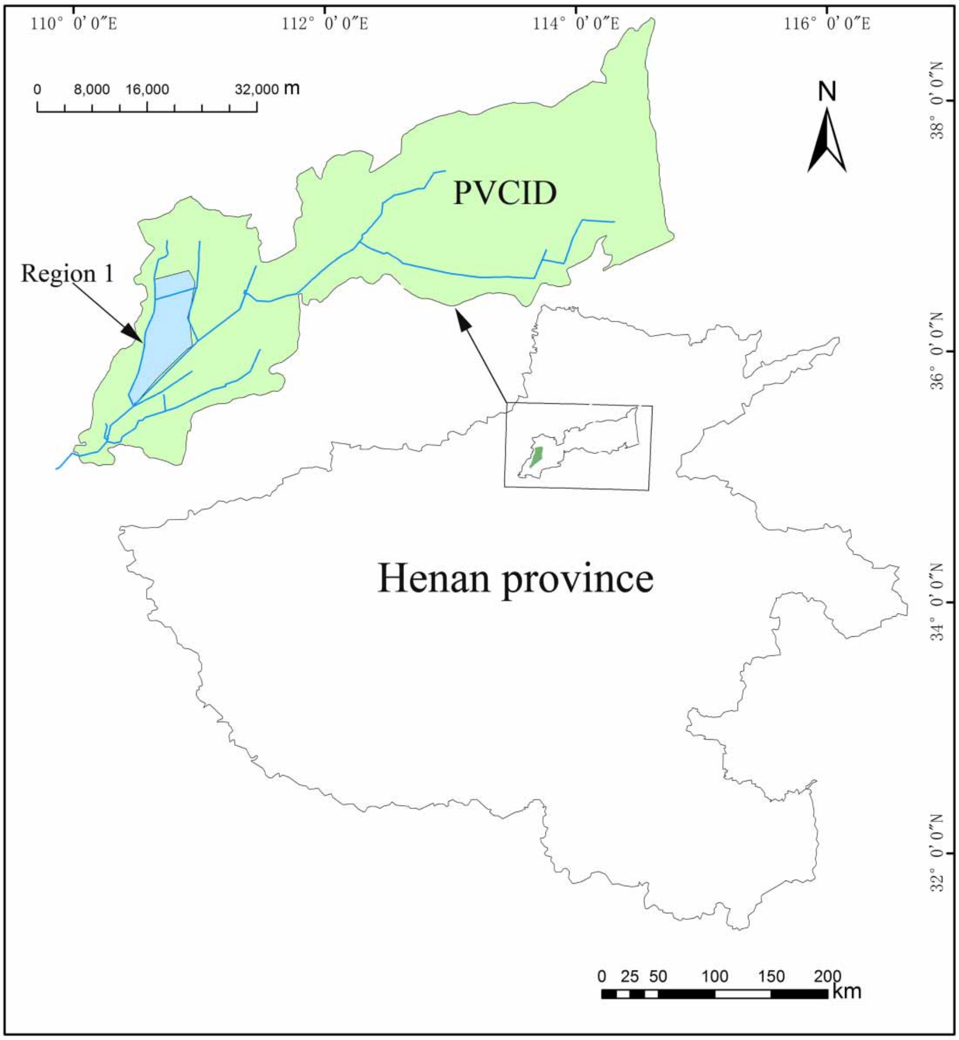

Fig. 1. Location of the study area.

supply and the farmers' choice of irrigation water source. Several water sources in the PVCID allow us to compare the impact of irrigation water source change on crop yield and revenue.

Face-to-face interviews were used to collect household survey data in April 2013 in Region 1 of the PVCID (Figure 1). The authors selected one township each in the upstream, midstream, and downstream because the water supply performance of the PVCID in the upstream is different from that in the downstream. Five to six villages were randomly selected from each township. The authors interviewed about 10 randomly selected households in each village. Overall, 182 farm households in 17 villages were interviewed. Structured interviews were conducted with the head of each household or the person responsible for farming activities. The questionnaire was developed based on a pre-survey conducted in March 2013. Trained interviewers asked farmers 64 questions in Chinese according to the questionnaire and wrote down the answers of the farmers in the interview because the farmers had minimal education. The method of data collection is also described in another study conducted in the same research field (Dai *et al*., 2015).

2.2. Data description

The authors collected detailed information on the largest plot from each household for 2012, such as yields of wheat, rice, and corn; selling prices of grains; cost of farmland input on different crops; irrigation status of different crops; plot characteristics; precipitation status; and the occurrence of natural disasters (whether the plot has experienced disasters, e.g., drought, flood, plant disease, and insect pests). The authors also collected data on household characteristics, such as age and educational level of farm household head, number of household adults at home, and main source of household income from each household in 2012.

In this study, net crop revenue refers to the gross crop revenue minus production costs, considering the market value of crops produced for home consumption. Net crop revenue was used as the dependent variable rather than crop gross revenue to better analyze the role of irrigation on the income of farmers. The water delivery performance of the irrigation district was evaluated by water adequacy and water timeliness, which accorded with the research of Unal *et al*. (2004) and Dai *et al*. (2015). In the interview, farmers were asked to evaluate the water adequacy and water timeliness of the canal water. Assuming that farmers fully irrigated their cropland every time, irrigation times of farmers using different water sources were used to examine the impacts of irrigation frequency and irrigation water sources on crop yield and net crop revenue. The authors evaluated farmland inputs of seed, fertilizer, pesticide, and agricultural machinery by their monetary value instead of their quantity because a high price means a high quality of input. The inputs and outputs were calculated with the average conversion rate of USD to Renminbi (CNY) in 2012 (1 USD = 6.3 CNY). Precipitation status was collected by asking farmers whether they thought that 2012 brought greater precipitation than previous years. Table 1 provides a summary of the main characteristics of the variables used in subsequent analyses. The table summarizes the variables into three columns of wheat, rice, and wheat and rice together. The column for wheat and rice together includes the data of households that plant wheat and maize and households that plant wheat and rice. As maize is not included in the analysis, the data in the column for wheat and rice together are not the sum of the data in the individual columns for wheat and rice.

