Structural Estimation of Demand for Irrigation Water under Strategic Behavior

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Abstract

Government subsidies on electricity used for pumping groundwater by agricultural irrigators has long been suspected to be an important reason for overexploitation of aquifers in Mexico. We hypothesize that institutional arrangements that exacerbate non-excludability of groundwater also matter. We develop and estimate a model that accommodates strategic interactions among agricultural irrigators operating under distortive institutional arrangements. Results suggest that institutional arrangements are more important than electricity subsidies in explaining over extraction. Results also reveal that cost sharing of electricity by farmers may cause behavioral conjectures to change from negative (closer to Bertrand conjectures) to positive (closer to collusive conjectures). A new source of externalities is identified in Mexico's institutional context (cost-share externalities) and found to be negatively linked to strategic externalities.

Introduction

Depletion of groundwater is cause of great concern among agricultural producers, urban consumers, and policy makers in Mexico. Among the most important reasons behind the alarming overexploitation of aquifers are subsidies on electricity used for pumping and institutional arrangements that exacerbate non excludability of groundwater. To mitigate over extraction, the government can implement policies that increase the cost of extraction (e.g. eliminate subsidies and even tax electricity used for pumping) and/or it can introduce institutional reforms that alleviate non-excludability of groundwater resources. Assessment of the cost-effectiveness of these instruments requires quantification of their effects on farmers' behavior and welfare. Yet little is known about such effects. This study attempts to provide policy makers with critical information on farmers' reactions to price and institutional policies and, consequently, the welfare implications of alternative policy pathways.

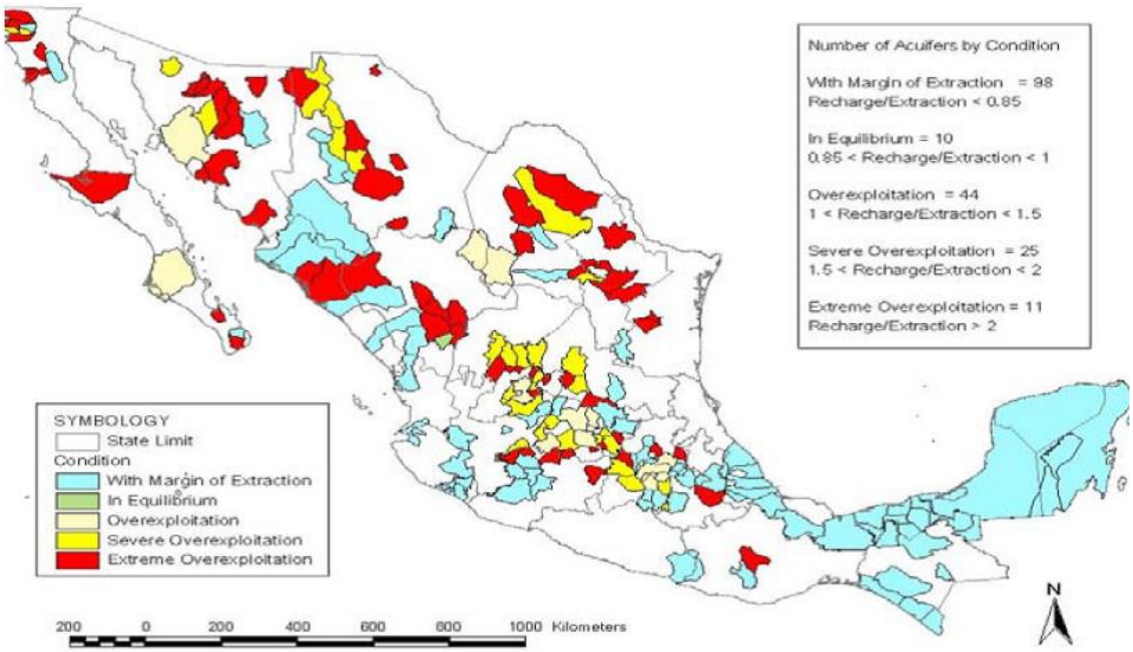
Background

Mexico is classified as an arid and semi-arid country. As a result of the Mexican revolution (1910) and the agrarian reform and especially after the creation of the National Irrigation Commission in 1926, Mexico's government initiated a number of structural reforms in the water sector aimed to introduce modern water management and irrigation. Currently, the agricultural sector plays an important role in the country's economy accounting for 8.4% of gross domestic product (GDP) and employing 23% of the economically active population. An important portion of Mexican's total land area (23%) is equipped for irrigated agriculture. Irrigated agriculture contributes about 50% of the total value of agricultural production and accounts for about 70% of agriculture exports. Of total irrigated land in Mexico, about 33% is irrigated by pumping groundwater and 67% is irrigated with surface water.

