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Estimating Production Inefficiency of Alternative Cost-Sharing Arrangements: a case study in groundwater pumping decisions

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Abstract

In Mexico, farmers only pay the cost of electricity used to pump groundwater from wells for groundwater consumption and also receive electricity subsidy from government. It causes the fact that farmers consume groundwater under the situation that private marginal cost is lower than social marginal cost. Furthermore, in Mexico, different wells function under different institutional arrangements. Some wells are privately owned while others are shared by multiple farmers. In some shared wells, farmers pay for their own electricity consumption but in other shared wells farmers distribute total electricity cost based on a pre-specified rule. Both the jointly ownership and pre-specified payment rule may cause further distortion of groundwater pumping cost. By estimating the frontier demand function and technical efficiency of groundwater, we calculate the own-price elasticity of groundwater and test the effect of joint ownership and pre-specified electricity payment rule on the groundwater use efficiency. It is found that the groundwater has a negative and large (-0.5) own-price elasticity and that the number of farmers owning one well and the pre-specified payment rules do not affect the efficiency level significantly. The elimination of electricity subsidy may be the most effective policy to alleviate groundwater depletion in Mexico.

Key words: groundwater, elasticity, specific input technical efficiency, ownership externality, payment externality

Introduction

Groundwater irrigation efficiency is an important issue, especially when depletion of groundwater becomes stronger. Substantial research has focused on the estimation of demand of irrigating groundwater (Ogg & Gollehon (1989), Kanazawa (1992), Bontemps & Couture (2002), Schoengold et al. (2006), Wheeler et al. (2008), Huang et al. (2010), Sadeghi et al. (2010), Hendricks & Peterson (2012)), but none of these studies include inefficiency use of groundwater relative to each other and they assume that all farmers use groundwater efficiently. The assumption could cause the overestimation of irrigation demand since the most efficient use of groundwater may cause lower demand. The demand function which allows for inefficiency not only approaches true demand closer, but also provides ways to find out factors causing inefficiency and directions to improve efficiency.

In Mexico, for groundwater consumption, farmers only pay the cost of electricity used to pump groundwater from wells. The government provides electricity subsidies to farmers, further decreasing their pumping cost. As a public good, groundwater is consumed under the situation that private marginal cost of farmers is lower than the social marginal cost even if farmers pay electricity without any subsidy. In other words, groundwater is consumed with externality already and the electricity subsidy from government further aggravates the externality through decreasing private pumping costs. So, eliminating electricity subsidy, which can decrease pumping cost externality, may be an effective choice to alleviate groundwater depletion in Mexico.

Different wells in Mexico function under different institutional arrangements. Some wells are individually owned while others are shared by multiple farmers. For those shared wells, farmers have different ways to distribute the cost of electricity used in pumping. In some shared wells each farmer pays for his own actual electricity consumption. In other shared wells, farmers distribute the total electricity cost based on a pre-specified rule. There are two popular pre-specified rules to distribute the electricity cost: 1) when farmers sharing the well have similar size of land and similar demand on groundwater, they divide the electricity bill evenly regardless of how much groundwater each farmer actually pump and how much electricity they actually consume; 2) When the sizes of land of farmers differ greatly, they divide the electricity bill based on their land share in the total land irrigated by the well.

As public goods, groundwater may be exploited inefficiently because of three externalities: pumping cost externality, stock externality and risk externality. (Provencher & Burt, 1993) The drawdown of groundwater from a well pumping is decided by the distance between the location of groundwater and the pumping well, except other factors, (Theis, 1935) so the externalities can be stronger when the distance between pumping wells and affected wells is shorter. When one well is owned by more than one farmer, the distance between affected well and pumping well is zero, and effect of externalities on farmers in one well are stronger compared to farmers in one aquifer but not in one well. Even if externalities outsides the well are ignored, there may still exist externalities in the group of farmers who owning one well jointly because their more intensive mutual effect to each other than to farmers outsides the well. The stronger externalities cause stronger motivation of farmers to pump groundwater. We call the externality arising from the joint ownership of wells as ownership externality, which measures the higher externalities existing in shared wells than individually owned wells and is limited in the group of farmers sharing the well.