3. Model specification

3.1. Crop yield regression model

The authors developed an empirical model to investigate the relationship between irrigation and yield. In principle, the crop yield of a plot is influenced by input factors, external factors, plot-intrinsic factors, and household factors. Input factors refer to the application of water, seeds, fertilizer, pesticide, and agricultural machinery. External factors refer to those outside a household, such as market prices and accessibility to market and technology. Plot-intrinsic factors refer to plot characteristics, such as soil quality, plot size, and slope. Household factors refer to demographic characteristics, such as age and education of the household head and the number of adults in the household. The authors chose these variables according to literature investigation and pre-survey. External factors are similar throughout our study area, and are consequently not included in the model. The linear regression model was often used to estimate the impact of inputs on crop yield and revenue (Huang *et al*., 2006; Zhou

Table 1. Summary of the main variables affecting crop yield and net crop revenue[a].

Definition of variables	Wheat Yield ($n=87$[c])	Wheat Net revenue ($n=85$)	Rice Yield ($n=61$)	Rice Net revenue ($n=61$)	Wheat and rice[b] Yield ($n=86$)	Wheat and rice[b] Net revenue ($n=86$)
Dependent variables						
Crop yield on the largest plot (kg/ha)	5889.89 (1353.89)		8421.81 (1211.76)		12097.69 (3752.88)	
Net crop revenue on the largest plot (USD/ha)		872.99 (463.46)		2653.76 (648.19)		2847.09 (1321.07)
Independent variables						
Irrigation status						
Irrigation times using canal water	1.57 (1.11)	1.55 (1.11)	3.83 (2.25)		4.53 (3.09)	
Irrigation times using well water	0.57 (0.87)	0.59 (0.88)	1.06 (1.88)		1.45 (2.16)	
Irrigation times using local small river water	0.21 (0.73)	0.22 (0.73)	0.15 (0.81)		0.4 (1.55)	
Timeliness of canal water (0 if not timely, 2 if timely, 1 otherwise)	0.64 (0.85)	0.64 (0.86)	0.61 (0.84)		0.57 (0.83)	
Adequacy of canal water (0 if insufficient, 2 if sufficient, 1 otherwise)	1.21 (0.85)	1.21 (0.86)	1.21 (0.88)		1.21 (0.86)	
Other input factors						
Seed use (USD/ha)	168.96 (82.74)	169.86 (83.37)	108.34 (34.33)		258.06 (101.31)	
Fertilizer use (USD/ha)	427.63 (81.76)	427.89 (82.2)	460.32 (73.11)		812.82 (203.04)	
Pesticide application (USD/ha)	150.34 (64.07)	148.7 (62.78)	218.49 (91.62)		321.54 (159.82)	
Agricultural machinery use (USD/ha)	217.72 (81.85)	218.64 (82.59)	222.44 (89.98)		384.68 (139.86)	
Plot characteristics						
Slope (0 if the plot is bottomland, 1 otherwise)	0.72 (0.45)	0.72 (0.45)	0.69 (0.47)		0.71 (0.46)	
Soil fertility (2 if fertile, 0 if unfertile, 1 otherwise)	1.22 (0.65)	1.24 (0.65)	1.3 (0.69)		1.27 (0.66)	
Soil texture (0 if sandy soil, 1 others)	0.92 (0.27)	0.92 (0.28)	0.95 (0.22)		0.92 (0.28)	
Plot size (ha)	0.25 (0.11)	0.26 (0.11)	0.25 (0.1)		0.25 (0.11)	
Distance from home (km)	1.08 (0.89)	1.09 (0.9)	1.04 (0.76)		1.09 (0.9)	
Precipitation (0 if less than usual years, 2 if more than usual years, 1 otherwise)	0.87 (0.55)	0.87 (0.55)	0.84 (0.55)		0.88 (0.54)	
Natural disasters (0 if disaster is experienced, 1 otherwise)	0.94 (0.23)	0.94 (0.24)	0.92 (0.28)		0.93 (0.26)	

(*Continued.*)

Table 1. (*Continued.*)

Definition of variables	Wheat		Rice		Wheat and rice[b]	
	Yield ($n = 87$[c])	Net revenue ($n = 85$)	Yield ($n = 61$)	Net revenue ($n = 61$)	Yield ($n = 86$)	Net revenue ($n = 86$)
Household characteristics						
Age of farm household head (years)	54.39 (10.83)	54.48 (10.9)	54.87 (10.61)		54.62 (10.85)	
Educational level of farm household head (0 if no formal education, 1 if primary school, 2 if middle school, 3 if high school, 4 if university diploma or above)	1.82 (0.79)	1.81 (0.79)	1.66 (0.81)		1.78 (0.83)	
Number of household adults at home	2.49 (1.4)	2.52 (1.41)	2.72 (1.53)		2.56 (1.4)	
Main source of income (0 if farming, 1 otherwise)	0.55 (0.5)	0.56 (0.5)	0.52 (0.5)		0.56 (0.5)	

Source: Household survey in the People's Victory Canal Irrigation District, conducted by North China University of Water Resources and Electric Power in 2013.

[a]Table 1 shows the mean values and standard deviations of mean values for the variables used in the analyses. The standard deviations are in parentheses.

[b]The column of wheat and rice includes households that plant wheat and maize and households that plant wheat and rice. As maize is not included in the analysis, the mean value of the wheat and rice column is smaller than the mean value of the column for wheat added to that of the column for rice.