The economic crisis of the 1980s led to drastic changes in Mexico's irrigation policy. The National Development Plan (1989-1994) called for an increase in irrigation efficiency and the use of existent infrastructure. Under the National Program for Decentralization of Irrigation Districts, derived from the National Development Plan, Mexican government initiated the management transfer of irrigation districts to Water User Organizations (WUOs). Currently, 53% of irrigated land corresponds to irrigation districts (Distritos de Riego – DR) and 47% correspond to 30 thousand small size communal and irrigation units (Unidades de Riego – UR).

In 1993, the World Bank approved a US$303 million loan to support an integrated irrigation modernization project. This project, ending in 2009, aimed to assisting Mexico's government in its efforts to adopting a new model to improve the competitiveness of irrigated agriculture and the efficiency of irrigation water use. In the year 2006, preliminary evaluations of the situation in Mexico (Programa Nacional Hidrico 2007-2012) concluded that the inefficiencies in the use of water and population growth have made the water from rivers and lakes insufficient in some regions and have also caused an alarming overexploitation of groundwater reserves (Figure 1) and deterioration in water quality. It was also concluded that subsidies on electricity paid by the government to groundwater irrigators were an important cause of inefficient over extraction. Several institutional arrangements (e.g. many wells are shared by groups of farmers and cost sharing of electricity among farmer sharing a well) may also be partly responsible for over extraction. Therefore policy instruments designed to reduce over extraction may be aimed at increasing the cost of pumping water given institutional arrangements (e.g. elimination of electricity subsidies), or modify institutions driving pumping behavior, or both.

Figure 1. Aquifer Depletion in Mexico



An examination of potential effects of water policies requires quantification of farmers' reactions to those policies. Farmers' reaction to water price policies is driven by the elasticity of water demand to the cost of water, which includes the cost of electricity used in pumping and the price of water if a water market exists. Similarly farmers' reaction to institutional reform depends upon the influence that such institutions have on irrigation application rates, including potential strategic responses by farmers sharing the same well and the cost of electricity. We exploit a survey of groundwater irrigators to test the hypothesis that institutional reforms are more important than electricity subsidies in explaining over extraction and, hence, that institutional reforms are more likely to reduce over extraction than price-based policies. Quantification of behavioral responses is conducted in the context of a structural model which allows us welfare-rank alternative policies.

Body of knowledge

Economic theory has long recognized that (weak or total) excludability[1] of a natural resource causes (theoretically) overexploitation of that resource (e.g. Ostrom et al., 1999). In the case of groundwater, excludability is diminished by common access to an aquifer. Non excludability of aquifers and, consequently, their potential depletion, has been a source of concern and analysis (Kelso, 1961; Gisser and Mercado, 1972; Gisser and Mercado, 1973, and Cummings and McFarland, 1973).

Empirically, however, Gisser and Sanchez (1980) have shown that, if the slope of groundwater demand small relative to aquifer's capacity, inefficient over extraction is unlikely to be quantitatively significant. This has come to be known as the "Gisser and Sanchez Result" (henceforth, GSR). The GSR critically depends upon some rather strong hydrological and behavioral assumptions. GSR is derived based on a "bathtub" model in which water transmissivity is virtually perfect (i.e. water flows to the lowest point instantaneously and the water table is level throughout the aquifer). It was also assumed that irrigators did not act strategically, demand is time-independent (i.e. no growth in demand), and that irrigation demand and water table are linearly related (Koundouri, 2004).

While other assumptions may be reasonable, the assumption of non-strategic behavior is perhaps very inappropriate in the case of groundwater use for agricultural irrigation in Mexico. Strategic behavior is likely to emerge when non excludability and externalities are obvious. Externalities may be particularly strong in Mexico as irrigators not only share an aquifer, but they share the same well. In a typical situation of non-excludability, Provencher and Burt (1993) were able to theoretically distinguish two sources of externalities across irrigators that may drive

[1] Define excludability here.

inefficient over extraction of groundwater: a stock externality and a strategic externality. In Mexico externalities are further strengthened by the fact that farmers, in many wells, share electricity costs associated with groundwater pumping. We call this cost externality. We will formalize and quantify this source along with the two previously studied by Provencher and Burt (1993).

Theoretical literature analyzing pumping externalities (Dixon, 1989; Negri, 1989; Provencher and Burt, 1993) assume that, when acting strategically, each irrigator follows a Bertrand-type of conjecture in which they expect that increase in pumping will reduce other farmers' extraction rates. Thus each farmer expects to "crowd out" other irrigators when she increases her pumping rate. This, in turn, creates more incentives for extraction as reductions in others' extraction rates, reduces the effect of a farmer's own pumping on water table. Empirical evidence seems to support the existence of strategic behavior. Pfeiffer and Lin (2009) find evidence of strategic behavior among irrigators in Kansas. Huang et al. (2009) found evidence supporting strategic pumping in China. Finally Savage and Brozovich (2011) found that farmers act strategically but that evidence of strategic behavior is weaker after endogeneity of well density is accounted for.