In some shared wells, farmers distribute the total electricity cost based on a pre-specified rule instead of paying their actual electricity consumption. The pre-specified payment rule may introduce further distortion in the unit cost of pumping and cause more externality. Given the share of the electricity bill assigned to a given farmer, the marginal electricity cost of the farmer is lower than the group (constituted by all farmers sharing electricity bill based on the pre-specified rule) marginal electricity cost because all farmers need to pay the electricity from one farmer's pumping. Also, for a given farmer, the price paid per unit of water decreases as the farmer increases his pumping rate more than other farmers in the same well and it creates incentives for a "race for extraction". We call the externality arising from the pre-specified payment rule of electricity as payment externality. The same as ownership externality, payment externality is also limited in a small group.

Many studies already confirmed that externalities cause inefficient exploitation and excessive consumption of groundwater. The objectives of this study are to test whether the ownership externality and payment externality cause any inefficiency of groundwater use. If the relationship between ownership externality and inefficiency is confirmed, integrating farmers sharing a well into one cost-minimizing unit to eliminate ownership externality can be a potential choice to alleviate groundwater depletion except electricity subsidy elimination. If the relationship between ownership externality and inefficiency is confirmed, recording the exact electricity use of every farmer to eliminate payment externality can be another potential way to increase the efficiency and alleviate over-extraction of groundwater in Mexico. So in this paper, we propose the following hypothesis to test relationships between different externalities and efficiency.

Hypothesis 1: Eliminating electricity subsidy from government to increase all farmers' private pumping cost can decrease groundwater consumption of all farmers and alleviate groundwater depletion.

To test hypothesis 1, we estimate frontier demand function and calculate the own price elasticity of groundwater. If the own price elasticity is negative, we can conclude that eliminating electricity subsidy can decrease water consumption alleviate groundwater depletion.

Hypothesis 2: Farmers jointly owning one well may be affected by the ownership externality in the group, and consume more groundwater and be less efficient than farmers owning one well individually.

Hypothesis 3: Farmers with pre-specified electricity payment rule may be affected by the payment externality and consume more groundwater and be less efficient than farmers paying for their own consumption of electricity exactly.

To test hypothesis 2 and 3, we measure the efficiency level of farmers with different ownerships and electricity payments, and trace out the sources causing inefficiency to check whether ownership externality and payment externality have negative significant effect on efficiency.

Our interest in this study is to measure farmers' efficiency of groundwater use through analyzing how much groundwater can be saved if farmers using groundwater efficiently. Usually, inputs consumptions, as the production condition, are stable in certain period. In this study we are only interested in the efficiency of groundwater use and policies improving groundwater efficiency. Measures and improvements of other inputs efficiency are not included, and they are still stable. So the measure of the efficiency of groundwater should be done under the assumptions that the consumption of all other inputs, such as fertilizer, capital and other inputs, keep unchanged. Most efficiency estimation methods, including technical efficiency and allocative efficiency, require the radial or simultaneous changes of all inputs and are not appropriate for this study. In 1989, Kumbhakar (Kumbhakar, 1989) proposed a framework to measures the specific input technical efficiency through to measure the amount of specific input can be saved if the same amounts of all other inputs are used. The framework exactly matches our study and is chosen in this paper.

In the model, Symmetric Generalized McFadden function was used as cost function and advantages of the function is another reason we choose the model. To represent the true relationship between cost and explanatory variables as close as possible, cost function should be flexible enough. However, most flexible cost functions cannot satisfy the theoretical condition that cost function should be concave in factor prices. SGM is a flexible function form and also allows researchers to test the concavity conditions and, if the conditions are not satisfied, they can be imposed independently without losing any flexibility. (Diewert&Wales, 1987) Its flexibility and conformability to economic theory make it an appropriate choice for this study.