[c]*n* indicates the number of households. Two households were deleted in analyzing net revenue of wheat because of the lack of data.

et al., 2009; Blanc *et al.*, 2016) besides the Cobb–Douglas model. The authors also use the linear regression model to estimate crop yield and revenue. The crop yield estimation function is specified as follows:

$$Y_{hi} = \alpha + \beta I_{hi} + \gamma F_{hi} + \delta X_{hi} + \eta H_{hi} \tag{1}$$

where Y_{hi} denotes the *i*th crop yield of the largest plot of the *h*th household, including wheat yield, rice yield, and wheat and rice yield together; and I_{hi} refers to the irrigation status of the *i*th crop on the largest plot of the *h*th household, including irrigation times using canal water, well water, and local small river water, as well as the timeliness and adequacy of canal water. Variables of irrigation times using canal water, well water, and local small river water were used to analyze the impact of water source availability and type of water sources on crops yield. F_{hi} denotes other inputs on the largest plot of the *h*th household in planting the *i*th crop, including seed, fertilizer, pesticide, and agricultural machinery. X_{hi} denotes a set of plot-specific variables including slope (whether the plot is bottomland), soil fertility, soil texture (sandy soil or not), plot size, distance from home, precipitation status, and natural disasters. H_{hi} represents a group of household factors, including the age and education of the household head, the number of household adults at home, and the main source of household income. α, β, γ, δ, and η are the coefficients to be estimated. Each variable in the regression equation can be transformed to the same dimension, while some researchers also use the original dimension of each variable (Huang *et al.*, 2006; Blanc *et al.*, 2016). The authors used the original dimension of each variable because this treatment can better explain the change of every input on crop yield and revenue.

3.2. Net crop revenue regression model

The impact of irrigation on net crop revenue is analyzed based on plot-level data. Gross crop revenue is calculated by multiplying the output of a plot by the market price of wheat and rice in 2012. Thereafter, net crop revenue is calculated by the gross crop revenue minus the input cost, which includes cost of seed, pesticide, fertilizer, and agricultural machinery. As labor cost is difficult to investigate, it is not subtracted from the gross crop revenue.

The authors used the same equation and input variables to estimate the crop yield and revenue to compare the impacts of input changes on crop yield and revenue. The net crop revenue estimation model is specified as follows:

$$R_{hi} = \alpha + \beta I_{hi} + \gamma F_{hi} + \delta X_{hi} + \eta H_{hi} \tag{2}$$

where R_{hi} denotes the ith net crop revenue of the largest plot of the hth household, including the net revenue of wheat, rice, and integrated crop of wheat and rice. The other parameters are similar to those described in Equation (1).

3.3. Calculating the elasticities of affecting factors on crop yield or net crop revenue

The elasticities of affecting factors on crop yield or net crop revenue are calculated using the formula for demand elasticity (Carlson *et al.*, 1993), which is specified as follows:

$$\eta(Y_i) = \frac{\partial Y}{\partial X_i}\frac{\bar{X}_i}{\bar{Y}} \tag{3}$$

where $\eta(Y_i)$ denotes the elasticity of the ith impacting factor on crop yield or net crop revenue, Y refers to crop yield or net crop revenue, X_i denotes the ith factor affecting crop yield or net crop revenue, $\bar{X}_i$ and $\bar{Y}$ denote the mean value of X_i and Y, and $\partial Y/\partial X_i$ denotes the regression coefficient of affecting factor i in Equation (1) or (2).

3.4. Estimating the impact of AWR on crop yield and net crop revenue

Dai *et al.* (2015) found that AWR decreased the water supply quantity, timeliness, and reliability in the PVCID and found that the change of water supply performance significantly affected farmers' choice of irrigation water sources. A farmer's crop yield and revenue can be impacted by the change of irrigation water amount, irrigation timeliness, and irrigation water sources. Farmers usually changed irrigation water source from canal water to well water or local small river water with the deterioration of canal water supply performance in the PVCID. The irrigation water amount using a different water source is sufficient according to our survey. This indicates that irrigation water amount and irrigation timeliness were not impacted by AWR in the PVCID. Therefore, the impact of AWR on crop yield and net crop revenue can be calculated by multiplying the contribution of AWR to water source change with the contribution of water source change to crop yield and net crop revenue decrease. The calculation formula is specified as follows:

$$Y_T = S_T Y_S \tag{4}$$

where Y_T denotes the contribution of AWR to crop yield or net crop revenue, S_T refers to the elasticity of AWR on canal water choice, which was estimated in another study (Dai *et al*., 2015), and Y_S denotes the elasticity of irrigation water source change on crop yield or net crop revenue, which is calculated in Equation (3).

4. Results and discussion

4.1. Impact of irrigation on crop yield

In the PVCID, wheat is the major crop in the summer, and rice and maize are mainly harvested in the autumn. Maize is not included in the analysis because it is cultivated on a small scale. The data from our survey reveal that all of the wheat and rice in the study area are irrigated, except for those of one household in the study area. Therefore, the authors only analyzed the impacts of irrigation frequency, irrigation water sources, and canal water performance on crop yield and net crop revenue, without considering the difference of crop yield and revenue between irrigated and unirrigated crops.

4.1.1. Description analyses. Table 2 provides a summary of crop yield irrigated by different water sources. In general, crop yields under different irrigation sources are different. The yield of wheat irrigated only by canal water is 5,723 kg ha^{-1}, which is 435 kg ha^{-1} (7%) and 1,152 kg ha^{-1} (20%) lower than those irrigated only by well water and local small river water, respectively. This result means that wheat yield increases by 7% if the water source changes from canal water to well water and increases by 20% if the water source changes from canal water to local small river water. This finding emerged because canal water is supplied according to a schedule and is not always on time, and because farmers can use well water and local small river water freely unless no water is present. This finding is consistent with those of Dhawan (1988) and Zhou *et al*. (2009), who found that water sources with high flexibility and reliability perform better than unreliable and inflexible water sources because farmers have better control over the water supply and the timing of water deliveries.

