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Essays on User Response to Alternative Policies to Modifying Subsidies for Groundwater Extraction

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Environmental Sciences

by

Edgar Humberto Tellez Foster

August 2016

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ABSTRACT OF THE DISSERTATION

Essays on User Response to Alternative Policies to Modifying Subsidies for Groundwater Extraction

by

Edgar Humberto Tellez Foster

Doctor of Philosophy, Environmental Sciences
University of California, Riverside, August 2016
Dr. Ariel Dinar, Co-Chairperson
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This set of three essays analyzes the effects of and possible solutions to the overexploitation of groundwater due to implementation of pervasive subsidies for electricity used for pumping. Many countries face this problem, and these essays focus on the consequences Mexico has seen as a result of it. It subsequently proposes solutions to this problem.

The first essay outlines the theoretical framework that leads to testable hypotheses proposing policy interventions that could prevent the overexploitation of aquifers in Mexico for electricity subsidies. The second essay presents a set of experiments aimed to study the behavior of students in the laboratory when facing a change in the subsidy structure. The third essay uses the experimental design introduced in Essay 2 and tests the behavior of groundwater stakeholders with farmers of the region of León, Guanajuato. Results suggest that all policy interventions produce the expected results and that the decoupling treatment, as tested in the field, is an effective intervention, as is eliminating the subsidy without the political costs of the latter.

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Introduction

Water is both the scarcest natural resource and the most crucial for sustaining life, and 97.5% of it is not available for human consumption (Shiklomanov, 1993). Almost 30% of the available fresh water is contained in aquifer systems (Murayama, 2006). In a world with an increasing population and decreasing water availability, it is pertinent to ask if the current water allocation is efficient. The demand for water and its supply are competing forces that cause governments, institutions, and communities to change the way they manage water resources.

Reducing water consumption could involve designing more efficient technologies and incentive frameworks that achieve the socially optimal rate of water extraction. However, the political economy of water is complicated, and governments and institutions often act as opposing forces by creating insufficient incentives for water extraction decisions. In Mexico the government has introduced subsidies as a strategy to render Mexican agricultural products more competitive in the market. One such subsidy is “Tarifa 09,” which reduced the price of electricity used for pumping groundwater, potentially encouraging farmers to overexploit aquifers.

Changes in water and energy institutions often are both economically and politically costly, creating a need for methods of reliable and replicable testing that lead to inferences on the possible results of implementing a policy. Experimental economics provides a formal, replicable, and cost-effective analysis of policy and institutional changes (Murphy et al., 2000).

This set of three essays analyzes the effects of and possible solutions the overexploitation of groundwater due to the implementation of pervasive subsidies for electricity used for pumping. Many countries face this problem, and these essays focus on the consequences Mexico has seen as a result of it. The essays subsequently propose solutions to this problem.

The first essay analyzes in a dynamic framework the effects of the subsidy and simulates policy scenarios that analyze the possible outcomes of a subsidy modification; this serves as the primary analysis and produces several testable hypotheses for the experimental work. Results from computer simulations of two aquifers (one in León, Guanajuato and another in Kern County, California) suggest that elimination and decoupling equally reduce withdrawals from the aquifer, and both interventions lead to less height in the water table.

Using laboratory experiments, the second essay studies how the subjects determined their extraction decisions. Conditional on different subsidy modification arrangements, the theoretical predictions suggested that eliminating and decoupling the subsidy from the electricity price would produce the same effect, and reducing the subsidy would have a smaller effect. Results from the laboratory demonstrated that among the three policy interventions, decoupling the subsidy produced the largest effect, making this a viable policy intervention, especially considering the political difficulties of eliminating or reducing a subsidy.

The third essay will use the same model and experimental design described in Essay 2 to test the policy scenarios in the field with actual stakeholders (farmers). Results demonstrated that farmers' behavior follows the predictions of the model, leading to impacts that different from those the students experienced. In the field experiments, elimination produced the largest effect, followed closely by decoupling, and, as predicted, reduction produced the smallest effect. These results support those obtained in the laboratory experiments by demonstrating that decoupling is a viable policy intervention and a possible solution to groundwater overexploitation due to pumping subsidies.

Comparing Alternative Policy Interventions for Modification of Subsidized Energy: The Case of Groundwater Pumping for Irrigation

Abstract

This paper analyzes how profit-maximizing groundwater users respond to modifications (elimination, reduction, and decoupling) of the subsidy for electricity used frequently for water pumping. It proposes a theoretical model and numerically derives general results for a simplified case with homogeneous users. The model is applied to aquifers in Leon, Guanajuato, Mexico and in Kern County, California. The performance of the two traditional policy intervention measures—subsidy elimination and reduction—are compared to a new, innovative modification policy mechanism—decoupling the subsidy from the electricity bill— which is argued to be more acceptable politically. The results suggest that the rate of aquifer water extraction and the level of water in the aquifer, which are undesirable under the existing electricity subsidy, can be improved by changing the subsidy structure. Furthermore, decoupling represents a politically feasible alternative to solving the overexploitation of groundwater due to electricity subsidies.

Keywords: Groundwater, Energy Subsidies, Common Property Behavior, Optimal Behavior

JEL Codes: Q5, Q2

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Introduction

Many countries regulate scarce natural resources such as groundwater with subsidies. Although many subsidies produce the desired effects, others have perverse effects on the economy and the environment. Perverse subsidies were estimated at one point to reach \$1,450 billion dollars per year, and are held accountable for a \$30 trillion distortion in damages (Myers, 1999). In the developing world, water subsidies account for \$45 billion dollars of annual costs; meanwhile, agricultural subsidies (including irrigation subsidies) reach \$65 billion dollars in developing countries and up to \$335 billion dollars in developed countries (Pearce, 2003).

Electricity subsidies for pumping groundwater present a major challenge for groundwater regulators around the world. Mexico, India, and Pakistan, for example, have implemented subsidies for electricity used to pump groundwater in an effort to make the agricultural sector more competitive. This issue becomes socially crucial because the number of people depending on groundwater is significant. In India, 55 to 60% of the population relies on groundwater, mainly for agricultural production (Mukherji & Shah, 2005). The electricity subsidy often is leveraged as a political tool in India, with some regions such as Punjab taking the extreme approach of not charging for electricity used to pump groundwater at all (Jain, 2006; Shah et al., 2006).

A total volume of 29.5 km^3 is extracted from groundwater sources in Mexico annually. Of this amount, 70% is used in irrigated agriculture. The Mexican government decided in the early 1990s to provide a subsidy to electricity used in pumping water for irrigation. The subsidy—Tarifa 09—is volumetric; it is provided to farmers based on the amount of electricity they consume in pumping groundwater. As a result of the subsidized pumping cost and other policies, out of the 188 major aquifers in Mexico, 101 have been over drafted due to mismanagement practices and lack of incentives to use appropriate irrigation technologies (Muñoz et al., 2006). These practices are due mainly to perverse water and electricity subsidies (Asad & Dinar, 2006; Dinar et al., 2008).

According to the Mexican National Water Law, water used for irrigation is not priced. Rather, farmers have to pay only for the costs of extracting water (either from surface or groundwater sources). These incentives for farmers hide the real costs of pumping, which go beyond the costs of subsidizing: The scarcity of water and the negative results of its exploitation make groundwater priceless. The current institutional framework leads to inefficient exploitation of groundwater resources.

Previous Work

The vast body of literature concerning groundwater extraction and electricity use points to the intrinsic relationship between them. Most of the literature focuses on the inefficiencies of water allocation due to misleading price signaling to farmers. Shah et al. (2005) analyzed the groundwater irrigation economy in South Asia using results of a survey among groundwater users in India, Pakistan, Nepal, and Bangladesh. They found that the overextraction of groundwater resources have been shaped by South Asia’s energy pricing. They reported that the subsidy is regressive because prosperous landowners predominately have electric pumps, whereas underserved farmers choose diesel pumps or buy water from their wealthier neighbors.

Dubash (2007) analyzed the inherent relationship between electricity and groundwater by assessing the effect of subsidies on groundwater consumption, using the case in India as an example. His findings coincide with those of Shah et al. (2005) regarding the regressive nature of the subsidies for electricity. Dubash (2007) also assessed the impact of this subsidy on the quality of the electricity service provided by the State Electricity Board of India. He found that farmers prefer to continue receiving the subsidy, even it means low-quality service. Mukherji and Shah (2005) discussed the institutional arrangements and policies related to groundwater in India, Pakistan, Bangladesh, China, Mexico, and Spain and concluded that despite the wide range of institutional organization across these countries, the understanding of the social and economic impact of groundwater remains lacking, and scientific study in groundwater is biased toward the resource and its development rather than the externalities created by its use.

The groundwater literature also focuses on the implications of control policies. Gisser and Sanchez (1980) analyzed the benefits of command and control versus market allocation of groundwater. They presented a dynamic model that maximizes the value of net benefit and concluded that the changes in welfare associated with central regulations (such as pricing and quotas) on groundwater are negligible. Feinerman and Knapp (1983) supported this conclusion; they analyzed groundwater allocation using a similar dynamic model and applied it to the Kern County aquifer in California. Their results suggest that the social benefits of implementing command and control mechanisms (e.g., pumping quotas) are small compared to the status quo (Feinerman and Knapp, 1983, p. 709).

On the other hand, Esteban and Albiac (2011, 2012) applied Feinerman and Knapp's analysis to the Eastern and Western La Mancha aquifers and concluded that when taking into account the environmental damage caused by overdrafting groundwater resources, implementing a command and control policy benefits the public environment.

Burness and Brill's (2001) study discussed the role of policy in the case that farmers are allowed to switch technologies; the authors found that regulation can cause switches to more efficient technology because the future costs of pumping become more explicit. On the other hand, Kim et al. (1989) discussed adopting the farmers' behavior, particularly via crop choices, when the price of extracting groundwater increases. Their findings suggest that under social optimum behavior, farmers move away from water-intensive crops (sorghum) twice as much as they do while displaying common property behavior, thereby increasing the efficiency of groundwater use.

While the literature on the impact of energy costs on groundwater management is broad and sheds light on the complex conundrum of the relationship between these commodities, more research is needed to analyze alternative policy options for addressing energy subsidies, which could help solve the groundwater overexploitation problem.

Muñoz et al. (2006) propose different ways to modify the electricity subsidy and reduce extractions to a level that could help stabilize the overdrafted aquifers. These measures include two traditional interventions—elimination and reduction of the subsidy—and the decoupling of the subsidy from the electricity price, which would give farmers a cash transfer in the amount of the subsidy. Decoupling can be introduced using several methods, including:

- Grandfathering: The transferred sum is equivalent to the average consumption of electricity in the last i years (Muñoz et al. (2006) used $i = 3$);
- Land surface: The transferred sum is based on the amount of irrigated land;
- Egalitarian: The transferred sum is based on dividing the grand total of the subsidy among all farmers equally.

These alternative mechanisms, or reforms, each help to address the problem but have potential to create their own. Grandfathering is similar to the status quo; it could create an incentive to draw even more water than before in order to receive a higher financial transfer. Meanwhile, the surface-based decoupling system may promote an increase in the irrigated surface, and the egalitarian method could help resolve the concentration of the subsidy while harming big producers.

The political economy of the subsidy modification also must be addressed. In countries such as Mexico, the agricultural sector is overrepresented, and decisions to remove subsidies are unpopular among politicians because of the electoral consequences they may face as a result.

Our study develops and applies a model that focuses on potential changes in behavior due to changes in the subsidy mechanism (i.e.., complete elimination, decoupling, and reduction). We use the dynamic optimization model to analyze the changes in groundwater extraction under these mechanisms. The model is applied to data from Kern County to evaluate the effectiveness of the three policy interventions described above under optimal extraction behavior and common property behavior of the users.

A Dynamic Model of Demand

We propose a dynamic model based on previous work by Gisser and Sánchez (1980), Feinerman and Knapp (1983), Esteban and Albiac (2011), and Brozovic et al. (2006). Unlike models of previous works, this model introduces subsidy as part of the cost function, then implements various subsidy modification policies to simulate the alternatives under consideration. The model uses the simplifying assumption that all groundwater users are homogenous and that each employs an electric pump for extracting water.

Water Demand

The water demand function is represented by:

$$W_t = g + kP,$$

where W_t is the total demand for water, P is the real price for water, and g and k ($g \geq 0$; $k \leq 0$) are the intercept and price coefficients in the linear demand function, respectively. Integrating the demand function from zero to q (the total use of water, both surface and groundwater), we obtain our revenue function:

$$B(q) = gq - \frac{1}{2}kq^2, \tag{1}$$

where we define

$$q = (1 - \beta_{sw})q_{sw} + w.$$

In the latter equation, q is the total water consumption that includes surface water allocations and groundwater withdrawals. Surface water allocations, denoted by $q_{sw,}$ are considered constant and exogenous. β_{sw} is the amount of surface water that returns to the aquifer. Our control variable is the amount of groundwater consumed, *w*.