Theoretical Model

Kumbahkar's model was created for panel data to measure the efficiency of single firm based on their performance in multiple years. Sauer (Sauer 2007) modified it to be used for cross-sectional data through dividing firms to different groups to measure the specific input efficiency of each group. In this paper, we use cross-sectional data to measure the efficiency level of different farmers groups which are decided by whether they share wells with other farmers and whether they share electricity bill with other farmers. In Sauer's paper, all factors affecting efficiency are dummy variables. We modified the model to be suitable for non-dummy variables.

Kumbhakar chose SGM cost function form C*(.) as following

$$C^*(.)=g(p)y + \sum_i b_i p_i + \sum_i b_{ii} p_i y + \sum_i \sum_j d_{ij} p_i q_j y + \sum_j a_j (\sum_i \alpha_{ij} p_i) q_j + b_{yy} (\sum_i \beta_i p_i) y^2$$

$$+ \sum_k \sum_j \delta_{kj} (\sum_i \gamma_{ijk} p_i) q_k q_j y,$$

$$i=1,2,\ldots n, \quad k, j=1,2,...m \qquad (1)$$

Where the g(.) function is defined as

$$g(p) = p'Sp/2\theta'p \qquad (2)$$

In the function, variable p_i is the price of variable inputs i. y is the output. q_k or q_j is the quantity of fixed inputs k or j. S is an n x n symmetric negative semi-definite matrix such that $S'p^* = 0$. $\theta = (\theta_1,\ldots,\theta_n)'$ is a vector of nonnegative constants not all 0.

By applying Shephard's lemma and differentiating (1) with respect to input price, conditional demand function of input i, x_i^* is obtained. Dividing x_i^* by y, the conditional demand function of input i for every unit of output is obtained as following

$$\frac{dC(.)/dp_i}{y} = \frac{x_i *}{y}$$

$$= \frac{\sum_j s_{ij} p_j}{\sum_r \theta_r p_r} + \frac{\theta_i}{2} [\frac{\sum_i \sum_j s_{ij} p_i p_j}{(\sum_r \theta_r p_r)2} + \frac{b_i}{y} + b_{ii} + \sum_k d_{ik} q_k + \sum_k \frac{\alpha_{ik} q_k}{y} + \beta_i y$$

$$+ \sum_l \sum_k \gamma_{ilk} q_k q_l$$

j,r = 1,2,…,n,   k,l = 1,2,…,m   (3)

A concavity restriction on S is imposed by reparameterizing it as S = - AA', where A is a lower triangular matrix of order n and since p* is chosen to be a vector of ones, $\sum_i s_{ij}$ = 0 for all i. For estimation purpose, b_{yy}, a_j, δ_{kj} are normalized to be unity, θ_i is replaced by the mean values of x_i/y over the whole sample.

The own-price elasticity of groundwater is estimated by

$$\boldsymbol{\epsilon_{ii}} = \frac{\frac{\partial x_i/y}{x_i/y}}{\frac{\partial p_i}{p_i}} = \frac{\partial x_i/y}{\partial p_i} * \frac{p_i}{x_i/y} = \quad \textbf{(4)}$$

To estimate the specific technical efficiency of input i, we add some factors which may influence the efficiency of input i to (3) and estimate them with observed demand of input i,

$x_i/y = x_i^*/y + \delta_i Z_i + v_i$ (5)

Z_i is a vector of factors which may influence the efficiency of input i and δ_i is a vector of parameters with the same dimension as Z_i. Certain δ_{ij} matches Z_{ij} and measures the influence of Z_{ij} on the demand of x_i. The greater the value of δ_{ij} is, the more input i is used. So inefficiency τ_{ij} of input i caused by certain factor Z_{ij} can be calculated through

$\tau_{ij} = \delta_{ij} - \min(\delta_{ij})$ (6)

τ_{ij} can be considered as the quantity of input i that could be saved if the efficiency level of input i is increased to the efficient frontier without changing the usage of other inputs.