Nevertheless, Table 2 shows that the yield of rice irrigated only by canal water is 8,471 kg ha^{-1}, which is 929 kg ha^{-1} (11%) and 399 kg ha^{-1} (4.7%) higher than those irrigated only by well water and local small river water, respectively. One reason for this result is that rice can receive a better supply of canal water than wheat because paddy fields are almost always located in the upstream of the canal. Another reason is that canal water diverting from the Yellow River contains more nutrients than well water does. This result is consistent with Liao (2009), which shows that wheat and corn irrigated by well water result in lower yields than those irrigated by canal water.

Table 2. Average crop yield by type of irrigation water source.

	Irrigation water source					
	Canal water (1)[a]	Well water (2)	Local small river water (3)	(1) and (2)[b]	(1) and (3)[c]	Total
Wheat						
Average yield (kg/ha)	5,723	6,158	6,875	5,988	5,550	5,980
Standard deviation (S.D.)	155	190	278	200	465	96
Households (number)	72	38	16	42	5	174
Rice						
Average yield (kg/ha)	8,471	7,542	8,072	8,121	7,188	8,238
S.D.	157	517	559	227	313	124
Households (number)	53	9	4	28	2	96
Wheat and rice						
Average yield (kg/ha)	10,890	8,047	9,503	11,750	8,545	10,729
S.D.	540	656	1,224	476	1,498	332
Households (number)	60	24	12	61	8	147

Source: Household survey of authors.
[a]Irrigated with only canal water.
[b]Irrigated with both canal water and well water.
[c]Irrigated with both canal water and local small river water.

To analyze the impact of irrigation water source on integrated crop yield, the yields of wheat and rice together were also calculated under the irrigation of different water sources (Table 2). Moreover, the yield of wheat and rice together includes the cases that only have wheat data. Table 2 shows that the integrated crop yield irrigated only by canal water is 10,890 kg ha^{-1}, which is 2,844 kg ha^{-1} (26.1%) and 1,387 kg ha^{-1} (12.7%) higher than those irrigated only by well water and local small river water, respectively. As wheat yield increases and rice yield decreases when the water source changes from canal water to well water or local small river water, this result indicates that the increase quantity of wheat yield is lower than the decrease quantity of rice yield under the same water source change.

Considering that many croplands are irrigated with more than one water source, crop yield irrigated with several water sources was calculated. Table 2 shows that the yields of crops irrigated with canal water and well water are between the yields of crops irrigated with canal water only or well water only. However, the yields of crops irrigated with canal water and local small river water are lower than those irrigated with any single water source because the water quality of local small river water is poor (Guo *et al.*, 2009). Additionally, the water quantity of the local small river cannot satisfy the need of all croplands in the dry season. This result indicates that the combined irrigation of canal water and well water performs better on crop yield than the combination of canal water and local small river water.

4.1.2. Regression analyses. The authors estimated Equation (1) through linear regression using IBM SPSS Statistics. Table 3 presents the estimation results using wheat yield, rice yield, and integrated crop yield of wheat and rice. The integrated crop yield of wheat and rice also includes data on households that plant wheat and maize and households that plant wheat and rice. The coefficient for irrigation times

Table 3. Estimated parameters of three regression models of crop yield in the PVCID, China.

	Wheat		Rice		Wheat and rice	
	Coefficient (*t* statistics)[a]	Elasticity	Coefficient (*t* statistics)	Elasticity	Coefficient (*t* statistics)	Elasticity
Irrigation status						
Irrigation times using canal water	169.87 (1.05)	0.05	−94.79 (−0.94)	−0.04	343.85** (2.2)	0.13
Irrigation times using well water	480.5** (2.38)	0.05	−28.3 (−0.25)	−0.00	342.9* (1.66)	0.04
Irrigation times using local small river water	578.97*** (2.53)	0.02	−123.99 (−0.56)	−0.00	301.05 (1.26)	0.01
Timeliness of canal water	66.68 (0.4)	0.01	236.28 (1.09)	0.02	−42.12 (−0.09)	−0.00
Adequacy of canal water	94.97 (0.53)	0.02	−17.65 (−0.08)	−0.00	−417.43 (−1.02)	−0.04
Other input factors						
Seed use (USD/ha)	−0.79 (−0.46)	−0.02	9.57* (1.9)	0.12	11.12*** (2.87)	0.24
Fertilizer use (USD/ha)	0.04 (0.03)	0.00	1.48 (0.63)	0.08	5.1** (2.21)	0.34
Pesticide application (USD/ha)	0.54 (0.2)	0.01	−1.47 (−0.73)	−0.04	3.09 (1.04)	0.08
Agricultural machinery use (USD/ha)	1.71 (0.87)	0.07	−1.81 (−0.98)	−0.05	−2.47 (−0.94)	−0.08
Plot characteristics						
Slope	−193.81 (−0.58)	−0.02	103.89 (0.27)	0.01	−1097.37 (−1.46)	−0.06
Soil fertility	425.64* (1.81)	0.08	525.14* (1.95)	0.08	1025.97* (1.81)	0.11
Soil texture	1103.63** (1.97)	0.16	−837.63 (−1.04)	−0.09	5537.06*** (3.97)	0.42
Plot size (ha)	−282.35 (−1.89)	−0.01	−1316.36 (−0.74)	−0.04	2163.97 (0.57)	0.05
Distance from home (km)	−69.35 (−0.40)	−0.01	462** (2.07)	0.06	581.07 (1.41)	0.05
Precipitation	494.76* (1.77)	0.08	776.01** (2.39)	0.08	330.46 (0.5)	0.02
Natural disasters	1648.3*** (2.63)	0.25	−190.74 (−0.33)	−0.02	1409.85 (1.07)	0.11
Household characteristics						
Age of farm household head (years)	−12.54 (−0.86)	−0.11	−6.14 (−0.33)	−0.04	−3.67 (−0.1)	−0.02
Educational level of farm household head	290.81 (1.45)	0.09	−5.76 (−0.03)	−0.00	−205.04 (−0.44)	−0.03
Number of household adults at home	−51 (−0.5)	−0.02	−155.22 (−1.41)	−0.05	−316.02 (−1.25)	−0.07
Main source of income	162.78 (0.54)	0.01	351.85 (1.05)	0.02	305.09 (0.44)	0.01
Constant	1688.81 (1.03)		7720.53 (3.78)		−3794.22 (−1.04)	
Number of households	87		61		86	
R^2	0.40		0.44		0.58	
Adj. R^2	0.21		0.15		0.44	

[a]The *t* statistics are in parentheses.
***Significance at 1%, **significance at 5%, and *significance at 10%.

means that wheat yield and integrated crop yield, except for rice yield, increase with irrigation frequency. A possible reason for this is that the sample size of the rice plant is not large enough. Liao (2009) also found that irrigation water amount had a significant positive impact on the yield of wheat and maize.