Extraction Costs

Extraction costs are represented by:

$$C_t = C_0 + C_1(\gamma, x_t, \xi, w_t), \tag{2}$$

where

$$C_1(\gamma, x_t, \xi, w_t) = \gamma\xi(X - x_t)w_t.$$

The term C_t in Equation 2 is the total cost of pumping *w* units of groundwater in time *t*, where C_0 is the fixed cost, C_1 is variable cost that is a function of the water table (x_t), the price of the amount of electricity required to lift one million m^3 of water is ξ, and *X* is the distance of the land surface from the bottom of the aquifer.

The constrained maximization problem for the entire aquifer (where all farmers are assumed to be homogenous) is as follows:

$$\max_{w_t} \sum_{t=1}^{\infty} \alpha^t \{gq_t - \frac{1}{2}kq_t^2 - C_0 - [\gamma\xi(X - x_t)w_t]\} \tag{3}$$

$s.t.$

$$x_{t+1} = x_t + \frac{\beta_{sw}q_{sw}+\beta_{dp}\left((1-\beta_{sw})q_{sw}+w\right)+R-w}{AS},$$

(3.1)

where R is the recharge, β_{dp} is the deep percolation rate (the amount of water that is returned to the aquifer after irrigation), A is the area of the aquifer, S is the specific yield, and α^t is the discount factor, where $\alpha = \frac{1}{1+r}$, r is the discount rate, and x is the pumping lift. All lifts and pumping distances are measured with respect to the mean sea level, as demonstrated in Feinerman and Knapp's study (1983).

In this model the level of subsidy can vary by changing the values of γ to simulate the different levels. Both common property and optimal behavior scenarios are investigated using computer simulations for 200 periods and parameters in Leon, Guanajuato, Mexico. The level of subsidy γ is varied to simulate different subsidy reduction policies. Decoupling of the subsidy is tested by transferring money to users that is equivalent to their consumption in previous i periods and charging them the real price of electricity.

Common Property Extraction Behavior Results

Under the common property extraction behavior, users are assumed to have little to no incentive to take into consideration the future costs of pumping. This means that users will pump only until their marginal benefit of pumping equals their marginal cost. The first order conditions for the optimization problem for the myopic user are:

$$g - k(w + q_{sw}(1-\beta_{sw})) = \gamma\xi(\bar{X} - x_t). \qquad (4)$$

A lower marginal extraction cost (or the effect of the subsidy level γ) will induce a larger quantity of water extraction in time t, excluding any future cost. Equation 4 demonstrates that groundwater demand can be derived using the common property condition:

$$w_t = \frac{1}{k}[g + kq_{sw}(\beta_{sw} - 1) + (x_t - \bar{X})\gamma\xi]. \quad (5)$$

We proceed to present results of the simulations under common property for three conditions: status quo $(\gamma = 0.2)$, reduction of the subsidy $(\gamma = 0.5)$, and elimination $(\gamma = 1)$.

Below we present results of the common property extraction behavior for the level of extraction (Figure 1) and for the water level in the aquifer (Figure 2) using the parameters of the aquifer in Leon, Guanajuato, Mexico.

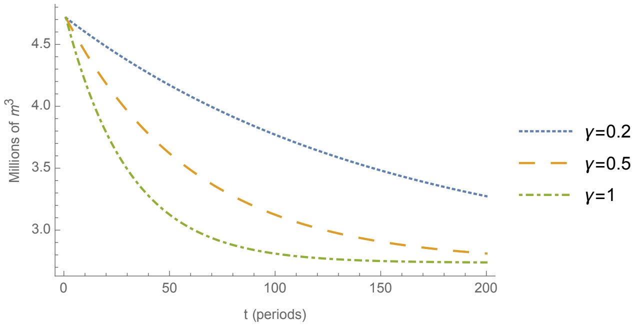

Figure I.1. Groundwater extractions under common property behavior.

Figure 1 presents the extraction per period for the common property extraction behavior under three policy scenarios. It demonstrates clearly that once the subsidy is introduced, the distortion effect leads to a greater extraction from the aquifer. A lower steady state level was reached following 90 and 130 periods, respectively, for $\gamma = 1 \ and \ 0.5$. No steady state was reached for $\gamma = 0.2$ within the 200 period horizon.

The aforementioned statements become clearer following scrutiny of Figure 2, where the collapse of the aquifer becomes more evident. The introduction of the subsidy clearly results in the collapse of the aquifer, and the trend of water depth is smaller and kept at a higher level where there is no subsidy (i.e., $\gamma = 1$).

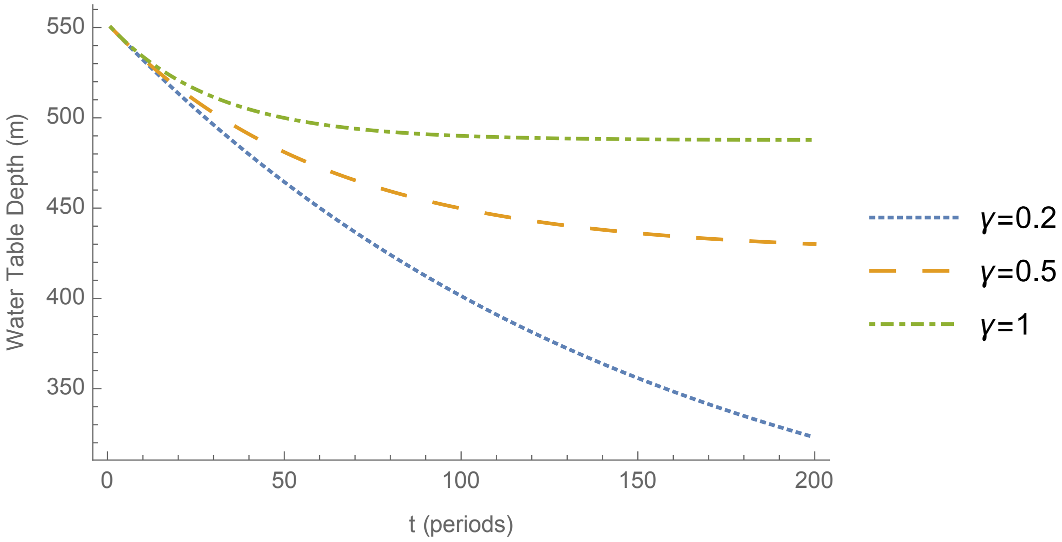

Figure I.1. Water table depth under common property extraction behavior.

Optimal Extraction Behavior Results

Under the optimal extraction behavior, users optimize their water extractions not only according to their marginal extraction cost, but also according to the marginal user cost. (The reduction in the discounted future net benefits from a withdrawal of one additional unit in the current period [Feinermann and Knapp, 1983].) The optimal extraction cost follows an optimal path that takes into account the present and future consequences of the extraction decision.

From the optimization problem demonstrated in Equation 3, we derive the Bellman equation:

$$V(x_t) = \max_{w_t}\left[gq_t - \frac{1}{2}kq_t^2 - C_0 - [\gamma\xi(X - x_t)w_t]\right] + \alpha V[x_{t+1}]. \qquad (6)$$

The Bellman equation simplifies the infinite horizon into a two-stage discounted function that could lead to computing the optimal path of extraction.

From the Bellman equation we derive the first order conditions that yield the following Euler equation:

(7)

$$g - \gamma\xi(\bar{X} - x_t) - k\big((1 - \beta_{sw})q_{sw} + w_t\big)$$

$$= \alpha\frac{(\beta_{dp} - 1)\left(\gamma\xi w_{t+1} - \frac{AS(g - \gamma\xi(\bar{X} - x_{t+1}) - k(1 - \beta_{sw})q_{sw} + w_{t+1}))}{\beta_{dp} - 1}\right)}{AS}$$

The Euler equation is used to derive the optimal path of extraction. It represents the marginal change of behavior by having the marginal net benefits equal the marginal costs in the present and in the discounted future (Parker, 2008). Raising the value of γ from 0.2 to 1 increases the present cost (indicated by the right-hand side of the equation); however, it also increases the marginal, or discounted, benefit in the future (left-hand side of the equation). Therefore, modifications of the subsidy can be anticipated to lead to a deviation from the extraction path with subsidy, which will lead to a shallower, steady state of the water table.

From the Euler equation we derive our policy rule that depends on the present and future values of the state variables. This implies that this policy rule will optimize extraction according to the present cost of pumping water and the future discounted loss in net benefits from pumping an additional unit in the current period:

$$w_t = \alpha \frac{AS(\gamma\xi(x_t - \bar{X}) + kq_{sw}(\beta_{sw} - 1) + 1)}{ASk}$$

$$+\alpha \frac{(\beta_{dp}-1)\left(w_{t+1}\gamma\xi - \frac{AS(g+\gamma\xi(x_{t+1}-\bar{X})-k(-\beta_{sw}q_{sw}+q_{sw}+w_{t+1}))}{\beta_{dp}^{-1}}\right)}{ASk} \quad .$$

(8)

We simulated the model for 200 periods using three policy scenarios for subsidy reduction and elimination ($\gamma = 0.2,\ \gamma = 0.5, and\ \gamma = 1$), with parameters from Leon, Guanajuato. As demonstrated in Table 1A, we obtained the following results presented in Figures 3 and 4.

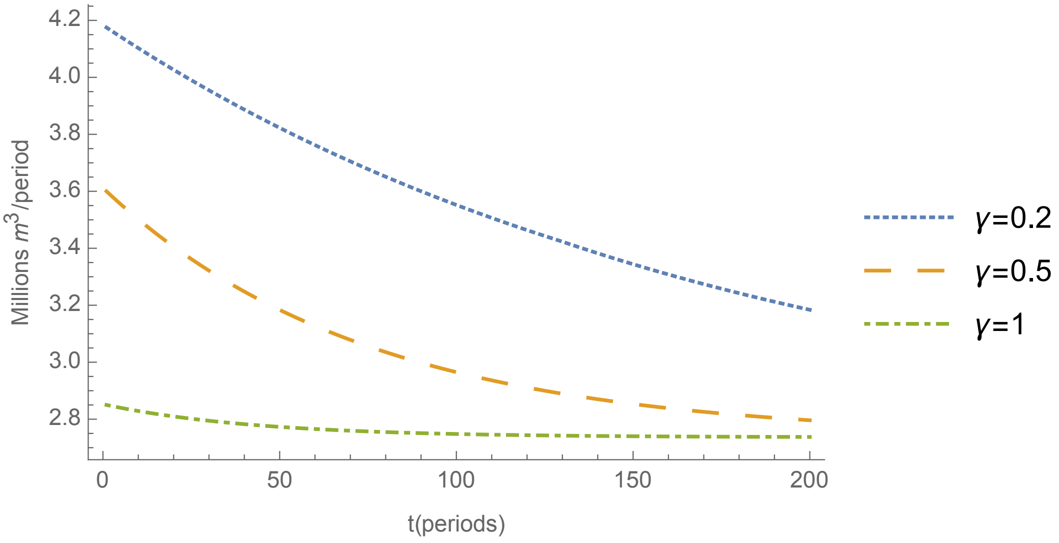

Figure I.2. Groundwater extraction under optimal behavior.

Figure 3 suggests that in the presence of the subsidy, the amount of water pumped is highest, and no steady state is reached for the case of $\gamma = 0.2$, which is consistent with the common property case. However, the figure also demonstrates that eliminating the subsidy induces a steady state in earlier periods (after 50 years in the case of $\gamma = 1$, and after 150 years in the case of $\gamma = 0.5$).

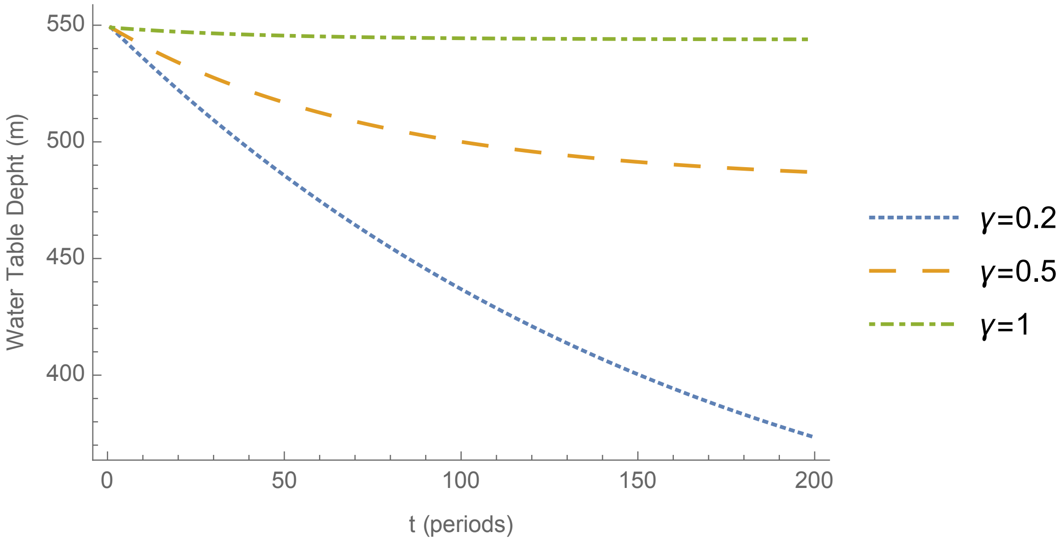

Figure I.3. Water table depth under optimal extraction behavior.