Modeling and estimation techniques used by these studies, though effective in offering answers to the questions posed in them, are of limited use for our purposes. Models employed by previous studies are reduced form in nature which limits inference on policy implications (Lucas critique). This is particularly limiting in this case as one of our objectives is to inform policy makers on the welfare impact of different policies. We propose to construct a structural model of pumping behavior capable of accommodating strategic interactions among irrigators. We also extend this model to incorporate rules to share the cost of electricity used in man wells in our sample.

Model of water demand

There is no market for groundwater in Mexico. The cost of water is only composed of the cost of electricity associated with groundwater pumping. We denote the cost per unit of water faced by an individual farmer pumping groundwater from well k in period t by:

$$P_{kt}^{w} = p_{kt}^{kwh} \frac{kw}{m^3}_{kt} \qquad (1)$$

Where P_{kt}^{w} denotes the cost per unit of water pumped in well k at time t, p_{kt}^{kwh} is the price of electricity per kilowatt-hour, and $\frac{kw}{m^3}_{kt}$ is the electricity consumed per cubic meter of water extracted from the well.

The amount of electricity used per unit of extracted groundwater is a linear function of the depth to water table in well k and period t, denoted by H_{kt}; i.e. $\frac{kw}{m^3}_{kt} = \alpha + \beta H_{kt}$. Parameter β is positive as greater depth requires running the pump for a longer time to extract the water which is in turn associated with greater electricity consumption. Similarly, parameter α is positive as the pump needs to be run even for surface water ($H_{kt} = 0$). We also assume that the depth to the water table in a given period t, is a linear function of depth to the water table in the previous period and total water pumped in that period in that well (W_{kt})[2], which is the sum of individual pumping rates in that well ($W_{kt} = \sum_{i=1}^{N} w_{kt}^{i}$). Because we are working with cross sectional data, we consider the depth to the water table in the previous period as an exogenous variable and denote the depth to the water table in period t by $H_{kt} = \mu + \varepsilon W_{kt}$; where parameter

[2] This is because pumping draws down the water table increasing the cost of pumping for all irrigators.

γ captures depth to water table in the previous period which, in turn, summarizes the history of groundwater pumping. Also because we have a cross sectional sample of farmers we drop the time sub-indexes from all equations. Thus, the cost per unit of water for farmer i in well k is:

$$P_k^w = p_k^{kwh}(a + b(w_k^i + \sum_{j \neq i} w_k^j)) \quad (2)$$

Where $\frac{kw}{m^3}_k$ has been replaced by $(a + b(w_k^i + \sum_{j \neq i} w_k^j))$ (after plugging H_k into this expression) with $a = \alpha + \beta\mu$, $b = \beta\varepsilon$, and the rest is as defined before.

Equation (2) formalizes the stock externality that the pumping behavior of a farmer bestows upon others. Increased irrigation by farmer i in well k (increase in w_k^i) reduces the water table for all other farmers in that well increasing their cost of pumping (captured by a positive b). This external cost is not however considered by the farmer when deciding on its optimal pumping rate.

We model demand for irrigation water based on a dual-cost function which allows for more flexibility than the primal (production function) specification. Our representative farmer i operating in well k is assumed to minimize cost by choosing a vector of variable inputs x_{ik} (that can be purchased at prices p_x) and the level of irrigation water which we treat as a quasi-fixed input (that can be obtained at a cost of P_k^w), subject to a single output y, fixed inputs (land area) and other exogenous variables (z_k^i). The cost function can then be written as:

$$C = C(p_x, y_{ik}, w_k^i, z_k^i) \quad (3)$$

Application of Hotelling's lemma to the cost function (3) results in demands for variable inputs and output supply. Water is considered a quasi-fixed input. Cost minimization with respect to the quasi-fixed input occurs after minimization with respect to variable inputs (in a sort of sequential optimization). Therefore, once the farmer has optimized with respect to variable inputs, she faces the following problem with respect to the quasi-fixed input (Paul):

$$\min_{w_i}\{C(p_x, y_{ik}, w_k^i, L_k^i) + p_k^{kwh}(a + b(w_k^i + \textstyle\sum_{j\neq i} w_k^j))w_k^i\} \quad (4)$$

The necessary condition for cost-minimization with respect to water is:

$$C_{w_{ik}} + p_k^{kwh}(a + b(w_k^i + \textstyle\sum_{j\neq i} w_k^j)) + \overbrace{p_k^{kwh} b(1+\gamma)}^{\frac{dP_k^w}{dw_k^i}} w_k^i = 0 \quad (5)$$

Where $\gamma = \frac{d\left[\sum_{j\neq i} w_k^j\right]}{dw_k^i}$ parallels the conjectural variation parameter in the new empirical industrial organization literature (Paul). This model allows testing of strategic over-extraction posited by theory.