Table 3 shows that additional time of irrigation using canal water, well water, and local small river water increases wheat yield by 5%, 5%, and 2%, respectively. This finding indicates that wheat yield does not significantly change if the water source changes from canal water to well water but decreases by 3% if the water source changes from canal water to local small river water. This result is different from the result in Table 2, which shows that wheat yield greatly increases if the water source changes from canal water to well water or local small river water. The reason for this may be that the contributions of other inputs decrease the impact of irrigation on crop yield.

Table 3 shows that integrated crop yield decreases by 9% and 12% if the water source changes from canal water to well water and local small river water, respectively. These decreases are lower than those shown in Table 2. A possible reason for this is that crop yield is partly attributed to other explanatory factors, such as soil fertility, soil texture, slope of plots, and other factors. Nevertheless, timeliness and adequacy of canal water have no significant association with crop yield.

Seed input has a significant positive impact on rice yield and has a very significant positive impact on integrated crop yield, but it has no significant impact on wheat yield. This finding indicates that seed input is more important for rice than for wheat. In Table 3, seed input shows an elasticity of 12% and 24% for rice yield and integrated crop yield, respectively. Meng *et al.* (2011) also found that crop variety significantly affects wheat yield and rice yield. More expensive seeds, which may have higher quality, have higher yields than others.

Fertilizer application contributes significantly to the yield of wheat and rice, which is consistent with the findings of Zhou *et al.* (2009) and Zhang *et al.* (2013). Fertilizer application shows an elasticity of 34% for the yield of wheat and rice, which is significantly higher than the fertilizer application elasticity of 9% for maize yield in Hebei Province in China (Zhou *et al.*, 2009). This finding indicates that the soil of the PVCID is not fertile enough and that wheat and rice need more fertilizer than maize does. Zhou *et al.* (2009) found that the use of agricultural machinery decreases rice yield, but our research shows that the input of agricultural machinery does not significantly affect crop yield. Table 3 shows that pesticide application also has no significant impact on crop yield.

Soil fertility has a slightly significant and positive impact on crop yield, which is consistent with Zhou *et al.* (2009) and Huang *et al.* (2006). Soil fertility elasticity means that wheat yield, rice yield, and integrated crop yield are 8%, 8%, and 11% higher, respectively, for a plot perceived by farmers as fertile against that perceived as average or infertile. Soil texture has a significant and positive association with wheat yield and integrated crop yield but not for rice yield. Soil texture elasticity shows that wheat yield and integrated crop yield of sandy cropland are 16% and 42% lower, respectively, than other croplands, a finding consistent with the result of Liao (2009), because sandy soil has higher water percolation than other soils and cannot supply enough water for crops.

The coefficient for precipitation means that rice yield on croplands that receive more precipitation is significantly higher than others. This result is consistent with the result showing that croplands with higher irrigation frequency have higher yields than others. Croplands without natural disasters have very significantly higher wheat yield than others, which is consistent with Zhou *et al.* (2009). The elasticity of natural disasters means that wheat yield without natural disasters is 25% higher than that suffering from natural disasters.

Zhou *et al.* (2009) found that a plot that is mostly level has a higher yield than a sloping plot. However, our research results show that crop yield does not significantly change regardless of whether the plot is bottomland. Plot size also has no significant impact on crop yield in our research, which is different from the result of Zhou *et al.* (2009) and Liao (2005), who found that crop yield increases with plot size. Similar to the results of Zhou *et al.* (2009), the positive sign of distance from home demonstrates that yield increases with the distance of the plot from home, reflecting that far plots have better farming circumstances.

Unlike the results of Zhou *et al.* (2009) and Liao (2009), our regression results show that the educational level of the household head has no significant correlation with crop yield. A possible reason for this is that the sampled household heads have nearly the same educational level. Other factors of household characteristics, such as age of household head, number of household adults at home, and main source of income, also have no significant impact on crop yield.

4.2. Impact of irrigation on net crop revenue

4.2.1. Description analyses. Net revenues of crops irrigated by different water sources are summarized in Table 4. Table 4 shows that the net revenue of wheat irrigated only by canal water is 7% (55.23 USD/ha) lower than that irrigated only by well water. This decrease is in accordance with the wheat yield decrease in Table 2, indicating that the change in net wheat revenue is mainly contributed to by wheat yield change when the water source changes from canal water to well water. The net revenue

Table 4. Average net crop revenue by type of irrigation reported in a household survey in the PVCID, China, in 2012.