Figure 4 confirms the aforementioned statement by exhibiting that the water table depth converges almost immediately to a steady state when the subsidy is eliminated, reaches a steady state after 70 years with $\gamma = 0.5$, and keeps a downward sloping trend when $\gamma = 0.2$. Depth of water table is also the lowest when the subsidy is eliminated.

Decoupling the Electricity Subsidy

The analysis presented previously includes two policy modifications aimed at addressing the distortions caused by the subsidy for electricity by reducing or eliminating the subsidy, demonstrated by the values $\gamma = 0.5$ and $\gamma = 1$, respectively. However, these two policies do not account for the political economy of the subsidy modification. Irrigation districts and farmers' unions comprise an influential political power with a strong lobby within the local and national governments of the countries with subsidies for energy irrigation. This influence often destroys attempts at subsidy reduction. Decoupling the subsidy from the electricity rate and returning the equivalent sums to the users may act to eliminate the subsidy without resulting in the political cost associated with an explicit subsidy elimination (Muñoz et al., 2006).

To analyze the impact of decoupling the electricity subsidy, the optimization problem must include the average cost of electricity paid in the previous i periods. The optimization problem with decoupling is demonstrated below:

$$\max_{w_t} \sum_{t=1}^{\infty} \alpha^t \{ g q_t - \frac{1}{2} k q_t^2 - C_0 - [\gamma \xi (X - x_t) w_t + \phi] \} \qquad (9)$$

$s.t.$

$$x_{t+1} = x_t + \frac{\beta_{sw} q_{sw} + \beta_{dp}\big((1 - \beta_{sw}) q_{sw} + w\big) + R - w}{AS}$$

$$\phi = \frac{\sum_{k=\tau-i}^{\tau} w_k (\gamma \xi (X - x_t))}{i},$$

where ϕ is the decoupling factor that ranges from $(\tau - i)$ to τ, $\tau < \infty$ being a predetermined number of periods, and i being the number of periods that will be used to calculate the average cost of pumping. This optimization problem can be divided into two stages for all values of t. In stage ,1 where $t \leq \tau$, the Euler equation takes the form:

$$\frac{\gamma \xi (\bar{X} - x_t)}{i} - \gamma \xi (\bar{X} - x_t) + g - k(\big(1 - \beta_{dp}\big) q_{sw} + w_t =$$

$$-\alpha \frac{(\beta_{dp} - 1)\left(\frac{\gamma \xi (i-1)(AS(\bar{X} - x_{t+1}) + \left(\beta_{dp} - 1\right) w_{t+1})}{\left(\beta_{dp} - 1\right) i}\right)}{AS},$$

(10)

where we can compute w_t to get the corresponding groundwater demand:

$$\frac{+AS(gi+\beta_{sw}ikq_{sw}-ikq_{sw}+\gamma\xi(ix_t-x_t)}{ASki}.$$

(11)

The second stage of this optimization problem is for all $t > \tau$. Because ϕ is constant, the demand for groundwater is the same as under the optimal extraction behavior with elimination of the subsidy ($\gamma = 1$):

$$w_t = \alpha\frac{AS(\gamma\xi(x_t - \bar{X}) + kq_{sw}(\beta_{sw} - 1) + 1)}{ASk}$$

$$\frac{+(\beta_{dp}-1)\left(w_{t+1}\gamma\xi-\frac{AS(g+\gamma\xi(x_{t+1}-\bar{X})-k(-\beta_{sw}q_{sw}+q_{sw}+w_{t+1}))}{\beta_{dp}^{-1}}\right)}{ASk}.$$

(12)

The model was simulated for 200 periods, with $i = [3, 5, 10, 15]$. This demonstrates that the decoupling factor was calculated separately for the preceding 3, 5, 10 and 15 periods. The choice of the magnitude of i was not arbitrary; the literature suggests using a three-period lag (Muñoz et al., 2006).

For our simulations, we decided to study the effects of four different magnitudes because land use and subsequent water use can be affected drastically by short-term shocks, both economic and environmental. Moreover, in semiarid climates, as in

Guanajuato, these shocks may result in a variability in short-term land use. Therefore, using longer lags results in an advantage when calculating the decoupling factor. The results of the simulations for subsidy elimination and for subsidy decoupling for $i = 15$ are demonstrated in Figure 5 for extraction level, water table level, and annual net benefit

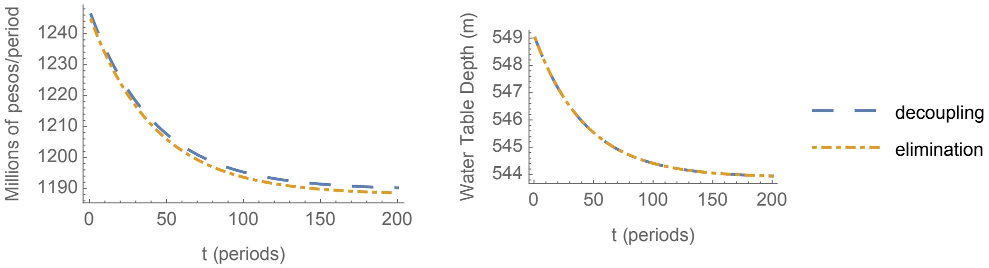

Figure I.4. Groundwater extractions and water table depth under decoupling and elimination of subsidy.

Figure 5 suggests that decoupling achieves the same results as elimination. However, a comparison of the annual net benefits of each method in Figure 6 demonstrates that the total net present value of benefits under decoupling (for i = 15 years) is 241,488 million pesos for the 200 periods, whereas it is 240,024 million pesos under elimination. The 0.6% difference is due to the fact that the cash transfer under decoupling enters as part of the benefit function but does not depend on the present water consumption.

Table 1 indicates the difference in net present value of benefits for i = 3, 5, 10, 15. The difference between the values is relatively small and declines as i decreases, meaning in the long-term, the length of the decoupling factor has marginal impact on user decisions. However, there is an advantage in using longer lags for calculating the decoupling factor. With longer periods of time, the average pumping cost is affected less by exceptionally dry years, where the surface water supply could be affected, leading to higher water consumption that is not related to the subsidy.

Table I.1

Total Net Present Value of Net Benefits

Value of *i* (Years)	Net Present Value for 200 periods (Millions of Pesos)
3	240,354 (99.5)
5	240,548 (99.6)
10	241,025 (99.8)
15	241,488 (100.0)[a]

Note. The percentage values compared to *i* = 15 are in parentheses.

Dinar (2000) wrote that water-pricing reforms may spark both support and opposition from various stakeholders, highlighting the importance of compensation mechanisms for ameliorating the losses of the affected groups. In our study, the decoupling transfer acts as a compensation mechanism that reduces the political implications of the groundwater price reforms. This conclusion is supported by Muñoz et al. (2006), who argue that the decoupling mechanism can raise the overall level of farmers' utility by providing them the option of allocating the subsidy money to the area most efficient for them, instead of constraining it to electricity consumption.

The decoupling policy intervention therefore is viable, given the less controversial political economy implications of this policy intervention versus eliminating or reducing the subsidy. This policy modification additionally provides the positive environmental implications of preserving the aquifer. Although this benefit is not the subject of this research, it should be noted.

Sensitivity Analysis

A sensitivity analysis tested the behavior of the model when facing changes in the price of electricity by varying ξ from 1.8 to 2.8 thousand pesos per 1 million m^3/m. The results displayed in Figure 6 reveal that the model behaves as expected. The aquifer becomes deeper when prices decrease, and water extraction increases when prices decrease. The annual net benefits decrease as ξ increases.

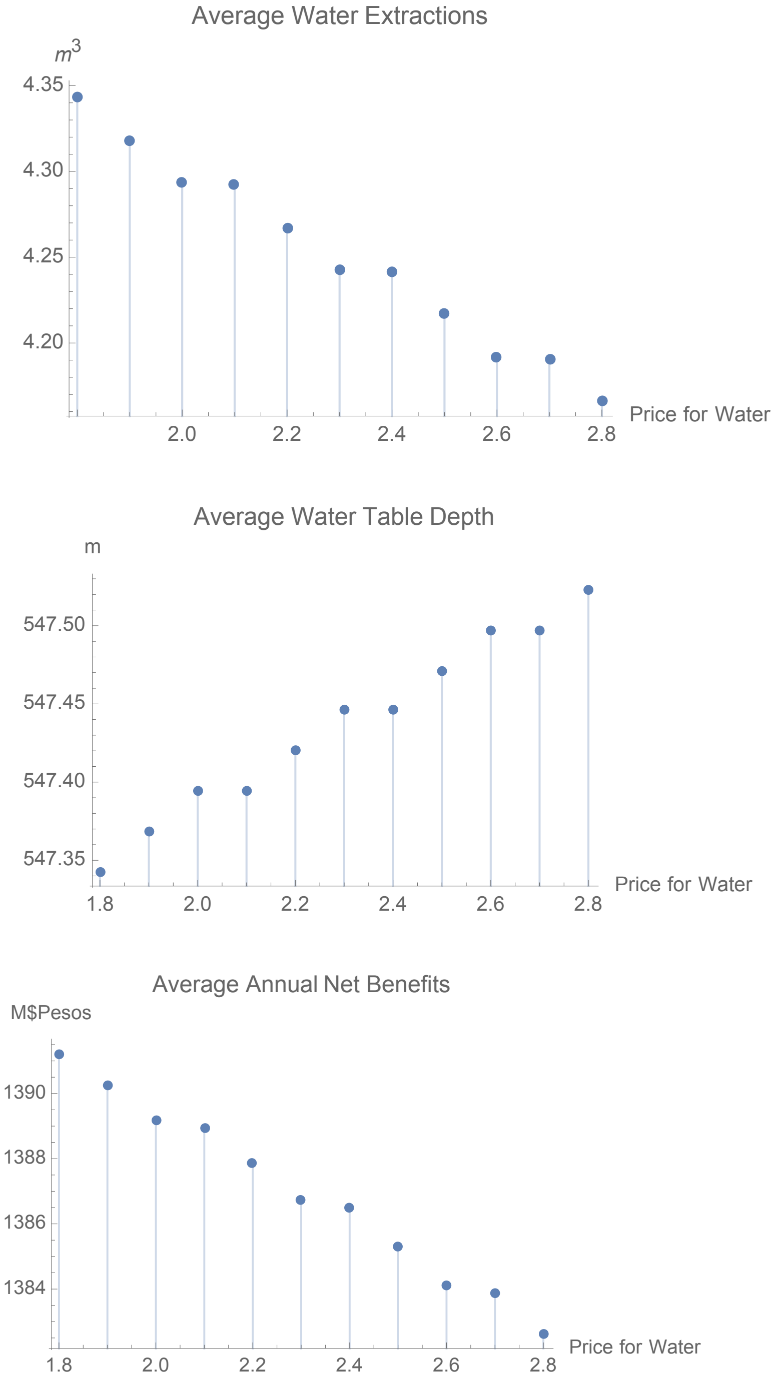

Figure I. 6. Sensitivity analysis for water pumping cost.

Robustness

We conducted simulations using another aquifer to test the robustness of the results. We applied a set of parameters from Feinermann and Knapp's (1983) study, displayed in Table 1B, to an aquifer in Kern County, California. Kern County has similar weather characteristics as the central region of Mexico, where the Leon aquifer is located. Both regions are semiarid and rely on groundwater supply for agriculture. However, some of the economic and geologic characteristics of these regions are different. Figure 7 presents the results for the Kern aquifer simulations.