Institutional arrangements in Mexico pose an additional challenge to our analysis. In many wells, farmers share the well's total cost of electricity which introduces a distortion in the cost per unit of water. This means that a farmer pays a pre-determined share of the total electricity bill of the well. From equation (1), total electricity cost for the well is $P_k^w = p_k^{kwh} \frac{kw}{m^3}_k W_k$ where W_k denotes total water pumped in well k. Let us denote the share of that cost paid by farmer i by s_i. Therefore the cost per unit (cubic meter) of water for farmer i in well k under electricity cost sharing is:[3]

$$P_k^w = \frac{\overbrace{p_k^{kwh}(a+b(w_k^i+\sum_{j\neq i} w_k^j))W_k}^{well's\ total\ electricity\ cost} \overbrace{s_{ik}}^{share\ paid\ by\ farmer\ i}}{w_k^i} \quad (6)$$

Note that expression (6) is the same as (2) except for the factor $\frac{W_k s_{ik}}{w_k^i}$. Expression (6) reveals that when cost share rules for electricity exist the farmer pays a fraction $\frac{W_k s_{ik}}{w_k^i}$ of the "true" per unit water cost $p_k^{kwh}(a + b(w_k^i + \sum_{j\neq i} w_k^j))$. This fraction will be lower (greater) than 1 if the farmer's share of total consumption $\frac{w_i}{W}$ is higher (lower) than the share assigned to him

[3] Electricity consumed per unit of water pumped $\frac{kw}{m^3}_k$ has already been replaced by $(a + b(w_k^i + \sum_{j\neq i} w_k^j))$.

through the cost share mechanism. Because the share assigned to him is fixed, an individual farmer may have incentives to increase her pumping as additional volumes of water can be obtained at lower per unit cost.

In our sample, electricity costs are shared among farmers in some wells but not in other. When farmers do not share electricity costs, the cost per unit of water pumped will be denoted by (2). When farmers, on the other hand, do share electricity cost the cost per unit of water is denoted by (6). We extend the model of cost minimization with water as a quasi-fixed input to account for these institutional arrangements. We model farm-specific unit cost of water in well k with an indicator function ($\theta_k = 0$ if cost-sharing):

$$P_{k,\theta_k}{}^{w} = \theta_k p_k^{kwh}(a + bW_k) + (1 - \theta_k)p_k^{kwh}(a + bW_k)\frac{s_{ik}}{w_k^i}W_k \quad (7)$$

Under this expression for water cost, the cost minimization problem becomes:

$$\min_{w_k^i}\left\{C(p_x, y_{ik}, w_k^i, L_k^i) + \left[\theta_k p_k^{kwh}(a + bW_k) + (1 - \theta_k)p_k^{kwh}(a + bW_k)\frac{s_{ik}}{w_k^i}W_k\right]w_k^i\right\} \quad (8)$$

The necessary condition for cost-minimization with respect to water is:

$$C_{w_{ik}} + P_{k,\theta_k}{}^{w} + \theta_k p_k^{kwh} b(1 + \gamma)w_k^i + (1 - \theta_k)p_k^{kwh}(a + 2bW_k)(1 + \gamma)s_{ik} = 0 \quad (9)$$

We will now proceed to extend this first order condition to accommodate mechanisms to share the cost of electricity among farmers using the same well.

Cost Share and Strategic Behavior

Sharing the cost of electricity may change the structure of strategic interactions among irrigators. In particular, when pumping by one farmer reduces the water table for everyone else and electricity cost is not shared by farmers, the conventional theory of strategic pumping applies. Increased pumping by one farmer increases everyone else's cost of extraction, which leads the farmer to expect a reduction in others' pumping rates. The expected reduction in others' pumping rates will bring the level of the water table (at least partially) back up. Therefore this crowding out of other farmers reduces the cost that an individual farmer imposes on herself when extracting groundwater, increasing incentives for extraction.

On the other hand and as revealed by equation (6), when farmers share the overall cost of electricity in a well based on a pre-specified rule there is a negative relationship between a farmers' share on total water consumed and the unit cost of water. A farmer's share of total water consumption in the well decreases when others increase pumping. In addition the unit cost of water for that farmer also increases, unless that farmer increases her own pumping. Therefore increased pumping by one farmer may drive other farmers to increase their extraction in response. Therefore rules for sharing the cost of electricity may result in the expectation of collusive behavior (i.e. farmers expect that increases in their own pumping will trigger increases in other farmers' pumping as well).

Expected strategic reactions in our model are summarized by conjectural variations. We then accommodate potential differences in strategic behavior by allowing a different set of conjectural variations under the presence of electricity cost sharing. Assuming symmetry (all farmers in the well display the same strategic reaction and, hence, conjectural variation), the first order condition then becomes:

$$C_{w_{ik}} + {P_{k,\theta_i}}^{w} + \theta_k p_k^{kwh} \overbrace{b(1+(N-1)\gamma_1)w_k^i}^{A} + (1-\theta_k)p_k^{kwh} \overbrace{(a+2bW_k)(1+(N-1)\gamma_2)s_{ik}}^{B} = 0 \qquad (10)$$

Where N depicts the number of irrigators sharing the same well, γ_1 is the conjectural variation when farmers do not share the cost of electricity, and γ_2 denotes conjectural variation under sharing electricity costs. Expressions denoted by A and B will be used later on.