	Irrigation water source					
	Canal water (1)[a]	Well water (2)	Local small river water (3)	(1) and (2)[b]	(1) and (3)[c]	Total
Wheat						
Average net revenue (USD/ha)	830.71	885.95	1164.45	878.81	721.52	886.57
S.D.	60.94	66.72	93.68	75.57	120.33	35.44
Households (number)	68	36	15	39	5	169
Rice						
Average net revenue (USD/ha)	2641.87	1840.28	2297.02	2508.09	NA[c]	2521
S.D.	91.63	339.26	278.97	112.48	NA	72
Households (number)	51	8	4	28	NA	93
Wheat and rice						
Average net revenue (USD/ha)	2393.57	1137.57	2010.23	2679.84	1936.67	2249.10
S.D.	190.33	214.66	385.97	167.17	611.39	109.68
Households (number)	58	24	11	60	8	168

Source: Household survey of authors.
[a]Irrigated with only canal water.
[b]Irrigated with both canal water and well water.
[c]Irrigated with both canal water and local small river water.

of wheat irrigated only by canal water is 40% lower than that irrigated only by local small river water. This decrease is higher than the decrease of wheat yield shown in Table 2, indicating that other factors besides wheat yield contribute to the change in net wheat revenue when the water source changes from canal water to local small river water.

Table 4 shows that the net revenue of rice irrigated only by canal water is 30% (801.59 USD/ha) and 13% (344.85 USD/ha) higher than that irrigated only by well water and by local small river water, respectively. These increases are higher than those of rice yield shown in Table 2. Dai *et al*. (2015) found that the average extracting cost of well water was 66.75 USD/ha/time, which was 2.79 and 1.76 times the irrigation cost of canal water and local small river water, respectively, in the PVCID. This finding indicates that the decrease in rice revenue is attributed to the change of rice yield and irrigation cost when the water source changes from canal water to well water.

Table 4 shows that the net revenue of integrated crop (rice and wheat) decreases by 52% (1,256 USD/ha) when the water source changes from canal water to well water and decreases by 16% (383.34 USD/ha) when the water source changes from canal water to local small river water. This finding indicates that the increase of wheat revenue cannot compensate for the decrease in rice revenue when the water source changes from canal water to other water sources. The reason is that the yield and net revenue of rice are significantly higher than those of wheat.

The net revenue of wheat or rice irrigated by both canal water and well water is between that irrigated by only canal water and only well water. The net revenue of the integrated crop irrigated by both canal water and well water is higher than that irrigated only by canal water or well water. This result indicates that the combined irrigation of canal water and well water performs better on net crop revenue than the combined irrigation of canal water and local small river water.

4.2.2. Regression analyses. Equation (2) is estimated through linear regression using IBM SPSS Statistics. The regression results of the net crop revenue estimation model are shown in Table 5, which shows that net crop revenue increases with irrigation frequency, and different irrigation water sources show different elasticities on net crop revenue. Net wheat revenue increases by 5% and 3% if the water source changes from canal water to well water and local small river water, respectively. Nevertheless, the net integrated crop revenue decreases by 16% and 19% if the water source changes from canal water to well water and local small river water, respectively. The reason for this result is the same as that analyzed before, showing that the deterioration of canal water performance has a smaller impact on wheat and rice together than on wheat because rice is mainly planted in the upstream of the irrigation district. Similar to the result of crop yield, the water supply performance of canal water has no significant impact on net crop revenue.

Seed input has a significant negative impact on net wheat revenue but a significant positive impact on net integrated crop revenue, which is consistent with the result of yield regression. Seed input shows an elasticity of minus 25% and 32% on net wheat revenue and net integrated crop revenue, respectively. Those revenue elasticities are higher than the yield elasticity estimated in Table 3, indicating that seed input has a larger impact on net crop revenue than on crop yield.

Fertilizer input has a slightly positive, significant impact on net integrated crop revenue and shows an elasticity of 44%, which is higher than the yield elasticity estimated in Table 3. This result agrees with Zhou *et al*. (2009). Although fertilizer input increases wheat yield, it shows an elasticity of minus 50% on net wheat revenue. This result shows that the increase of wheat yield cannot compensate for the high cost of fertilizer.

Table 5. Estimated parameters of three regression models of net crop revenue in the PVCID, China.

	Wheat		Rice		Wheat and rice	
	Coefficient (*t* statistics)[a]	Elasticity	Coefficient (*t* statistics)	Elasticity	Coefficient (*t* statistics)	Elasticity
Irrigation status						
Irrigation times using canal water	6.42 (0.12)	0.01	−55.41 (−1.06)	−0.08	134.59** (2.25)	0.21
Irrigation times using well water	95.42 (1.42)	0.06	−28.37 (−0.49)	−0.01	105.05 (1.33)	0.05
Irrigation times using local small river water	162.48** (2.13)	0.04	6.73 (0.06)	0.00	146.1 (1.6)	0.02
Timeliness of canal water	25.79 (0.46)	0.02	159.13 (1.42)	0.04	79.77 (0.47)	0.02
Adequacy of canal water	34.32 (0.58)	0.05	−119.5 (−1)	−0.05	−237.78 (−1.52)	−0.10
Other input factors						
Seed use (USD/ha)	−1.29** (−2.2)	−0.25	2.21 (0.84)	0.09	3.57** (2.4)	0.32
Fertilizer use (USD/ha)	1.74	−0.50	0.27 (0.22)	0.05	1.54* (1.74)	0.44
Pesticide application (USD/ha)	−0.21 (−0.22)	−0.04	−1.09 (−1.05)	−0.09	0.7 (0.61)	0.08
Agricultural machinery use (USD/ha)	−0.08 (−0.11)	−0.02	−2.26** (−2.36)	−0.19	1.54* (1.74)	−0.26
Plot characteristics						
Slope	−139.91 (−1.24)	−0.12	39.61 (0.2)	0.01	−431.86 (−1.5)	−0.11
Soil fertility	158.11** (1.95)	0.22	268.33* (1.92)	0.13	416.39* (1.92)	0.19
Soil texture	481.03*** (2.58)	0.51	−358.51 (−0.86)	−0.13	2059.19*** (3.85)	0.66
Plot size (ha)	124.12 (0.25)	0.04	−633.24 (−0.69)	−0.06	948.02 (0.65)	0.08
Distance from home (km)	−1.28 (−0.02)	0.00	248.17** (2.14)	0.10	242.59 (1.53)	0.09
Precipitation	125.13 (1.35)	0.12	401.66** (2.39)	0.13	46.09 (0.18)	0.01
Natural disasters	575*** (2.74)	0.62	34.59 (0.11)	0.01	641.24 (1.26)	0.21
Household characteristics						
Age of farm household head (years)	−3.06 (−0.63)	−0.19	−2.32 (−0.24)	−0.05	1.95 (0.14)	0.04
Educational level of farm household head	107.18 (1.59)	0.22	29.52 (0.27)	0.02	−46.84 (−0.26)	−0.03
Number of household adults at home	−16.6 (−0.48)	−0.05	−63.62 (−1.11)	−0.07	−123.5 (−1.28)	−0.11
Main source of income	66.87 (0.66)	0.04	236.33 (1.36)	0.05	220.44 (0.84)	0.04
Constant	179.9 (0.33)		2949.12 (2.78)		−2475.13 (−1.78)	
Number of households	85		61		86	
R^2	0.43		0.47		0.50	
Adj. R^2	0.26		0.20		0.34	