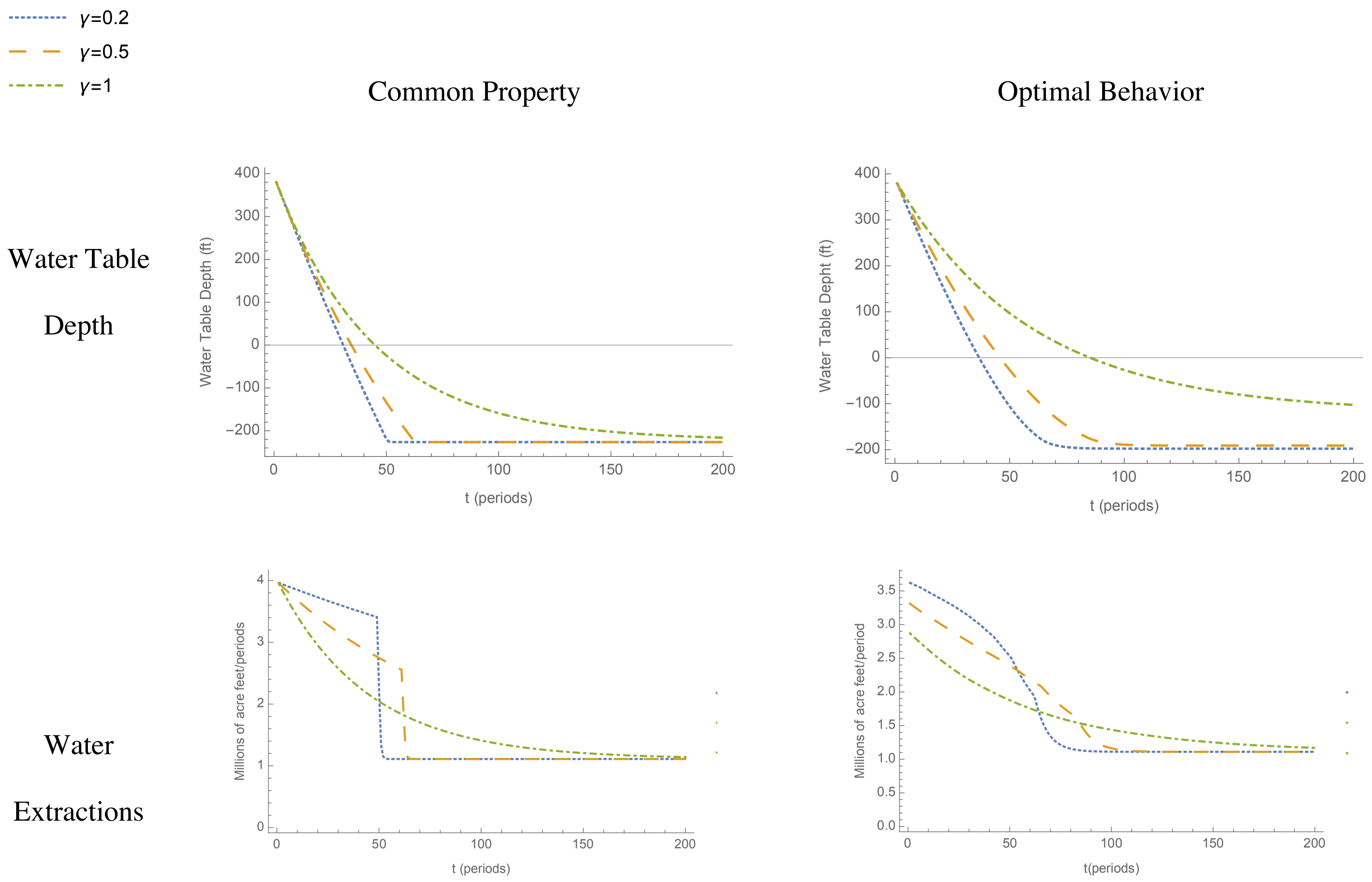

Figure I.7. Sensitivity analysis for Kern aquifer under common property, optimal behavior scenarios.

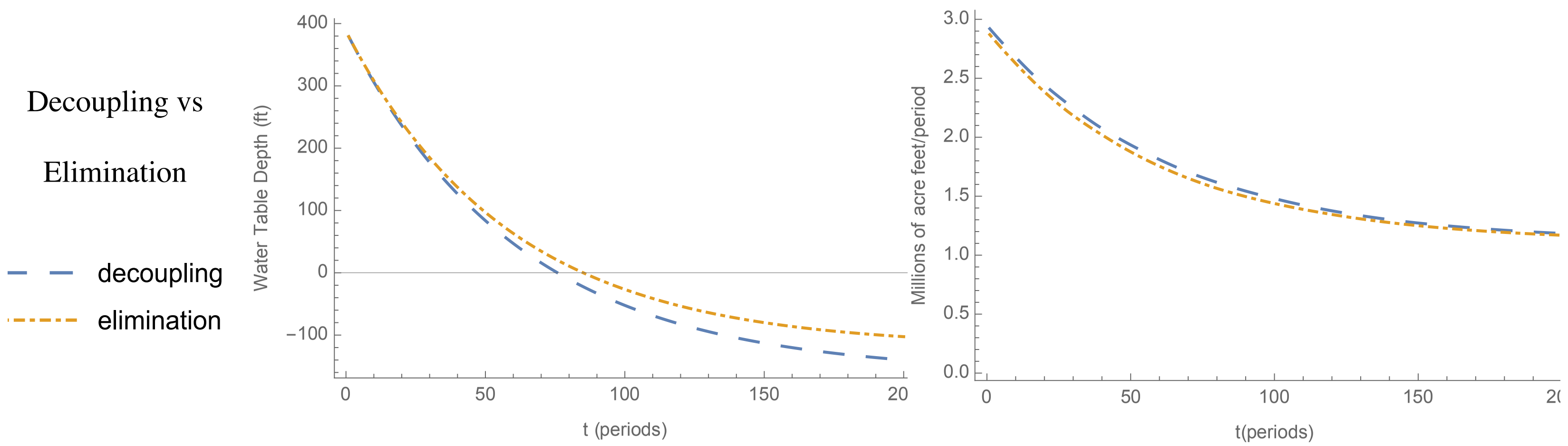

Figure I.7.1. Sensitivity analysis for Kern aquifer: Decoupling and full elimination scenarios.

The results of the common property extraction behavior simulation, restricted to the level of extraction and the water level in the aquifer, show that a lower (higher) steady state level was reached after 50 and 60 periods, respectively, for $\gamma = 0.2 \ and \ 0.5$, compared to a steady state that had been reached after 200 periods for no subsidy $(\gamma = 1)$.

After the subsidy is introduced, the distortion effect leads to the collapse of the aquifer (after 50 periods for $\gamma = 0.2$ and after 60 periods for $\gamma = 0.5)$. Withdraw more than 1 million acre-feet a year (the steady state extraction level) thus becomes economically unviable. The extractions for no subsidy decline over time at a lower rate than the other two subsidy levels for 60 years, then exceed them for the rest of the period, although the total extractions (over 200 years) with no subsidy are lower (323 M acre-feet) compared with extractions with any subsidy level (342.9 M acre-feet for $\gamma = 0.2$ and 341.5 M acre-feet for $\gamma = 0.5$). The trend is monotonic and outperforms the level of the performance under subsidy, reaching a steady state level of extraction after 200 periods at 1.2 million acre-feet.

Inspection of the water table depth, where the collapse of the aquifer is more evident, corroborates the aforementioned statements. The introduction of the subsidy results in the collapse of the aquifer, and the trend is smoother and monotonic where there is no subsidy (i.e., $\gamma = 1$).

The comparison results from the decoupling and elimination interventions (third row) suggest the existence of a slight deviation of the number of units pumped in the first 150 periods under the decoupling policy compared with the number of units pumped under the elimination policy. This results in a slight difference in the depth of the water table, leaving the aquifer slightly deeper through the decoupling intervention.[1]

Conclusions and Policy Implications

This study focused on analyzing the effects of subsidy structures and policy modifications on sustainability of groundwater, given the perverse incentives provided by electricity subsidies for groundwater pumping in the farming sector. The effect of different policy interventions were measured by introducing the subsidy in the cost function. The analysis resulted in several conclusions, reported below, on various institutional arrangements and policy interventions.

Common Property vs. Optimal Behavior

The results across policy interventions for the common property behavior institution demonstrate that the aquifer would collapse in the presence of the subsidy, and the number of periods before the aquifer would become economically unviable depend on the rate of the subsidy, γ. The exception is the subsidy elimination policy where, even when the aquifer does not collapse under common property, higher levels of the water table are evident. The elimination and decoupling policies sustain the aquifer similarly because the common property behavior under the decoupling policy is the same as under the elimination case, as the optimization problem takes into account only the benefit function and the cost function. The definition of common property solutions, identified by Feinerman and Knapp (1983), applies to users who

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[1] However, when compared with the water table depth, where $\gamma = 0.2\ and\ \gamma = 0.5$, the value is significantly less deep.

behave myopically, considering the marginal extraction costs and marginal benefit for the current period only and ignoring the costs imposed on others and themselves from future pumping, cash transfers that are not tight to the cost, and present benefit structures.

Policy Modifications

Our analysis includes several policy interventions, which are displayed in Annex Table 1A and 1B. We simulated subsidy levels by systematically changing the *y*-values ($\gamma = [0.2, 0.5, 1.0]$). We also simulated the decoupling of the subsidy from the electricity price, leading to a cash transfer equivalent to the average cost of extraction. The behavior of the users in our model changed in response to these policy interventions.

In the Kern County case, we observed that introducing electricity subsidy (i.e., $\gamma = [0.2{,}0.5]$) led to the collapse of the aquifer in less than 100 periods. However, eliminating the subsidy ($\gamma = 1.0$) caused the aquifer to reach a steady state that was shallower, compared to the case that included a subsidy.

When introducing the decoupling policy intervention, we observe that the results are close to those of the subsidy elimination policy, although the total net present value of net benefits is slightly higher with decoupling.

This result is consistent across different values of i, implying that the length of the lag used for calculating the decoupling factor has a minimal impact on the long-term results. However, we do not consider in our paper the political economy associated with the selection of i.

The Kern County parameters resulted in the same behavior, despite the difference in geological and economic characteristics. Therefore, we hypothesize that the policy intervention results are robust and may be extended to other aquifers.

Sensitivity Analysis

We analyzed the model's sensitivity to variation in electricity price. As expected, the model displays trends typical to a normal good, with a downward sloping annual net benefit when ξ increases, and a downward sloping water extraction with an increase in ξ. This is consistent with the behavior of the depth to the water table, where we observe that the aquifer becomes deeper as electricity prices decrease.

Policy Implications

The econometric analysis performed by Muñoz et al. (2006) suggested that a 100% increase in the price of electricity leads to a decrease of 16% in the amount of water pumped from the aquifers. These results, along with the analytical results, suggest that changes in the subsidy lead to a reduction in the aquifer water pumped by farmers. Given the political power and strong lobby the farmer organizations have, it is politically infeasible to simply eliminate the subsidy. Thus, we propose a different policy alternative to address this problem with lower social/political cost.

Moreover, as discussed earlier, changes in the institutional arrangements are costly (both politically and economically), slow to implement, and, in many cases, irreversible. Our simulation results give rise to the hypothesis that decoupling is a feasible policy modification for achieving the stabilization of the over drafted aquifer.

Decoupling would have similar effects as drastically reducing or eliminating the subsidy would, but without the political burden that the latter policies implicate. While these results are based on computer modeling and simulations, the hypotheses drawn from such results may be tested experimentally to strengthen the conclusions drawn from the theoretical results and generate better policy recommendations.

Appendix A

Table I.1A

Parameters Used in Simulations for Leon, Guanajuato, Mexico

Parameter	Value	Units
ξ	2.722	Thousands of pesos /1 million m^3/m
$\bar{X}$	550	meters
α	0.95238095	-
g	490.39	pesos/m^3
k	85.81	pesos/m^3
β_{dp}	0.2	-
β_{sw}	0.3	-
q_{sw}	1.43	millions m^3
A	7.07	million m^3
γ	$[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]$	-
S	0.13	-
R	1.56	millions m^3/year
Max depth	-126	meters

Note. Copyright 2009 and 2011 by Comisión Nacional del Agua and 2006 by Muñoz et al.

Table I.1B

Parameters Used in Simulations for Kern County, California.

Parameter	Value	Units
ξ	0.13	USD/acre-feet/foot
$\bar{X}$	385	Feet
α	0.95238095	-
g	146.9	USD/acre-feet
k	27.66	USD/acre-$feet^2$
β_{dp}	0.2	-
β_{sw}	0.3	-
q_{sw}	1.9	Millions acre-feet
A	1.29	Million acres
γ	$[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]$	-
S	0.13	-
R	0.052	Millions acre-feet/year
Max depth	-233	Feet

Note. Copyright 1983 by Feinerman and Knapp.

Groundwater and Electricity Consumption under Alternative Subsidies: Evidence from Laboratory Experiments

Abstract

Pervasive energy subsidies for groundwater pumping pose a challenge to policy makers around the world who cope with lower water tables due to increased reliance on groundwater resources for irrigation. This paper outlines a series of laboratory experiments aimed to study the groundwater extraction decisions of stakeholders under alternative subsidy structures. We propose a model and a methodology for testing the implications of the model and the modification of energy subsidies for irrigation. We analyze the performance of two traditional policy interventions—elimination and reduction of subsidy—then analyze a novel policy: decoupling the subsidy from the electricity rate by replacing it with a lump sum transfer. Our results suggest that the rate of water extraction and the level of water in the aquifer, which are undesirable under the existing electricity subsidy, can be significantly improved by altering the subsidy structure. An important finding for policy makers is that the decoupling leads to outcomes similar to those of eliminating the subsidy.