Econometric estimation

We know specify a functional form for our cost function $C(p_x, y, w, z)$, where p_x and z are vectors of variable inputs and exogenous variables respectively, and y and w are scalars representing output and irrigation pumping respectively. The functional form chosen for this cost function is a Generalized Leontief (GL). The GL is a flexible function and as noted by Paul (2001) the GL function, is more likely to satisfy curvature restrictions than other flexible forms such as the translog especially, as it is the case here, when quasi-fixed and fixed inputs are included. The cost function is written as:

$$C(p_x, y_k, w_k, z_k) = \sum_j \sum_i \alpha_{ji}\, p_j^{.5} p_i^{.5} + \sum_j \delta_j p_j y + \sum_j \gamma_j p_j w + \sum_j \sum_m \delta_{jm} p_j z_m + + \sum_j p_j \big(\gamma_p y^2 + \sum_m \delta_{jm} y z_m + \sum_m \sum_n \delta_{jm} z_n z_m\big) \quad (11)$$

Variable inputs in (11) are fertilizer, machinery, and a composite of other inputs. The farmer produces a single output and we treat water as a quasi-fixed input. We have a total of 3 exogenous variables namely, soil infiltration, climate regime, and dynamic depth to groundwater. Application of Hotelling's lemma results in a system of derived demands for variable inputs and an output supply:

$$x_j = \sum_j \alpha_{ji} \left(\frac{p_j}{p_i}\right)^{.5} + \delta_j y + \gamma_j w + \sum_m \delta_{jm} z_m + \gamma_p y^2 + \sum_m \delta_{jm} y z_m + \sum_m \sum_n \delta_{jm} z_n z_m; \qquad j = f, m, o \quad (12)$$

The system to be estimated is composed of the cost function (11), the system of 3 variable inputs demands (12), and the first order condition for irrigation demand (10). Note that, in equation (10), all four parameters of interest (a, b, γ_2, and γ_2) are exactly identified. The first order condition for irrigation is nonlinear in parameters. Therefore we apply nonlinear seemingly unrelated regressions to our system of equations. The system has a total of 49 independent parameters to be estimated.

Data

The data collection process occurred from late-2007 until mid-2008. A total of 198 irrigation well surveys are sufficiently complete to use for analysis. These irrigation wells are a sample of the entire country, and represent the full distribution of irrigation wells in Mexico. 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.

Farm-level data on quantity and prices of inputs (including irrigation water) and outputs was obtained from a cross section of 198 irrigators. This information included not only variable inputs (fertilizer, machinery, and an aggregate of "others") but also land area which is considered a fixed input and exogenous variables (soil infiltration, climate regime, and dynamic depth to groundwater). All irrigators surveyed operated in different wells, so 198 wells were sampled. Farmers in our sample produce a combination of several outputs (Table 1). Most farmers produce only a subset of these outputs. We aggregate these crops according to Jorgenson's procedure for "exact" aggregation. This procedure allows aggregation even in the presence of zeros in some individual components.

In each well, besides data from a representative farmer in the well, information was obtained on electricity price and total expenditure. Based on information obtained on energy requirements of the pumping equipment in each well (kilowatt hours per cubic meter of water pumped) an estimate of total water pumped was obtained (W_k). Information on the number of irrigators sharing the well (N),[4] whether or not those irrigators shared the cost of electricity ($\theta_k = 0\ or\ 1$), and the share of total electricity expenditure paid by the individual farmer surveyed in that well (s_{ik}) were also obtained. Individual and aggregate water pumping (W_k and w_k^i), the number of irrigators in a well (N), the price of electricity (p_k^{kwh}), and cost share (θ_k) are all the information we need to estimate the first order condition for optimal irrigation (9).

Table 1: Definitions of Crop Categories

Crop Type Category	Crops Included
1	Field crops (alfalfa, cotton, forage, prairie, barley, sorghum, wheat, oats, pasture, rice)
2	Citrus (citrus, oranges, lemon, grapefruit)
3	Other fruits (fruit, banana, blackberry, grapes, melon, watermelon, strawberry, mango, tamarind, coconut, avocado, mamey)
4	Vegetables (basil, lettuce, tomatoes, jitomate, tomatillo, vegetables, onion, nopal, carrot, cucumber, cilantro, chile, garlic, pumpkin)
5	Beans (also garbanzo beans)
6	Corn
7	Flowers and nurseries

One of the goals of the survey was to adequately represent the entire country of Mexico. It is difficult for a database of 198 surveys to represent an entire country, but the following map and table show the distribution of surveys throughout the country. On the map, states that have complete surveys in the final database are denoted with diagonal stripes.

One thing that is clear from the map is that certain regions of the country are better represented in the database than others. For example, the Northern and Central regions are well represented, but the Southern region is not adequately represented in the database. In the Yucatan Peninsula, the state of Yucatan is well represented, with 28 surveys (over 10 percent of all the surveys), but the other states are not included in the database. One explanation for this distribution of surveys is that the costs of surveying in every state became too high to be feasible.