[a]The *t* statistics are in parentheses.
***Significance at 1%, **significance at 5%, and *significance at 10%.

Although the use of agricultural machinery shows no significant impact on crop yield, it shows a significant adverse impact on net rice revenue and a slightly significant, adverse impact on net integrated crop revenue. Agricultural machinery input only increases wheat yield and shows an elasticity of minus

19% and minus 26% on net rice revenue and net integrated crop revenue, respectively. These elasticities indicate that agricultural machinery dramatically decreases net crop revenue and has a larger impact on net crop revenue than on crop yield. Unlike Zhou *et al.* (2009), we found no significant impact of pesticide input on net crop revenue.

The respective revenues of wheat, rice, and integrated crop on a fertile plot are 22%, 13%, and 19% higher than those on other plots. Soil fertility has a larger impact on net crop revenue than on crop yield because fertile croplands require less fertilizer. This result agrees with Zhou *et al.* (2009), who found that soil fertility shows an elasticity of 17% on net crop revenue, and Zhang *et al.* (2013), who found that soil fertility shows an elasticity of 20% on net crop revenue per m^3 of water.

Soil texture has a very significant and positive association with the net revenue of wheat and integrated crop, which is the same as crop yield, indicating that sandy croplands have lower crop yield and net crop revenue. Soil texture shows an elasticity of 51% and 66% for the net revenue of wheat and integrated crop, respectively. Soil texture has the largest elasticity among all the factors, indicating that it is a key factor affecting net crop revenue. It also has no significant impact on net rice revenue because rice is cultivated in the paddy field, which always has water.

Table 5 shows that net rice revenue significantly increases with cropland distance from home, which is similar to the estimate in Table 3. Similar to the result of the crop yield regression, precipitation also shows a significant and positive impact on net rice revenue, which means that croplands with more precipitation increase net crop revenue by 13%.

Natural disasters have a very significant positive impact on net wheat revenue. The elasticity coefficient means that net wheat revenue without natural disasters is 62% higher than that suffering from natural disasters, which is significantly higher than the yield increase estimated in Table 3. This result is consistent with Zhou *et al.* (2009) who found that natural shock decreases crop yield and net crop revenue by 57% and 59%, respectively.

Although some researchers found that slope (Zhou *et al.*, 2009), land area (Meng *et al.*, 2011), and plot area (Zhou *et al.*, 2009) have significant impacts on net crop revenue, our research shows no significant correlation between net crop revenue and these factors. Some researchers found that the education of adults (Zhou *et al.*, 2009), education of household heads (Meng *et al.*, 2011), and age of household heads (Meng *et al.*, 2011) significantly affect net crop revenue, but our research found no significant impact of household characteristics on net crop revenue.

4.3. Impact of AWR on crop yield

The regression results in Table 3 show that integrated crop yield decreases by 9% and 12% if the water source changes from canal water to well water and local small river water, respectively. Therefore, the average reduction rate of integrated crop yield is 11% if the water source changes from canal water to other water sources. Table 2 shows that the average total crop yield of wheat and rice is 10,729 kg/ha. Dai *et al.* (2015) found that the ratio of irrigated croplands using canal water is 22% lower if the water supply quantity is perceived by farmers as insufficient against their perception of average or sufficient when canal water and well water can be used. The ratio is 23% lower when canal water, well water, and local small river water can be used. Therefore, in Equation (4), the contribution of AWR to the decrease of integrated crop yield equals $2\% = 9\% \times 22\%$ if the water source changes from canal water to well water. Furthermore, the decrease of integrated crop yield caused by AWR equals 214.58 kg/ha $=$ $2\% \times 10{,}729$ kg/ha under the same change of water source. If the water source changes from canal water to well water and local small river water, AWR decreases integrated crop yield by 2.4%, which was calculated by multiplying 11% by 23%. Decrease of integrated crop yield caused by AWR equals 257.5 kg/ha = 2.4% × 10,729 kg/ha under the same condition.

4.4. Impact of AWR on net crop revenue

The adverse impact of AWR on net crop revenue can also be calculated from Equation (4). Table 5 shows that the net integrated crop revenue decreases by 16% and 19% if the water source changes from canal water to well water and local small river water, respectively. Therefore, the average reduction rate of net integrated crop revenue is 17.5% if the water source changes from canal water to other water sources. Our household survey shows that the average total net crop revenue of wheat and rice is 2249.1 USD/ha. Therefore, AWR decreases net integrated crop revenue by 3.5% (16% × 22%) or 78.72 USD/ha (3.5% × 2249.1 USD/ha) if the water source changes from canal water to well water, and decreases the net integrated crop revenue by 4% (19% × 22%) or 89.96 USD/ha (4% × 2249.1 USD/ha) if the water source changes from canal water to well water and local small river water.