The input-specific technical efficiency TE_i can be calculated through

$$TE_{ij} = 1- \tau_{ij}/x_i \qquad (7)$$

The welfare change W_{ij} of farmers from increasing efficiency of input i through changing factor j can be calculated by

$$W_{ij} = p_i \, \tau_{ij} \qquad (8)$$

W_{ij} is the cost of farmers can be saved through changing factor j to increase efficiency level of input i for the production of per unit of output.

Data

Data we used are collected by the Inter-American Development Bank Project ME-T1029. The data collection process occurred from late-2007 until mid-2008. Cross sectional data was obtained for one farmer per well in a sample of 256 wells. In wells shared by multiple famrers, one farmer was chosen randomly. Of 256 samples, a total of 198 observations contained complete information so this is the size of our sample. These irrigation wells are a sample of the entire country, and represent the full distribution of irrigation wells in Mexico. The data collection process was very time intensive for two reasons. First, the needs of the project require surveys of irrigation wells throughout the country and the survey requires detailed information from an irrigation district and from a sample of the producers in the district. Therefore, it was not atypical for that the data collection portion of a single survey took several hours. The second reason was the difficulty of finding the irrigation wells for the survey. A sample was initially drawn based on a national survey of irrigation wells, and the enumerators tried to find those wells from the sample. However, in many cases the irrigation wells that were chosen did not exist. In those cases the enumerators tried to replace the sample well with another well from the same area.

The statistic description of farmers' groundwater consumption is shown in Table 1. In the 198 wells, 77 wells are owned by only one farmer and 121 wells are shared by multiple farmers. In the 121 shared wells, in 46 wells the electricity use of every farmer can be recorded and all farmers pay their actual electricity consumption. In 75 wells, the electricity used by every farmer cannot be recorded and all farmers pay one electricity bill based on a pre-specified rule. For groundwater consumption, farmers jointly owning one well and paying electricity jointly have the highest mean of groundwater consumption. The lowest mean happens to farmers jointly owning one well but paying their own groundwater consumption.

Table 1: Statistic descriptions of farmers' groundwater consumption under different institutional arrangements

Farmer Type	Quantity	Mean	Standard Deviation
One farmer in one well	77	15686.8	26535.5
Multiple farmers paying electricity individually in one well	46	9316.6	25352.7
Multiple farmers paying electricity jointly in one well	75	17465.9	32945.6
Total	198	14880.8	29056.4

Detailed data on quantity and prices of inputs and outputs have been obtained from those farmers along with data on irrigation application and cost of electricity used in pumping groundwater. Data includes quantities and prices of four variable inputs (machinery, fertilizer, a composite of others and irrigation water), and one fixed input (land). A vector of outputs (that includes field crops, fruits, and vegetables) were aggregated into one single output applying Jorgenson's procedure for "exact" aggregation. Other exogenous variables include dynamic depth of water table, soil characteristics, number of farmers in each well, mechanism for sharing of electricity cost, and climate type.

Results

To estimate the effect of electricity payment rule of groundwater and the number of farmers sharing one well, we choose the following variables to be added to (5) to get the function we use to estimate groundwater demand and its efficiency.

$$WiQ_i/y = WiQ_i^*/y + a2*CS + a3*N + a4*SI + a5*CL + a6*DEPTH + aa1*N*CS + vi \qquad (9)$$

CS is the cost share rule dummy variable. It denotes the payment rule used by farmers and can be used to measure the payment externality. CS=0 means that farmers pay electricity bill based on pre-specified rule. CS=1 means that farmers pay electricity based on their actual electricity consumption. N is the number of farmers owning one well and can be used to measure the ownership externality. Except the payment rule and farmer number of one well, climate type, soil type and the depth of well may also influence the water exploitation. To control their effect, these variables are also included in the model. In (7), SI is the soil type. CL is the climate type. DEPTH is the depth of well.