[4] In some cases $N = 1$ which means the surveyed farmer does not share the well with other farmers.

While this is understandable, it does mean that the results from the study may not be fully representative of the entire country. However, a large enough portion of the country is included that the results are still important and extremely useful for policy makers.

Chart 1: Map of Mexico with States

Source: http://milebymile.com

Table 2 shows the distribution of observations across States in Mexico. The distribution is not uniform, but those states with the highest number of surveys (Zacatecas, Guanajuato, Yucatan) will provide variation in crop choice and general economic conditions.

Table 2: Total Number of Observations by State

State	Percent of all Observations
Aguascaliente	0.8%
Baja California Sur	4.3%
Coahuila	6.7%
Colima	6.3%
Chihuahua	0.8%
Durango	2.4%
Edo. De Mexico (Mexico State)	1.6%
Guanajuato	14.6%
Hidalgo	3.1%
Jalisco	2.8%
Michoacan	5.9%
Morelos	0.8%

Nuevo Leon	2.0%
Puebla	8.7%
Tamaulipas	5.9%
Tlaxcala	3.9%
Yucatan	11.0%
Zacatecas	18.5%
Total	100.0%

In addition, Table 3 shows the distribution of wells in the sample that are privately used or shared by a group of producers. As expected, we observe a large number of wells that are shared by multiple irrigators. Of those with usable results, 70 out of 253 (27.7 percent) state that the well is used by a single producer, while 183 (72.3 percent) have multiple producers that share the irrigation well. In comparison, the 2004 survey found 35.4 percent of wells with a single user, and 64.6 percent with multiple users.

Table 3: Distribution of Wells by Number of Users

	Number (N=253)	**Percentage**
Single Producer	70	27.7 %
Multiple Producers	183	72.3 %

Table 4 shows the distribution of the number of users for wells with multiple producers. The mean and median number of users is 23.3 and 13, respectively. While there are some cases where a large number of producers share a well, the median size of the group is 13 people, and 80 percent of the wells are shared by less than 30 people. There are a few cases where very large groups of users are reported (200 or more); although it is clear that these are outliers. The theoretical literature on strategic groundwater pumping has concluded that if an irrigator shares an aquifer (or a well as in this case) with a relatively small number of other farmers they are more likely to act strategically. Results in table 4 suggest then that strategic pumping may be likely in our sample.

Table 4: Distribution of Number of Users for Multi-producer Wells

Number of Users	**Frequency**	**Percentage**
2 – 5	43	23.5%

6 – 10	34	18.6%
11 - 15	22	12.0%
16 - 20	21	11.5%
21 - 30	26	14.2%
31 - 40	16	8.7%
41 - 50	6	3.3%
51 - 75	4	2.2%
76 - 100	5	2.7%
101 - 200	4	2.2%
>200	2	1.1%
Total	**183**	

Results

Coefficients resulting from nonlinear SUR estimation of system (9)-(11) are reported in Table 5. About 60% of parameters estimated were statistically significant. Many insignificant parameters are probably explained by the relatively small number of degrees of freedom in the estimation. Own price elasticity of demand for irrigation water is a combination of parameter estimates. Because all parameters involved in the elasticity expression are significant we have some level of confidence on our estimate. Based on coefficient estimates, the own price elasticity of irrigation demand is -0.05. This suggests that irrigation demand is quite inelastic to its own price which is in line with previous estimates of elasticity of water demand (REFERENCES).

Additionally, conjectural variation parameters are significantly different from zero which supports the hypothesis that farmers act strategically when deciding on groundwater pumping. The conjectural variation parameter when the cost of electricity is not shared by farmers in the same well ($\gamma_1 = -0.40$) confirms previous theoretical predictions (Provencher and Burt, 1993) in that irrigators seem to follow Bertrand-type conjectures.