Given that labor cost is not subtracted from the gross crop revenue, the impact of water source change on irrigation labor cost is not included in the analysis above. Dai *et al*. (2015) found that crops irrigated by canal water take an average of 24 h/ha/time, which is 31% lower than the time for those irrigated by well water and 32% higher than the time for those irrigated by local small river water in the PVCID. This finding indicates that the change of water source from canal water to well water further decreases the net crop revenue if labor cost is considered. Our household research shows that the average labor cost in the PVCID was 16 USD/person/day in 2012. If one worker works eight hours per day, then the transition of canal water to well water increases labor cost by 15 USD/ha/time. Table 1 shows that average irrigation times of wheat and rice is 4.53 times. Therefore, increased labor cost due to AWR was estimated to be 67.95 USD/ha (15 USD/ha/time × 4.53 times). As most of the changes in the water source are from canal water to well water, the impact of agricultural reallocation on net crop revenue may be even larger if irrigation labor cost is considered.

4.5. Compensation for the loss of farmers from AWR

The compensation paid to affected farmers can be estimated by the loss of crop yield and net crop revenue from AWR. As analyzed above, the impact of AWR on integrated crop yield is 214.58 kg/ha when the water source changes from canal water to well water and 257.5 kg/ha when the water source changes from canal water to substitute water of well water and local small river water. With the average integrated crop price of 0.38 USD/kg in 2012, which was obtained through household research in 2013, the loss of integrated crop yield from AWR is calculated to be 81.54 USD/ha when the water source changes from canal water to well water or 97.85 USD/ha when the water source changes from canal water to substitute water.

The impact of AWR on net integrated crop revenue is 78.72 USD/ha or 89.96 USD/ha when the water source changes from canal water to well water or substitute water respectively. Therefore, the compensation for farmers affected by AWR is between 78.72 USD/ha and 81.54 USD/ha when the water source changes from canal water to well water, or between 89.96 USD/ha and 97.85 USD/ha when the water source changes from canal water to well water or local small river water. This compensation does not include the increase of irrigation labor cost, the damage to groundwater resources because of increasing well water use (Dai *et al*., 2015), and the possible pollution of the soil because of the increasing use of local small river water with poor water quality.

In addition to economic compensation, improving other factors affecting crop yield and net crop revenue can compensate for the losses of farmers. Tables 3 and 5 show that seed input, fertilizer input, soil texture, and natural disasters are the main factors affecting crop yield and net crop revenue. Household research found an excessive number of seed and fertilizer varieties, many of which are of poor quality. Farmers do not know the type and amount of nutrient elements that are scarce on their cropland and cannot choose a suitable fertilizer. Hence, eliminating seed and fertilizer varieties with poor quality, guiding farmers in choosing suitable seeds and fertilizer varieties, and compensating for the cost of seeds and fertilizer are necessary. In reducing the adverse impact of soil texture on crop yield and revenue, popularizing and compensating for irrigation equipment that can be used on sandy soil, such as micro spray irrigation, are necessary. In remitting the loss of natural disasters, the introduction of agricultural insurance is also necessary.

The adverse impact of AWR on groundwater can be compensated through irrigation using canal water and well water. Household research found that farmers upstream of canals waste canal water because the price of water is charged by the irrigated area of croplands. Many farmers choose well water or local small river water before the canal water is supplied because they are not informed in a timely manner of the adjustment of canal water supply. In increasing the canal water irrigation of the downstream, charging the water fee based on irrigation time or the amount of water and improving the irrigation information exchange between the irrigation administration and the farmers are necessary.

Some farmers change their irrigation water source from canal water to local small river water with poor water quality, which may have adverse impact on soil and crop quality in the PVCID. As this study is delimited to the pollution of local small river water in the PVCID, estimating the impact of local small river water irrigation on soil and crop quality is difficult. Limiting the irrigation using local small river water and improving the study of the pollution of local small river water in the PVCID are necessary.

5. Conclusions

First, irrigation frequency shows a significant positive impact on crop yield and net crop revenue, and different irrigation water sources show different elasticities on crop yield and net revenue. Compared to well water and local small river water irrigation, canal water irrigation has a lower elasticity on wheat yield and net wheat revenue but higher elasticity on integrated crop yield and net integrated crop revenue. The change of irrigation water source from canal water to well water and local small river water decreases integrated crop yield by 9% and 12% and net integrated crop revenue by 16% and 19%, respectively. As irrigation water source increasingly changes from canal water to well water in North China and other areas of the world, the impact of this change on crop yield and revenue should be paid attention to.

Second, the performance of canal water supply has no significant impact on crop yield and net crop revenue. The impact of AWR on crop yield and net crop revenue is due to the change of irrigation water source. AWR decreases integrated crop yield by 2% (214.58 kg/ha) and 2.4% (257.5 kg/ha), and decreases net integrated crop revenue by 3.5% (78.72 USD/ha) and 4% (89.96 USD/ha) if the irrigation water source changes from canal water to well water and substitute water of well water and local small river water, respectively. This result indicates that existing studies have underestimated the impact of AWR because these studies did not calculate the impact of irrigation water source change on crop yield and revenue. The calculation method developed in this research is useful for evaluating the complete impact of AWR on crop yield and revenue.

Third, the estimated compensation for farmers affected by AWR is between 78.72 USD/ha and 81.54 USD/ha when the water source changes from canal water to well water or between 89.96 USD/ha and 97.85 USD/ha when the water source changes from canal water to well water and local small river water. Inputs of seeds, fertilizer, soil texture, and fertility have significant impact on crop yield and revenue. To compensate for the adverse impact of AWR, some countermeasures were put forward. The calculated compensation amount and the countermeasures put forward are helpful for the government to propose compensation policy on the impact of AWR.

Household research found that some farmers changed rice to maize to adapt to the deterioration of canal way supply performance. Further studying the impact of planting structure change because of AWR on crop yield, crop revenue, and farmers' revenue is meaningful. Studying the impact of AWR on third parties, such as suppliers of seeds, fertilizers, pesticides, and other inputs, is also necessary.

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