Table 2: Estimations of coefficients

Parameters	coefficients	t-statistic	Parameters	coefficients	t-statistic
s_{fk}	-2655.00***	-62.90	b_{oo}	3.14***	3.35
s_{fo}	-7179.70***	-34.38	b_o	3.45***	3.28
s_{fw}	39.86	0.50	d_o	0.02	0.56
s_{ko}	-7.21	-1.34	α_o	0.93***	10.30
s_{kw}	2695.50***	64.38	β_o	0.00	-0.23
s_{ow}	7222.70***	34.99	γ_o	0.00	-1.30
b_{ff}	1012.70	1.36	b_{ww}	-10927.00**	-2.13
b_f	-6921.60***	-5.26	b_w	50392.00***	14.32
d_f	-184.99***	-4.71	d_w	131.27	1.28
α_f	1964.80***	19.35	α_w	515.75**	1.98
β_f	2.73	0.76	β_w	1.43	0.15
γ_f	-0.31	-1.15	γ_w	2.48***	3.62
b_{kk}	0.33	0.39	CS	17.00	0.01
b_k	2.59***	2.91	N	95.25	0.86
d_k	0.08***	2.77	SI	1019.30	0.92
α_k	0.21***	2.91	CL	-1112.70**	-1.97
β_k	0.00	-0.35	DEPTH	3.69	0.30
γ_k	0.00	1.44	N*CS	-94.08	-0.64

Using SUR, (5) is estimated together with demands of fertilizer, capital and other inputs. Totally 36 parameter are estimated. In matrix [S_{ij}], only 6 parameters are estimated and all other s_{ij} can be calculated through symmetric property of [S_{ij}] and the relationship $\sum_i s_{ij} = 0$ from the 6 estimated parameters.

Based on the parameter value showed in Table 2 and function (4), the own-price elasticity of groundwater in Mexico can be calculated to be -0.5. The negative sign confirms our Hypothesis 1 and indicates that the elimination of electricity subsidy from government, which increases the private pumping cost of farmers, decreases the groundwater consumption. Eliminating electricity subsidy is an effective way to alleviate the depletion of groundwater in Mexico.

In the case of the effect of number of farmers sharing one well, when farmers pay their own electricity bill, with one more farmer sharing a well, the groundwater consumption increase 1.17 (95.25-94.08) units. Compared to the average groundwater consumption 9316.6, 1.17 can be ignored and there is almost no difference between the groundwater consumptions of farmers individually owning one well and farmers sharing one well but paying their actual electricity consumption.

However, when farmers pay joint electricity bill, with one more farmer sharing the well, groundwater consumption increases 95.2 units, which is obviously higher than 1.17. If we compare farmers paying their actual electricity consumption and farmers paying joint bill, the similar result is found. Farmers pay electricity bill based on pre-specified payment rule, have 94.1*N-17.0 units higher pumping than farmers paying their actual electricity consumption. With more farmers (N is bigger) sharing one well, the difference between their pumping is greater.

Based on the estimated value of parameters, we calculate the efficiency level of farmers and show them in table 3. Farmers owning individually one well use groundwater the most efficiently, while farmers sharing one well but paying their actual electricity consumption are slightly less efficient, but they stay very close to the efficient frontier and almost are fully efficient. If farmers can pay their actual electricity consumption, sharing one well doesn’t decrease the efficiency of water use obviously. However, when farmers sharing well pay electricity based on a pre-specified rule, the technical efficiency decrease gradually with the increase of number of farmers sharing the well and the bill. More farmers paying electricity bill jointly, more groundwater is pumped and less efficiently the groundwater is used.

Table 3: Technical efficiency of famers with different ownership and different electricity payment rule

	Farmers number in one well	τ	TE		Farmers number in one well	τ	TE
Farmers paying their own electricity bill	1	0	1				
	2	2.2	0.9998	Farmers paying joint electricity bill	2	190.4	0.99
	3	3.3	0.9998		3	285.6	0.98
	4	4.4	0.9997		4	380.8	0.97
	5	5.5	0.9996		5	476	0.97
	6	6.6	0.9995		6	571.2	0.96
	7	7.7	0.9995		7	666.4	0.95
	8	8.8	0.9994		8	761.6	0.95
	9	9.9	0.9993		9	856.8	0.94
	10	11	0.9992		10	952	0.93
	11	12.1	0.9992		11	1047.2	0.93
	12	13.2	0.9991		12	1142.4	0.92
	13	14.3	0.9990		13	1237.6	0.91
	14	15.4	0.9989		14	1332.8	0.91
	15	16.5	0.9989		15	1428	0.90
	16	17.6	0.9988		16	1523.2	0.89
	100	110	0.9924		100	9520	0.34

The influence trend of number of farmers and electricity payment rule has the clear pattern. However, all coefficients related to farmer number and payment rule are not significant. When we test CS, N and N*CS jointly, the Chi-square statistic is 1.345, which is not significant either.