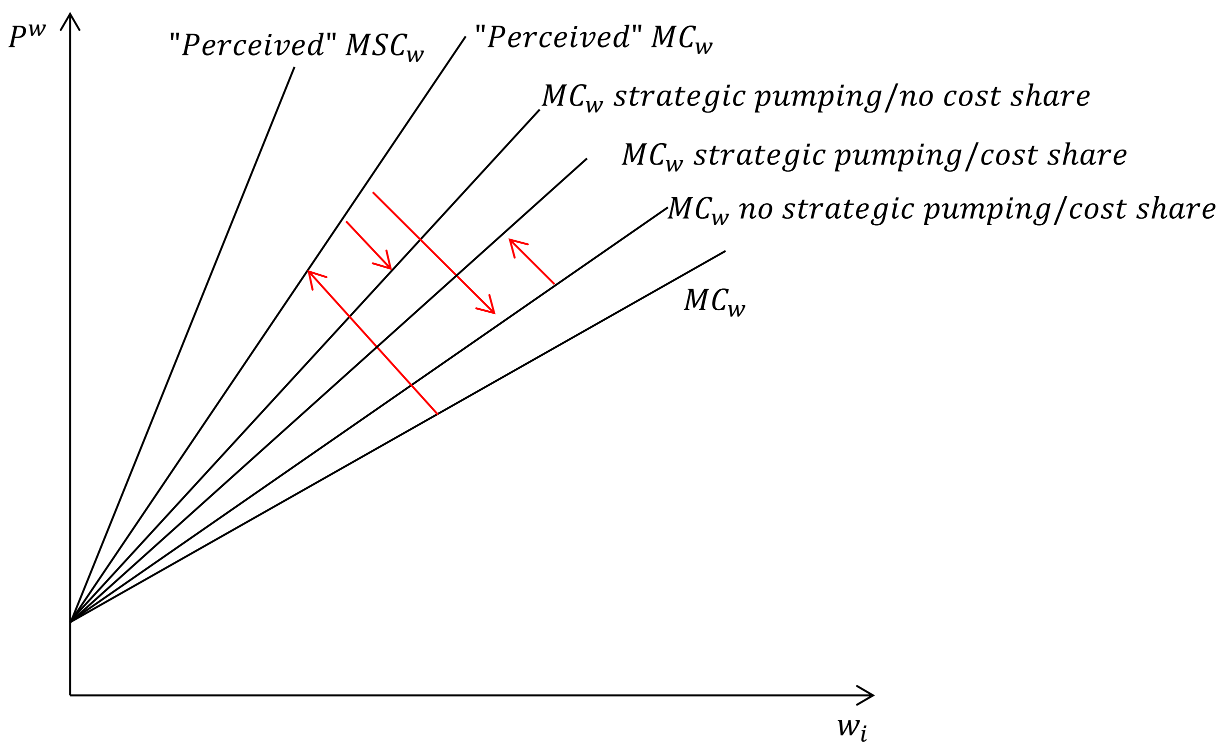
Moreover when farmers share the cost of electricity based on some pre-determined rule, the estimated conjectural variation parameter suggests that farmers expect collusive behavior ($\gamma_2 = 0.23$). This is important for the overall rate of groundwater extraction because the expectation of collusive behavior in pumping rates tend to disincentivize extraction. This is due to the fact that farmers anticipate that increasing their pumping will also increase others' pumping magnifying the effect of own extraction on water table and future cost of irrigation. On the other hand sharing the cost of electricity creates a negative relationship between a farmers' share of total water consumed and the unit cost of water, incentivizing groundwater pumping. If expression A in equation (10) is larger (smaller) than B then the effect of collusive behavior conjectures is larger (smaller) than the effect of cost-sharing on unit cost of water and overall extraction increases (decreases). The expression denoted by B in equation (10) is bigger than the expression denoted by A (both expressions are evaluated at the sample average) suggesting that sharing the cost of electricity increases groundwater extraction.

Distinguishing between Sources of Over Extraction

Figure 2 offers a graphical interpretation of the difference between stock, strategic, and cost share externalities. First, the farmer faces an upward sloping supply of groundwater (this is because pumping reduces water table and increases cost). The irrigator recognizes this situation and identifies a perceived marginal cost curve (just like a monopsonist would when facing an upward sloping input supply). The perceived marginal cost only internalizes increases in the farmer's own cost but not increases in other farmers' cost which results in private marginal cost being smaller than marginal social cost of pumping. This is the first source of cost distortion and over extraction. This is the so called *stock externality*.

As argued before increased pumping by one farmer increases everyone else's cost of extraction, which leads the farmer to expect (if the cost of electricity is not shared by farmers based on a pre-specified rule) a decrease in others' pumping rates. This crowding out compensates (at least partially) the original decrease in the level of the water table which reduces the cost that an individual farmer imposes on herself when extracting groundwater. This effect is captured in Figure 2 by a rotation of the private marginal cost curve from "$Perceived$" MC_w to "MC_w $strategic\ pumping/no\ cost\ share$". The source of this distortion has come to be known as *strategic externality*.

Figure 2. Effects of institutional arrangements on marginal cost of pumping



On the other hand when the cost of electricity is shared based on some pre-determined mechanism farmers can extract additional units of water at decreasing cost as depicted by equation (6). This effect is captured in Figure 2 by the rotation of marginal cost from "$Perceived$" MC_w to "MC_w $no\ strategic\ pumping/cost\ share$". Increased extraction by one farmer reduces others' share on total consumption increasing their unit cost of water. This externality is not, of course, internalized by the farmer. We call the source of this distortion *cost share externality*.