Keywords: Groundwater; Experimental Economics; Energy Subsidies

JEL Codes: Q5, Q2, Q25, C9, C92

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Introduction

Common pool resource (CPR) dilemmas have been studied extensively in the environmental, biological, and social sciences. In his influential paper, Hardin (1968) argued that the only possible outcome for selfish individuals who attempt to maximize their expected utility is the collapse of the commons. Traditionally, the two major solutions aimed at address his conclusion have been the assignment of property rights and the imposition of government regulations (Ostrom, 1990).

As a CPR, groundwater is subject to these solutions. Governments and policy makers around the world have been attempting to address overexploitation of aquifers while simultaneously guaranteeing quality supply of this resource. Too often they have not been successful. Several misguided or poorly designed policies have exacerbated the tragic outcome prophesized by Hardin (1968) by providing incentives that cause users to increase their extraction of groundwater. This has been the case of subsidies for energy used to pump groundwater; the artificially reduced cost of pumping water has fostered the overexploitation of aquifers and exacerbated the negative externality generated by their users.

Reforms in the water and energy sectors often are economically costly and difficult to implement politically. Generating methods of testing reforms in a reliable, replicable way helps provide insight into the potential results of their implementation. Experimental economics provides procedures for analyzing these policy and institutional changes in a cost-effective way (Murphy et al., 2000).

This paper analyzes the impact of eliminating, reducing, and decoupling the subsidy for electricity from the demand for groundwater. It derives testable hypotheses, then chooses parameters for testing these hypotheses on the basis of the results from the simulations proposed in Tellez Foster et al.'s (2016a) study. Our approach calls for implementing a CPR dilemma game in the laboratory, where participants make a series of intertemporal production decisions (the amount of water pumped for agricultural production) and subsequently receive monetary payoff contingent on the water table level. The pumping costs are negatively related to the height of the water table so that the more water is pumped, the deeper the water table becomes, and the more electricity is required for pumping, therefore increasing the pumping costs.[2] The water table level lags for one period so that the players face an intertemporal optimization problem.

Our experiment is similar to the one introduced by Fischer et al. (2004), who used a growth model to simulate the rate of regeneration of the resource. Fischer et al. (2004) include four generations of three subjects each. Our experiment differs because it includes the same subjects in all periods, and the resource stock in period t depends on the stock level in period t-1. The model used to predict the subjects' strategies is similar to the one proposed by Salcedo et al. (2013), who introduce a dynamic optimization model that sums the present value of net benefits over several periods of time, and where the equation of motion describes the height of the water table that depends on the collective action of the users and the height of the water table in the previous period.

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[2] Since we are only interested in the amount of revenue from irrigation water, the payoff does not depend on the production level. Extensions of the model could include production level, type of crop, and price of crops as alternate determinants of water consumption.

Suter et al. (2012) developed a dynamic model that includes spatial relations based on the position of the wells and their implications for the exploitation of groundwater. They include physical and geological relations to ensure that the model is as realistic as possible. Our study accounts for the changes in behavior when the users face various increases in the price for electricity, which are compensated by a monetary transfer or a subsidy of another kind.

Literature Review

A substantial body of literature explores CPR problems from the experimental economic perspectives. This is because changes in the management of such resources are costly, slow, and, in many cases, irreversible. Therefore, experimental economics provide policy makers with sound and robust evidence that might give rise to changes in policy toward more effective management of such resources.

Fischer et al. (2004) asked four generations of subjects to extract water from a CPR with a known regeneration rate. They concluded that subjects generally expected other participants to extract less, and that there was always a temptation to free ride. On the other hand, Suter et al. (2012) explored the relationship between the decisions made by stakeholders on the amount of groundwater extracted when the physical characteristics of an aquifer are taken into consideration. They reported that when farmers realize that the effects of exploiting the aquifer (social costs) exceed their own private costs (due to the cone of depression created by pumping), they tend to approach the optimal extraction rate. Ward et al. (2006) compared results from the lab and the field in a groundwater extraction experiment and reported that the results were comparable in both cases. Their study is relevant to our research because it compares the effects of a policy manipulation with subjects in the lab and stakeholders in the field. Botelho et al. (2014) analyzed the effect of time and uncertainty in CPR dilemmas, finding that across all treatments, CPR users make decisions that lead to the depletion of the resource (or terminate the game immediately). In another study, Botelho et al. (2012) examined how property rights and the provision of public goods affect the depletion rate of CPR, finding that appropriation and the option of contributing to the preservation of the common resource are substitutable actions for reducing the rate of destruction of the CPR and may explain the emergence of tacit cooperation in the common resource dilemma.

Murphy et al. (2000) conducted a series of experiments with highly sophisticated software that calculated in real time the equilibrium prices and allocations for trade in water rights. These experiments were designed to test the mechanism of "smart" water markets that could achieve efficiency and the highest benefits from trading using technology. Their conclusions stated that the design of water markets with the aid of technology could help achieve efficiency at a reasonable cost.

These studies did not explore the effects in subjects' behavior when subsidies for extraction are modified in a CPR dilemma context. Our proposed experiment is designed to study how agents make extraction decisions based on the level of subsidy to electricity for pumping groundwater. This implies that the cost of extracting groundwater varies not only according to the water table but also according to the subsidy mechanism in each treatment.

A Model for Groundwater Extraction

The model considered in this section builds off the model of Provencher and Burt (1993), and the functional form of the profit function builds off that of Salcedo and Gutierrez (2013). The aquifer considered here is boxed-shaped, and the pumping cost function is linear in height of the water table as the state variable. The farmers (players) are assumed to be homogenous with a single crop and same-sized farm.

The benefit function for pumping groundwater for farmer *j* at period *t* is:

$$B_{jt} = \delta u_{jt} - u_{jt}\left[\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}\right] - C_0 \ , \qquad (1)$$

where δ is the constant marginal product of water extracted, u_{jt}, by farmer *j* at period *t*; γ is the subsidy to electricity for pumping groundwater; P_E is the price for electricity; and ξ is the amount of electricity required to pump one cubic meter of water to a height of one meter. As mentioned earlier, the cost function is linear in height of the water table following the modification of Provencher and Burt (1993) made by Salcedo and Gutierrez (2013). In our model, $\bar{X}$ is the maximum height of the aquifer; x_t is the height to water table at period *t*; A is the area of the aquifer; S is the storativity; and AS is the volume of the aquifer available for storing water. C_0 is the fixed cost of pumping; it is generally associated with installing and maintaining pumping equipment.

The equation that relates users' behavior at period *t* with the pumping conditions in the next period is given by:

$$x_{t+1} = x_t + \frac{\sum_{j=1}^{N} u_{jt} - R}{AS}, \qquad (2)$$

where the height of the water table in the next period, x_{t+1}, is equal to the current height plus the amount of water pumped in the current period $\sum_{j=1}^{N} u_{jt}$, minus the recharge rate R, all divided by AS.

The model maximizes the present value of net benefits (profits) over an infinite period horizon. Two types of users are considered independently: a myopic user, who does not take into account the cost his or her actions impose on other users or on personal future profits; and a strategic user, who makes an extraction decision based on the other users' actions.

Myopic users are assumed to adopt the common property strategy; they are called *myopic* because they choose to pump the maximum amount of water as long as the benefit of doing so is positive. Therefore, the myopic user strategy, u_{mt},[3] is represented by:

$$u_{mt} = \begin{cases} \overline{u_t} & when \quad x_t \leq \bar{X} - \frac{\gamma P_E \xi}{AS\delta} \\ 0 & \qquad otherwise \end{cases}, \qquad (3)$$

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[3] The subscript *m* represents the myopic user.

where $\overline{u_t}$ is the maximum amount of water per period that the myopic user pumps as long as the condition $x_t \leq \bar{X} - \frac{\gamma P_E \xi}{AS\delta}$ is satisfied.

The behavior of the strategic user may be described by the dynamic optimization problem:

$$\max_{u_t} \sum_{t=1}^{\infty} a^t J \left[\delta J u_t - u_t \left(\frac{\gamma P_E \xi}{(\bar{X} - x_t)AS}\right)\right] - C_0$$

$$s.t. \qquad \begin{matrix} x_{t+1} = x_t + \frac{Ju_t - R}{AS} \\ x_t + \frac{Ju_t}{AS} \leq \bar{X} \end{matrix} ,$$

where *J* is the number of users extracting groundwater from the aquifer.[4]

We then write the Bellman equation:

$$V(x_t) = \max_{u_t} \left[J\delta u_t - u_t \left(\frac{\gamma P_E \xi}{(\bar{X} - x_t)AS}\right) - C_0\right] + \alpha V[x_{t+1}].$$

The Bellman equation breaks down the infinite horizon problem into a two-stage discounted function that we use to derive the optimal path of extraction.

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[4] Given that we previously assumed that all farmers are homogenous, the subscript *j* is dropped.

From the Bellman equation we can derive the first order conditions that yield the following Euler Equation:

$$J\delta - \frac{\gamma P_E \xi}{(\bar{X}-x_t)AS} = -\alpha \left[\frac{Ju_{t+1}}{(\bar{X}-x_{t+1})AS} - \frac{J\delta - \left(\frac{J\gamma P_E \xi}{(\bar{X}-x_{t+1})AS} \right)}{\frac{J}{AS}} \right] \frac{J}{AS} .$$

The Euler equation is used to derive the optimal path of extraction. In our equation, systematically increasing the value of gamma from 0 to 1 increases the cost in the present, $\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}$, but also increases the marginal (discounted) benefit in the future, $\frac{J\delta - \left(\frac{J\gamma P_E \xi}{(\bar{X}-x_{t+1})AS} \right)}{\frac{J}{AS}}$. Therefore, we may anticipate that changes in the subsidy will lead to a deviation in the optimal extraction path that, in turn, will further lead to a better steady level of the state variable.

We tested the behavior of the model under status quo conditions ($\gamma = 0.2$, meaning a subsidy level of 80%), using parameter values from Salcedo and Gutierrez (2013) and the MATLAB package CompEcon by Miranda and Fackler (2002). The results are exhibited in the next set of graphs:

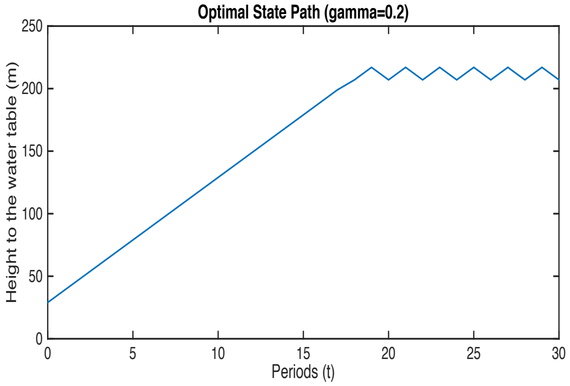

Figure II.1. Optimal value function and optimal state path under status quo.

Figure 1 shows that the height of the water table increases and reaches a steady state around period 20, then continues *zigzagging* across the remaining periods. This zigzagging occurs because users switch on each period from the maximum extraction level to zero because the recharge rate makes it profitable to extract groundwater on every other period after the steady state is reached.

Policy Interventions

This section moves beyond analyzing users' behaviors when given an electricity subsidy for pumping groundwater to examine the effects of three different policy interventions: the elimination, reduction, and decoupling of the subsidy. To analyze the first two, we simulate the users' response by varying the value of γ from 0 to 1 in increments of 0.1. For this analysis, we use the parameters in the study by Salcedo and Gutierrez (2013) of users' behavior to pumping groundwater in the region of Aguascalientes, Mexico. We also use the CompEcon toolbox for MATLAB developed by

Miranda and Fackler (2002). The model in our analysis was simulated for 100 periods, varying the parameter γ from 0 to 1 in 0.1 increments.

Figure 2 indicates that the steady state of the height of the water table increases as the level of subsidy increases. This suggests that the subsidy to electricity influences the amount of water pumped from the aquifer, resulting in deeper steady state levels for higher rates of subsidy.

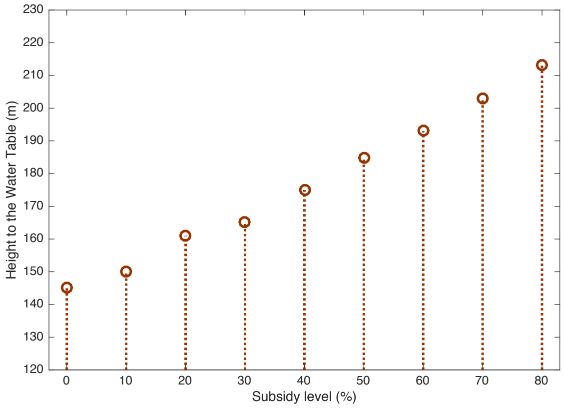

Figure II.2. Height of the water table for different subsidy levels.

Figure 3 shows the level of the steady state for three different levels of gamma. The highest levels of subsidy again lead to deeper levels of the water in the aquifer; furthermore, the time of convergence to the steady state is longer for higher levels of subsidy.