So based on the estimated value of parameters and significance level, the effect of ownership externality and payment externality can be found. For ownership externality, since the number of farmers sharing well cannot affect the groundwater consumption obviously and significantly, the ownership externality does not decrease the efficiency of groundwater consumption. The result is opposite to what we expected from our deduction. The reasons of this result may come from the magnitude of its effect and the influence of groundwater supply.

Farmers sharing a well are affected by pumping in the well stronger than farmers outside the well but the magnitude of the stronger effect may be small and it causes that the ownership externality is small. Even though the ownership externality can cause inefficiency of groundwater use, its effect is too small to be significant.

Another reason is from the groundwater supply of the well. In left-hand side of equation (5), we use realized groundwater consumption as groundwater demand since pure groundwater demand of farmers cannot be observed. In fact, the realized consumption of groundwater is affected not only by demand but also supply of groundwater. If we assume all wells have the same recharge rate and then they have the same groundwater supply. For wells owned by one farmer, the farmer receives the whole supply from the well. Form farmers sharing a well, each farmer only receive part of the whole supply. The higher price, higher pumping cost, may not completely catch the effect of less supply of groundwater if less supply not only cause higher pumping cost but also cause the possibility that there is not enough water available in drought season and some farmers cannot pump enough water they need. It means that the effect of less supply is not caught up by x_i*/y completely so the effect of N is messed up by it. The higher motivation to pump from ownership externality increases farmers' demand and groundwater consumption but simultaneously the sharing of well decreases the groundwater supply and groundwater consumption. The offset of supply effect on demand effect causes the similar efficiency level of farmers individually owing one well and farmers sharing one well.

For payment externality, the pre-specified share rule did increase consumption and decreases the efficiency of groundwater, but its effect is not significant either. We cannot conclude that payment rule of electricity has significant effect on groundwater consumption and efficiency and payment externality decrease the efficiency of groundwater exploitation significantly. The reason of this result can be also the fact that even though the payment externality exists, its magnitude is too small.

From the result, we also can find that soil type and well depth do not influence water demand significantly either. However, climate type shows significant effect on water demand. It is not surprising since with better climate farmers need less groundwater to irrigate land and can be more efficient.

Conclusions

Results suggest the own-price elasticity of groundwater is **( )** , which indicates the lower groundwater pumping with higher pumping cost. The elimination of electricity subsidy can decrease the groundwater consumption and is an effective way to alleviate groundwater depletion in Mexico.

Sharing of a well does not increase groundwater consumption and decrease efficiency in water use if farmers can pay their actual electricity consumption when they share a well. Based on the result, integrating farmers sharing a well into one cost-minimizing unit may not be an effective policy to alleviate groundwater depletion in Mexico.

The sign and magnitude of parameter of cost-sharing of electricity show that when farmers do not pay their actual electricity consumption, groundwater consumption is higher and efficiency level is lower. However, the effect of cost-sharing rule is not statistically significant, so we cannot conclude that the cost-sharing rule can influence water consumption and its efficiency significantly. Policies that can guarantee every farmer pay their own electricity consumption may alleviate groundwater over-exploitation, but its effect may not be significant. The cost of implementing these policies, such as installing equipment, may further decrease the attractiveness of these policies.

Since policies eliminating ownership externality and payment externality cannot alleviate significantly groundwater depletion, eliminating electricity subsidy of pumping, which alleviates the pumping cost externality of groundwater, seems to be the most attractive method to alleviate groundwater over-extraction in Mexico.

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