By the same logic, under electricity cost-sharing, a farmer's faces a higher unit cost of water when others increase pumping unless that farmer increases her own pumping. Therefore when a farmer increases extraction others may respond by increasing their own pumping rates. Conjectures about this type of collusive behavior increase the expected cost that an individual farmer imposes on herself when extracting groundwater. This effect is captured in Figure 2 by a counter-clockwise rotation of the marginal cost curve from "MC_w $no\ strategic\ pumping/cost\ share$" to "$MC_w$ $strategic\ pumping/cost\ share$". Therefore cost-sharing of electricity unleashes two forces that influence groundwater pumping in opposite directions. Technological parameters estimated in this study reveal that, overall, electricity cost sharing increases groundwater extraction.

Conclusions

We have hypothesized that institutional arrangements (in particular, non-excludability of wells and sharing of electricity costs by farmers) are more important than price policies in explaining Mexico's high pumping rates. The framework developed here allows us to test that hypothesis and disentangle the relative importance of non-excludability and electricity cost sharing on over extraction. Quantification of the different components of marginal cost (equation 10) suggests that our hypothesis is correct and that distortions introduced by non-excludability of wells (strategic interaction caused by non-excludability) and sharing of electricity costs have a larger impact on over-extraction than subsidies on electricity.

This study also sheds light on potential links between the institutional arrangements under which farmers operate and their conjectures regarding other players' strategic responses. In particular our analysis reveals that irrigators in Mexico may base their decisions on conjectural variations that are closer to collusive or Loschian conjectures (i.e. $\frac{\partial W_k}{\partial w_k^i}$>0) than those predicted by previous theoretical work which are closer to Bertrand conjectures (i.e. $\frac{\partial W_k}{\partial w_k^i}$<0). This convergence towards Bertrand conjectures will occur if farmers share the cost of electricity in a well based on some pre-specified rule instead of paying for actual individual electricity used.

Our framework allowed us to distinguish the effect of a new source of inefficient over extraction that we call cost externality. This is in contrast to conventional (i.e. previously studied) sources of inefficient over extraction which are stock and strategic externality. As it turns out the cost externality and strategic externality seemed to be negatively linked. Cost sharing of electricity which causes the cost externality may trigger Loschian conjectures that tend to weaken the strategic externality.

Finally, an important policy lesson is embedded in these parameter estimates. Institutional reforms may be much more effective in bringing down groundwater depletion than price-based policies. Specifically, integration among well users (reduction in N) and elimination of electricity cost-sharing rules would be more effective in reducing groundwater extraction than elimination of the electricity subsidy currently in place.

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Appendix – estimation results

	COEFFICIENT	ST. ERROR	T-RATIO
B1	-1.7773	8.5844	-0.20704
B2	174.81	61.582	2.8387
B3	5.0682	1.0442	4.8535
B4	-16278.	5779.6	-2.8165
B5	377.79	36.117	10.460
B6	-1.1185	8.5394	-0.13098
C1K	1.8272	0.24404	7.4871
C1F	898.85	176.68	5.0873
C1O	-0.70750	0.22515	-3.1424
C2K	-0.94348E-02	0.61655E-02	-1.5303
C2F	-14.568	4.2931	-3.3934
C2O	0.50820E-02	0.23102E-02	2.1998
C3K	0.16801	0.19482	0.86236
C3F	-87.491	112.31	-0.77904
C3O	-0.47214	0.13761	-3.4310
C4K	-5.8352	2.0600	-2.8326
C4F	1093.9	1533.6	0.71328
C4O	12.636	2.5306	4.9933
C5K	0.55544E-04	0.61970E-04	0.89630
C5F	0.72547E-01	0.41551E-01	1.7460
C5O	0.13726E-03	0.37005E-04	3.7093
C6K	-0.61066E-03	0.34296E-02	-0.17805
C6F	0.24895E-02	0.99445E-02	0.25034
C6O	0.13218E-02	0.17377E-02	0.76067
C7K	-0.11355E-01	0.25755E-01	-0.44089
C7F	3.5021	10.582	0.33096
C7O	-0.62228E-01	0.20310E-01	-3.0639
C8K	0.17483E-01	0.25857E-01	0.67612
C8F	-2.6251	11.546	-0.22736
C8O	-0.26371E-01	0.23570E-01	-1.1188
C9K	-0.90864	0.82716	-1.0985
C9F	558.76	455.15	1.2276
C9O	1.5314	0.63135	2.4256
DK	-1.4278	3.3585	-0.42512
DF	-1120.1	2514.2	-0.44552
DO	-5.8780	3.0017	-1.9582
EK	4.3038	1.8406	2.3382
EF	2220.8	1364.9	1.6272
EO	-6.7733	1.6174	-4.1877
D1	-182.23	74.298	-2.4526
D2	310.41	2599.2	0.11942
D3	24.322	56.048	0.43395
D4	6671.1	2646.5	2.5207
C	-0.14496E-06	0.57330E-07	-2.5284
C1	0.12125E-07	0.50492E-08	2.4014
G1	0.23187	0.90817E-01	2.5532
G2	-0.40656	0.32436	-1.2534
AO	0.15939	0.59972E-01	2.6578
A1	-0.12079E-01	0.29215E-02	-4.1344