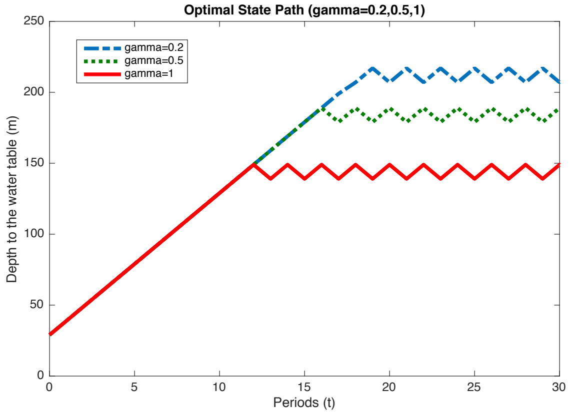

Figure II.3. Optimal state path for different values of gamma.

One of the most relevant aspects to policy makers is finding out which policy achieves a shallower steady state in the shortest time possible. Figure 4 demonstrates how many periods must pass to achieve the steady state at each level of the subsidy.

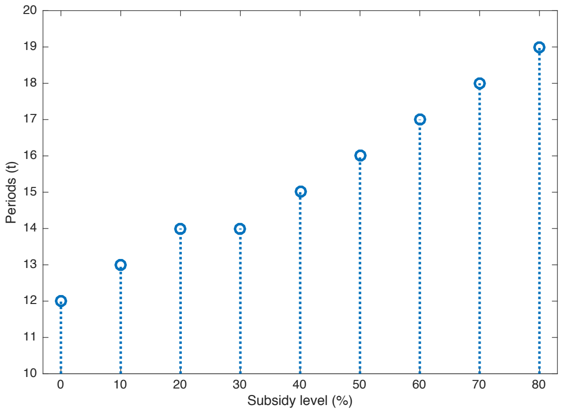

Figure II.4. Time of convergence to steady state.

The third policy instrument is the decoupling of the subsidy from the electricity price. In this case, users receive a transfer equivalent to their consumption during the last i periods.[5] The optimization problem in this case is:

$$\max_{u_t} \sum_{t=1}^{\infty} a^t J\left[\delta J u_t - u_t\left(\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}\right)\right] - C_0 + \frac{\sum_{k=t-i}^{t} \frac{u_k \gamma P_E \xi}{(\bar{X}-x_k)AS}}{i}.$$

The Bellman equation takes the form:

$$V(x_t) = \max_{u_t}\left[J\delta u_t - u_t\left(\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}\right) - C_0\right] + \frac{\sum_{k=t-i}^{t} \frac{u_k \gamma P_E \xi}{(\bar{X}-x_k)AS}}{i} + \alpha V[x_{t+1}].$$

This optimization problem is similar to the one presented in last section, although here we include the decoupling to the electricity subsidy $\frac{\sum_{k=t-i}^{t} \frac{u_k \gamma P_E \xi}{(\bar{X}-x_k)AS}}{i}$, which is the mean consumption of the last i periods ($i > 0$).

As in the first optimization model, the Bellman equation is used to derive an Euler equation that sheds light on how the behavioral responses to changes in the subsidy affect the optimal path:

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[5] The number of periods considered for calculating the mean consumption is *i*; it ranges from 1 to *t*-1 for all *t*>2.

$$J\delta - \frac{\gamma P_E \xi}{(\bar{X}-x_t)AS} + \frac{\gamma P_E \xi x_t}{i} = -\alpha \left[\frac{J u_{t+1}}{(\bar{X}-x_{t+1})AS} + \frac{\gamma P_E \xi u_{t+1}}{i} - \frac{J\delta - \left(\frac{J\gamma P_E \xi}{(\bar{X}-x_{t+1})AS} \right) + \frac{\gamma P_E \xi x_{t+1}}{i}}{\frac{J}{AS}} \right] \frac{J}{AS}.$$

This equation shows that the term $\frac{\gamma P_E \xi x_t}{i}$, which represents the marginal change in the decoupling transfer due to changes in the level of subsidy (γ), keeps the equation balanced, as it is added on both sides of the equation to the costs and benefits. Based on this, the behavior of the users under decoupling is expected to either be the same or close to the behavior under the elimination instrument.

The hypothesis is that changing the incentives by either eliminating the subsidy or giving users a cash transfer decoupled from the subsidy results in a decrease in the amount of water pumped and in a higher steady state level of the water table.

The results portrayed in Figure 5 represent a comparison between status quo, subsidy reduction from 80% to 50% rate, and 15 periods for calculating the mean decoupling factor. Decoupling accomplishes a steady state of the height to water table that is lower than reducing the subsidy to 50%. These results suggest that decoupling is a viable policy intervention.

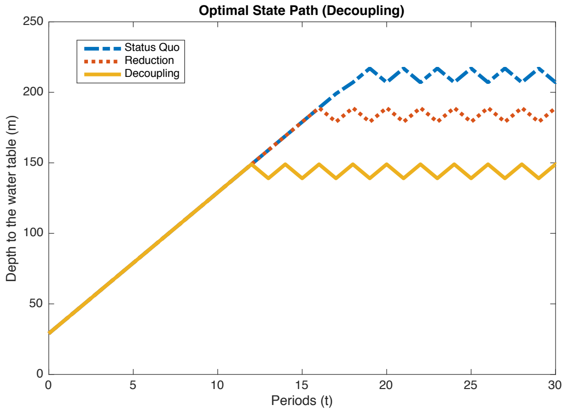

Figure II.5. Optimal state path for different policy interventions.

The optimal strategy for myopic users is to extract the maximum amount of water possible (we set a limit of 10 units) until it is no longer profitable. Figure 6 exhibits the extraction path for the cases of decoupling and status quo (elimination and reduction follow the same path as decoupling because myopic users care only about maximizing the current period profit).

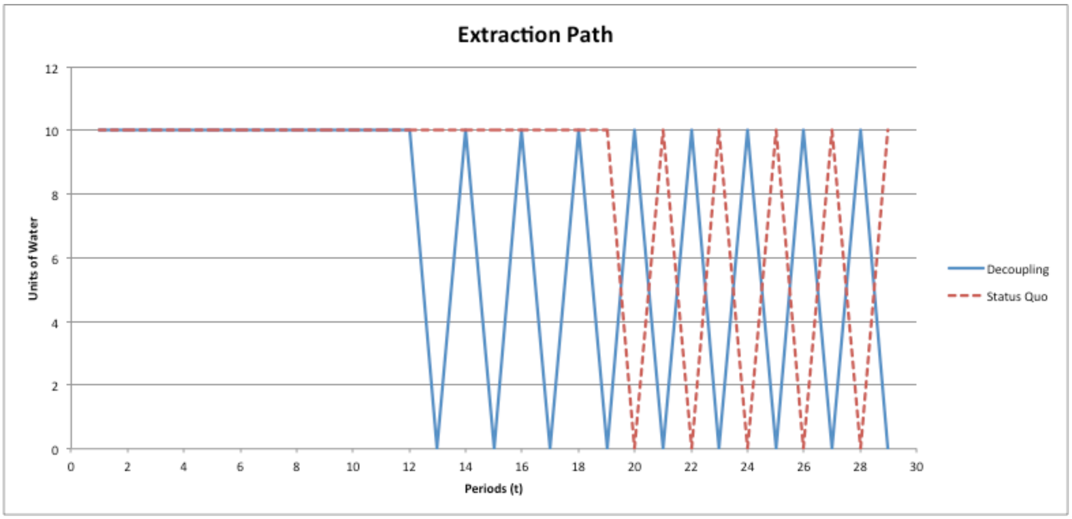

Figure II.6. Extraction path comparison: Status quo vs. decoupling.

The behavior exhibited in Figure 6 demonstrates why the steady state of the height of the water table fluctuates over periods. After a specific height is reached, extracting water is no longer profitable however, the recharge rate makes extraction profitable again in the next period.

Laboratory Experiments

We tested the analytical results in the laboratory. To ensure robustness and statistical power of the experiments, we recruited for each of the four conditions five groups of six members each for a total of 120 subjects. All the subjects for each of the three policy interventions first played the status quo game (Condition 1), then proceeded to play the policy intervention (reduction, elimination, or decoupling). The control groups played status quo in both parts of the experiment.

The subjects were randomly assigned to groups. No communication was allowed during the experiment.

The experiments were conducted in a large laboratory. Subjects were seated in individual cubicles that prohibited communication. They were recruited through an automated online system from a pool of all undergraduate students at the University of California Riverside (UCR); none of the students had participated in similar experiments before. Sessions lasted no longer than two hours, including check-in and payment time. The procedures for the five conditions are summarized below.

Condition 1: Status Quo (No Changes to the Subsidy)

Subjects playing the status quo were instructed to request an amount of water to be pumped from the aquifer. The water table level at the beginning of each period was commonly known by the group members. Subjects were provided with a schedule that listed the profits for each combination of height of the water table and the set of possible requests. Once they submitted their requests, the subjects proceeded to the next period, where they were informed of the new height of the water table. The extraction game had an infinite horizon; each round was terminated randomly, with probability p set at $p = 0.15$[6], or continued for at least one more period, with the complementary probability of 0.85. At the end of the session, subjects were paid contingent on their performance (profits were given in tokens).

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[6] This is following the experimental procedure for infinite horizon used by Suter et al. (2012).

Condition 2: Reduction of Subsidy

Subjects playing reduction were instructed to request an amount of water to be pumped from the aquifer. They faced a reduction in the amount of subsidy (from 80% to 50% of electricity price subsidized). As in Condition 1, they were informed of the height of the water table and the profit conditional on the aggregate request.

Condition 3: Elimination of Subsidy

Subjects performed the same task as that of Conditions 1 and 2, with the same per period termination probability of 0.15. For this condition, the subsidy was removed completely (setting $\gamma_t = 1$).

Condition 4: **Elimination of Subsidy and Transfer of Payment (Decoupling)**

In Condition 4, the subjects performed the same task as that of Conditions 1 and 2. However, after 15[7] consecutive periods, they were told that the subsidy would be removed (setting $\gamma = 1$), that their individual mean subsidy would be calculated, and that they would be granted a token transfer equivalent to the subsidy they received during the first 15 periods of the first part (Condition 1).

Condition 5: Control

In Condition 5, the subjects performed the same task as in Condition 1. After the random termination of Part 1, they proceeded to play the same game as under Condition 1 with the same subsidy level ($\gamma_t = 0.2$) until it was terminated randomly. This condition

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[7] We used 15 periods to reduce bias for periods of high requests or low requests, as explained in Tellez Foster et al. (2016)

was conducted to gather data on subject behavior under no treatment to establish a baseline for comparing and calculating the treatment effects of the previous three treatments.

Results

We compare below only the results of Condition 1 with the policy treatment conducted in each of the other conditions; we do not compare the status quo results across conditions due to the different characteristics of each group being exposed to status quo and to the treatment. Determining the difference in technique entails comparing groups both pretreatment and posttreatment, but does not require a cross-comparison between pretreated and post-treated groups.

Elimination

For the elimination condition, we recruited 30 undergraduate students to form five groups of six members each. Subjects read the instructions at their own pace. This was followed by a brief oral summary and a short question-and-answer period. This same procedure was implemented for all conditions.

In this subsection, we compare group results for the status quo and elimination conditions. Figure 7 exhibits the mean total requests of the groups who played these two conditions. It demonstrates that as subjects adapt to the policy change in periods 1–3, they play the strategy that they used consistently in Part 1 of the experiment (status quo condition). As they realize that pumping becomes more expensive, they lower their requests consistently.

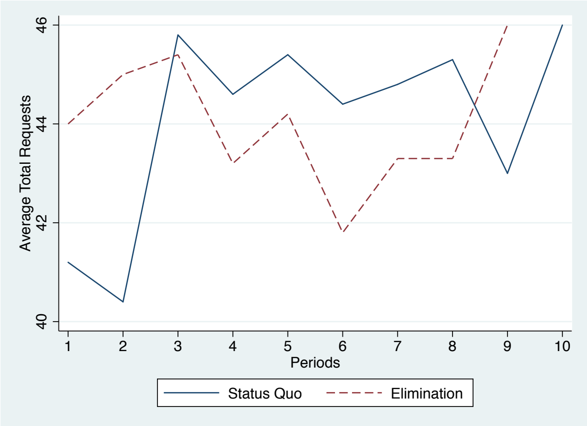

Figure II.7. Mean total request by group. Condition: Elimination.

Figure 8 displays the mean height of the water table across groups. The mean height of the water table in status quo condition is consistently but slightly lower up to the 7th period. In the last two periods this trend is reversed, and the height of water table for the elimination condition stabilizes, whereas the one for the status quo condition accelerates.

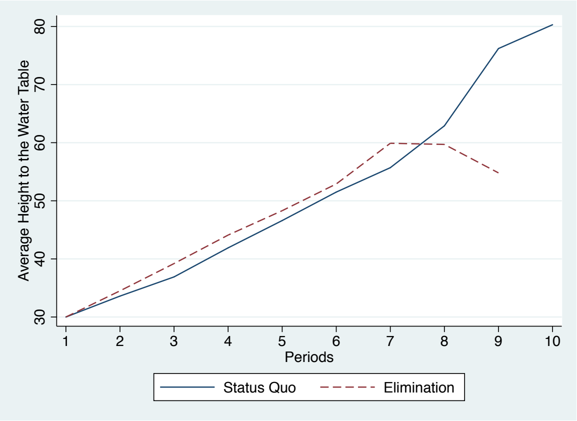

Figure II.8. Mean Height of the water table. Condition: Elimination.

Reduction

The subjects in the reduction condition performed the same task they completed for Condition 1, except in this case, they faced a reduction in the subsidy from 80% to 50% (changing $\gamma = 0.2\ to\ \gamma = 0.5$).

Figure 9 illustrates the mean request for the status quo and reduction conditions. With the exception of round 9, mean requests across groups for the status quo condition were relatively stable across periods, ranging from 44 to 50. In contrast, subjects in the reduction condition increased their requests steadily across the 13 periods, from 36 to 55.

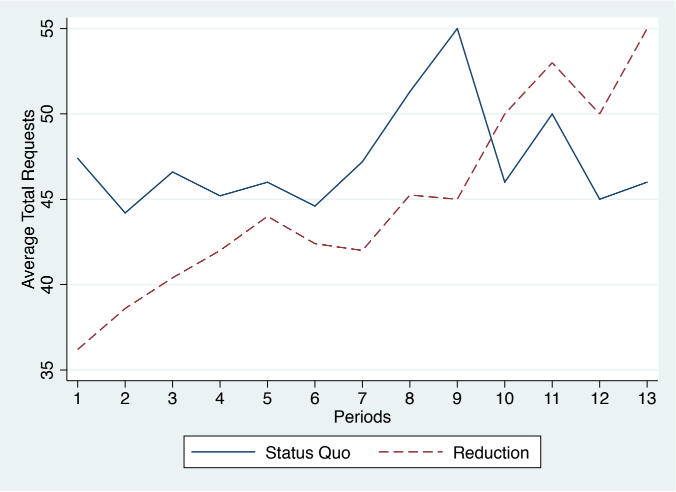

Figure II.9. Mean Total Requests per Group. Condition: Reduction

The effect of the change in policy is displayed in Figure 10. The mean height of the water table across groups is consistently lower in the reduction condition compared with the status quo condition, although the difference between these two conditions never exceeds 11 meters.

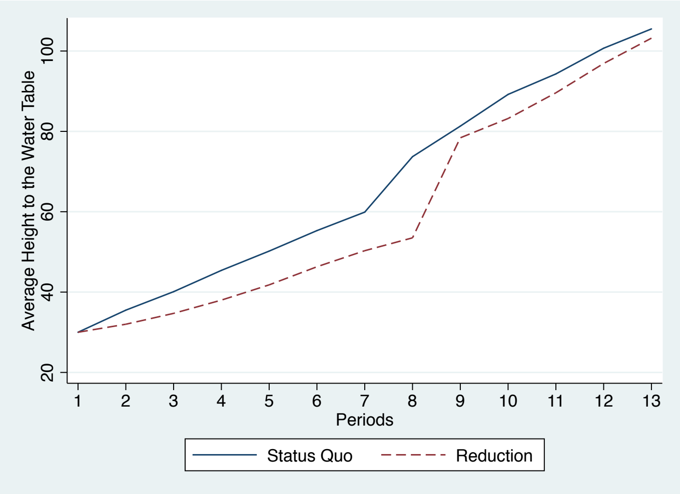

Figure II.10. Mean height of the water table. Condition: Reduction.

Decoupling

The procedure in the decoupling condition was similar to the procedure in the previous two conditions. The major exception was that the requests were recorded, and at the end of period 15 (Part 1 of the experiment), the mean cost was computed, and each subject was informed that the subsidy had been removed and replaced by a token transfer (lump-sum subsidy). The token amount was equivalent to the mean individual request in Part 1 of the experiment; it was granted at the end of each subsequent period in Part 2, regardless of the requests in Part 2 of the experiment.

The effect of decoupling the subsidy is the strongest among all conditions; we observe in Figure 11 that the average request per group is significantly lower once the subsidy is decoupled. This is reaffirmed when we observe the behavior of the height of the water table in Figure 12, where it is evident that once the subsidy is decoupled, the pace at which the aquifer becomes deeper decreases, creating a gap between the height of the water table under status quo and decoupling.

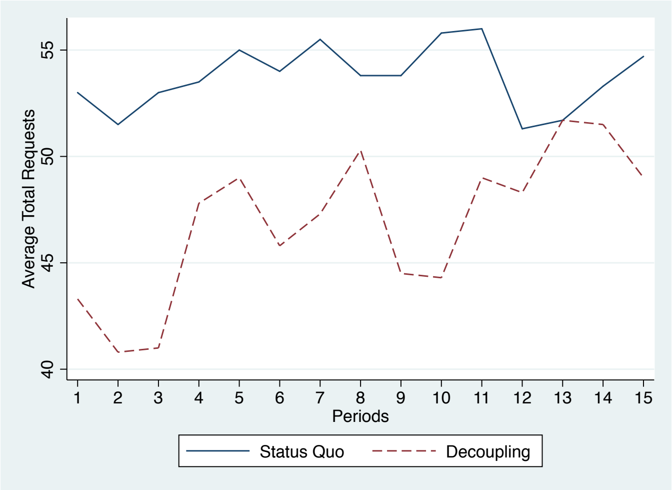

Figure II.11. Mean total requests per group. Condition: Decoupling.

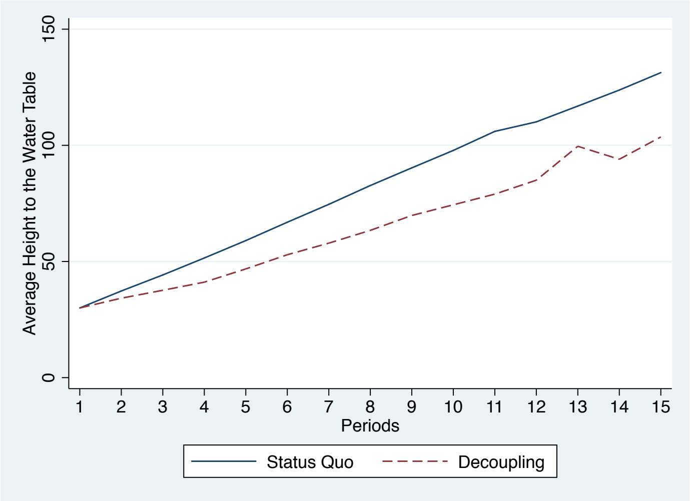

Figure II.12. Mean height of the water table. Condition: Decoupling.

Control

For comparative purposes, we also ran a control experiment in which students played the status quo condition in both parts, using the same procedure as in the previous conditions demonstrated in Figures 13 and 14. The results suggest that subjects tend to play more aggressively in the second part of the experiment, when they have a better understanding of how to play. The observations of this experiment allowed us to capture any unobservable variable that may affect the requests so we can calculate more accurately the treatment effect.

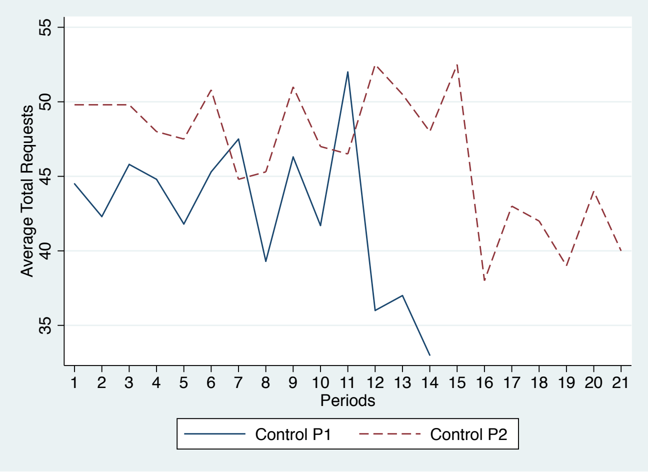

Figure II.13. Average total requests per group.

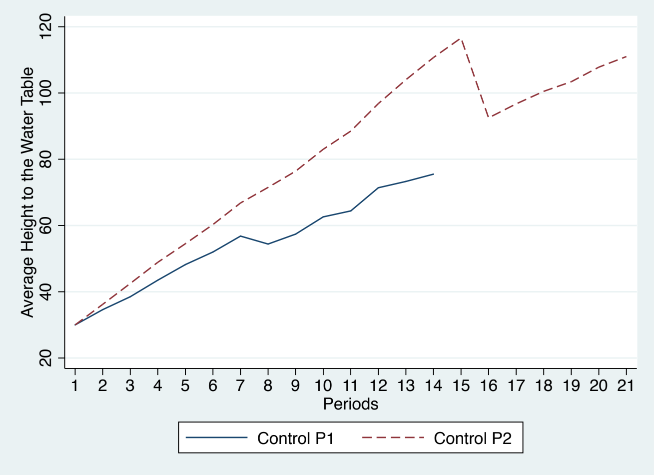

Figure II.14. Average height of the water table.

Effectiveness of the Policy Interventions: An Econometric Analysis

In this section we analyze the treatment effect of each condition, provide a quantitative analysis of the behavior of participants under different conditions, and use the results as a base for drawing policy implications. For the purpose of this experiment we will use the difference in differences method since it allows us to compare the difference in extractions under the different conditions.

The difference in differences estimation method is a common technique in the literature. It determines the effect of treatment across individuals with similar characteristics and uses counterfactual scenarios to observe the behavior of individuals who have not received the same treatment and compare it to that of the individuals who did.

This technique has been used widely in the economic literature. In a milestone study, Card and Krueger's (1994) estimated the effect of employment after the increase in minimum wage in New Jersey.

We chose the difference in differences method to compare the effectiveness of the policy interventions. We estimated a series of econometric models in an attempt to capture the quantitative effect change in subsidy level has on requests for water. To ensure sound and robust estimations, we repeated this process 1,000 by bootstrapping from a uniform distribution for the random drawings. We then estimated the effects of treatment using the following model:

$$\Delta w = \beta_1\, Pretreatment + \ \beta_2\, Posttreatment + \beta_3\, Interaction\ term\ (pre * post)$$

where Δw is the change in the requests for water after the treatment is applied, β_1 is the estimator for the status quo (Pretreatment) condition, β_2 is the treatment estimator and β_3 is our relevant estimator where we obtain the final effect of the treatment.

We present the estimations for the three treatments in three separate tables:

Table II.1

Treatment Effect Estimation. Condition: Elimination

Number of observations in the Diff-in-Diff: 1032

	Baseline	Follow-up	
Control:	246	318	564
Treated	234	234	468
	480	552	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	7.264			
Treatment (T)	7.333			
Diff (T-C)	0.069	0.249	0.28	0.781
Follow-up				
Control (C)	8.041			
Treatment (T)	7.321			
Diff (T-C)	-0.720	0.235	-3.07	0.002***
Treatment effect	-0.789	0.342	-2.31	0.021**

Inference: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

Table 1 shows that the sign of the treatment effect is negative and statistically significant as expected, revealing that eliminating the subsidy reduces the requests by 0.789 units of water per individual, on average, for each period. Even though the effect is small, it is the cumulative effect of each diminished request that yields a better outcome as compared with the status quo condition.

Table II.2

Treatment Effect Estimation. Condition: Reduction

Number of observations in the Diff-in-Diff: 1086

	Baseline	Follow-up	
Control:	246	318	564
Treated	258	264	522
	504	582	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	7.264			
Treatment (T)	7.810			
Diff (T-C)	0.546	0.226	2.41	0.016**
Follow-up				
Control (C)	8.041			
Treatment (T)	7.053			
Diff (T-C)	-0.988	0.211	-4.68	0.000***
Treatment effect	-1.534	0.309	-4.96	0.000***

Inference: *** p<0.01; ** p<0.05; * p<0.1

In the reduction treatment, Table 2 indicates a stronger effect when compared to the control group. In this case, we observe that the subjects reduce their request on average by 1.534 units per period. This result does not coincide with our initial prediction, where the reduction condition treatment effect seemed smaller as compared to the other two conditions; however, the sign is negative, as expected, and statistically significant.

Table II.3

Treatment Effect Estimation. Condition: Decoupling

Number of observations in the Diff-in-Diff: 1224

	Baseline	Follow-up	
Control:	246	318	564
Treated	336	324	660
	582	642	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	7.264			
Treatment (T)	8.979			
Diff (T-C)	1.715	0.195	8.79	0.000***
Follow-up				
Control (C)	8.041			
Treatment (T)	7.741			
Diff (T-C)	-0.300	0.183	-1.64	0.10*
Treatment effect	-2.015	0.268	-7.53	0.000***

Inference: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

The decoupling treatment (Table 3) yielded the greatest effect among all conditions, with a reduction in the average request per subject of 2.015 units. This result indicates that subjects reacted more forcibly to decoupling the subsidy than to its reduction or elimination. This result may be explained by a behavioral change to a more conservative strategy after receiving the transfer lump-sum every period.

Conclusions and Policy Implications

This paper analyzes the effects of subsidy structures and policy modifications on sustainability of groundwater, given the perverse incentives of electricity subsidies for groundwater pumping in the farming sector. By embedding the subsidy into the cost function, we measured the effect of different policy interventions. Our analysis gives rise to several conclusions that are reported below with respect to various institutional arrangements and policy interventions.

Comparing Predictions with Experimental Results

By comparing the observed behavior of the subjects to the predicted behavior, we find that all three policies have a negative effect on the water requests; however, decoupling the subsidy produces the strongest effect among the three, which supports our hypothesis that this intervention method yields the most desirable results.

Despite the theoretical predictions indicating that elimination and decoupling would produce similar effects, we found that elimination sustained the least effect among the three conditions. This may be due to the more conservative strategy the subjects adopted during the first part of the experiment, which captured a smaller effect when compared to reduction or decoupling the subsidy.

In the Reduction condition, subjects chose a more aggressive strategy in the first part of the experiment, and when they faced a reduction in the subsidy, they took a more conservative approach. The group’s behavior across treatments was different when playing Condition 1: Some groups acted more conservatively in the first part of the experiment, as demonstrated in the Elimination condition, while other groups acted in a more aggressive manner, as in the Reduction and Decoupling conditions. This was a result of subject expectations of group behavior rather than experiment design.

Policy Implications

The joint results of the simulations and experiments suggest that farmers may reduce water pumping when the subsidy is modified by reduction, elimination, or decoupling. The importance of this finding is that, given the political power that farmer organizations bear and the strong lobby they mobilize, it is politically infeasible to eliminate the electricity subsidy. We propose a different policy alternative to address this problem with lower social/political cost. Our results support the conclusion that decoupling is a feasible policy modification for achieving the stabilization of over drafted aquifers. In addition, decoupling would have similar effects as drastically reducing or eliminating the subsidy, with a much lower political burden than the latter policies implicate.

Alternative Policies to Manage Electricity Subsidies for Groundwater Extraction: A Field Study in Mexico

Abstract

We designed a series of field experiments to study the behavior of farmers under alternative electricity subsidies for extracting groundwater. Users' water pumping decisions are based on the price of electricity, level of subsidy, and height of the water table. The paper opens with a brief description of common pool resource dilemmas and the value of field experiments in the analysis of such issues. It then describes the model used to draw predictions. We analyze the theoretical effectiveness of three policy interventions: elimination, reduction, and decoupling—an innovative policy that substitutes the electricity subsidy for a cash transfer. Results from the experiments conducted in the city of León, Guanajuato, México, suggest that all three policy interventions sustain positive effects on the pumping level: Elimination has the largest effect, whereas reduction results in only a marginal effect on the rate of water extraction. Decoupling proves to be a viable policy, as it produces an effect similar to elimination while avoiding political and social damage. We then compare these results with lab experiments conducted in the United States.

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Introduction

Most natural common pool resource (CPR) dilemmas are intertemporal and subject to environmental uncertainties. Examples include groundwater, fishery resources, and climate change, all of which are dynamic in size and duration. CPR size may change over time in part as a function of previous user appropriation (Bailey et al., 2010; Barrett & Dannenberg, 2012; Koundouri, 2004). The uncertainty about the duration of the dilemma may be endogenously or exogenously determined, or both. The analysis of strategic behavior in the face of environmental uncertainty traditionally has been conducted under the assumption of single-period interaction (e.g., Budescu, Rapoport, & Suleiman, 1995; Rapoport & Suleiman, 1992), whereas the analysis of strategic behavior in time-dependent settings has ignored environmental uncertainties altogether. Dynamic models, which integrate these two dimensions, have been proposed and tested experimentally by Herr, Gardner, and Walker (1997), Mason and Phillips (1997), and Botelho, Dinar, Pinto, and Rapoport (2015).

Our proposed study of groundwater extraction in a dynamic setting differs from previous studies in three ways. First, the intertemporal uncertainty we embed in the CPR setting concerns the duration of the groundwater game rather than the size of the common pool (which is determined exogenously in our study). Second, rather than focusing exclusively on laboratory experiments, we propose conducting both a laboratory study in the United States and a comparable field study with farmers in Mexico. The third and most important difference is that our study is heavily policy oriented. It intends to examine the behavioral responses of profit-maximizing users, whether these are students volunteering for CPR laboratory experiments or farmers regularly pumping groundwater for irrigating their fields, to the proposed systematic modifications of the electricity subsidy mechanism for groundwater extraction.

Electricity subsidies for pumping irrigation water is common in many countries around the world (Shah, 2009, p. 148–150). In Mexico, the focus of the present study, a total volume of 29.5 km^3 is extracted annually from groundwater resources. Of this amount, 70% is used in irrigated agriculture. The Mexican government decided in the early 1990s to provide a subsidy, Tarifa 09, for electricity used in pumping water for irrigation. The subsidy (pesos/KwH) is provided to farmers based on electricity used. The subsidized pumping cost has led to mismanagement practices and lack of appropriate irrigation technology, causing 101 out of the 188 major aquifers in Mexico to be over drafted (Muñoz et al., 2006). According to the Mexican National Water Law, water used for irrigation is not priced, so farmers have to pay for the cost of extracting groundwater from aquifers only. The current institutional framework with no price that reflects the scarcity value of the water pumped leads to inefficient exploitation of groundwater resources with high social damage.

The CPR dilemma has been studied using normative game-theoretical perspectives by introducing models developed to explain and predict social outcomes, given the environmental and institutional contexts. The dilemma also may be studied from the experimental perspective, in which the environmental and institutional contexts are simulated and the predictions of user behaviors (based on a normative model) are tested. There is a concern about conducting experiments in the lab since they restrict our sample to university students, who constitute a highly-selected group in terms of age, socioeconomic status, educational background, and experience. Therefore, variations between the results of controlled experiments in the laboratory and the results of field studies may exist due to differences in subject population, culture, and experience.

Several field experiments on CPR dilemmas have been conducted in the past, all of which are relevant to our work. The following paragraphs provide a brief review of these works.

Cárdenas (2011) addressed the importance of field experiments by conducting a series of experiments with a mixed population that mostly consisted of participants in the field but also of college students in the lab, where they participated in exact replications of the field experiments. His experiment addressed a common CPR decision problem with a negative externality in consumption. He found that behavior in both lab and field experiments did not change substantially, and any differences between the two subject populations that did occur were due to the fact that participants in the field and in the lab bring their own personal experience to the game. Cárdenas's (2011) comparison of subject populations in experimental and field studies illustrates the value of testing a policy change in the field with stakeholders, as this offers sound, replicable, and reliable insight into the policy's potential effects on convenience and cost effectiveness.

There exists a large body of literature on experiments in the field. Velez et al. (2005) explore exploitation of CPRs with a series of experiments in the field. They found that subjects balance self-interest and conformity in selecting the average strategy. Salcedo et al. (2013) conducted a series of experiments about how cooperation could help reduce the amount of groundwater pumped in the state of Aguascalientes, Mexico, and they found that differences between the theoretical predictions and the outcomes from the experiments exist due to the fact that some subjects act irrationally or take into account other factors that increase the costs of pumping. Cárdenas (2011) analyzed the social norms and behavior in CPR settings using data from field experiments that he conducted in Colombia, and Cardenas and Ostrom (2004) explored cooperation in common with experiments conducted in Colombia as well. The first compares results from field experiments with replications of the experiments conducted among students in a laboratory setting in Colombia. The general results suggest that differences in behavior may be accounted for in the subject's experience that is brought into the lab and influences decisions.

Ward et al. (2006) demonstrated the relevance of conducting experiments both in the field and in the lab. They claimed that the environmental and institutional conditions could lead to different results. They conducted lab and field experiments, evaluating different institutional arrangements for water administration, and concluded that different arrangements work better in the lab than in the field. Therefore, researchers must take into account different institutional arrangements, social norms, group reputation, and social connections to better translate experimental results into policy.

This study seeks to explore the effects of modifications to a subsidy mechanism on users' behavior concerning pumping rates, and, as a consequence, on the status of an aquifer over time. Using field experiments, this paper investigates how farmers change their behavior when they face policy interventions, including: complete elimination of the subsidy, reduction of the subsidy, and decoupling the subsidy from its volumetric nature and substituting it with a lump-sum subsidy calculated on the basis of the average subsidy received in a predetermined number of previous periods. The data collected from these field studies allow the evaluation of the impact the policy interventions have on the groundwater pumped from the over drafted aquifers, which should help in proposing the implementation of policies with stakeholder feedback.

Theoretical Model and Predictions

We follow the Tellez Foster et al. (2016b) model, in which an intertemporal optimization problem is presented with a dynamic equation of motion representing the height of the water table over time. Because a more detailed exposition of the model is presented in Tellez Foster et al. (2016b), we present below a reduced form of a normative model followed by theoretical predictions.

The benefit function below is based on the simplifying assumptions of a box-shaped bathtub aquifer shared by homogenous, single crop farmers; it is inspired by similar models introduced by Provencher and Burt (1993) and Salcedo and Gutierrez (2013). The benefit function for pumping groundwater for farmer *j* in time *t* is:

$$B_{jt} = \delta u_{jt} - u_{jt}\left[\frac{\gamma P_E \xi}{(\bar{X} - x_t)AS}\right] - C_0, \qquad (1)$$

where δ is the constant marginal product of water extracted u_{jt}, γ is the subsidy to electricity for pumping groundwater, P_E is the price for electricity, ξ is the amount of electricity required to pump one cubic meter of water to a height of one meter, $\bar{X}$ is the maximum depth of the aquifer, x_t is the height to water table in time *t*, A is the area of the aquifer, and S is the storativity. AS is the available volume of the aquifer that can store water, and C_0 is the fixed cost of pumping, generally associated with installing and maintaining pumping equipment, which, for simplifying purposes, are assumed as zero.

The motion equation of the water table is:

$$x_{t+1} = x_t + \frac{\sum_{j=1}^{N} u_{jt} - R}{AS}, \qquad (2)$$

where the height to the water table in the next period, x_{t+1}, is equal to the current height plus the amount of water pumped in the current period, $\sum_{j=1}^{N} u_{jt}$, minus the recharge rate R, all divided by the area multiplied by the storativity. The dynamic optimization problem for the entire aquifer is then described by:

$$\max_{u_t} \sum_{t=1}^{\infty} a^t J \left[\delta J u_t - u_t \left(\frac{\gamma P_E \xi}{(\bar{X} - x_t) AS} \right) \right] - C_0$$

$$s.t. \qquad \begin{aligned} x_{t+1} &= x_t + \frac{J u_t - R}{AS} \\ x_t + \frac{J u_t}{AS} &\leq \bar{X}, \end{aligned}$$

where *J* is the number of users in the aquifer.[8]

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[8] Given that we assumed previously that all farmers are homogenous, the *j* subscript is dropped.

This model was simulated to obtain predictions in three policy interventions (elimination: $\gamma = 1$, subsidy level of 0%; reduction: $\gamma = 0.5$, subsidy level of 50%; and decoupling: $\gamma = 1$, subsidy level of 0% and cash transfer equivalent to the average subsidy received in the previous i periods) using the parameters used by Salcedo and Gutierrez (2013) that are presented in Appendix A.

The following Bellman equation is derived from the above optimization model and is used recursively to simplify the optimization problem by breaking it down into a two-stage function that is used to calculate the optimal path of extraction:

$$V(x_t) = \max_{u_t}\left[J\delta u_t - u_t\left(\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}\right) - C_0\right] + \alpha V[x_{t+1}]. \qquad (3)$$

The first order conditions yield the following Euler equation:

$$J\delta - \frac{\gamma P_E \xi}{(\bar{X}-x_t)AS} = -\alpha\left[\frac{J u_{t+1}}{(\bar{X}-x_{t+1})AS} - \lambda\right]\frac{J}{AS}\,, \qquad (4)$$

where

$$\lambda = \frac{J\delta - \left(\frac{J\gamma P_E \xi}{(\bar{X}-x_{t+1})AS}\right)}{\frac{J}{AS}},$$

where we observe that changes in the value of $\gamma \rightarrow 1$the costs in the current period by increasing the value of the numerator in $\frac{\gamma P_E \xi}{(\bar{X}-x_t)AS}$ and simultaneously increasing the discounted benefit of extracting one extra unit in the future (λ) leading to a likely decrease in the extractions for every period that will yield a less deep steady state value for the height of the water table.

Policy Interventions

After establishing the theoretical framework of the optimization problem, we analyzed a set of policy interventions to be tested in the field. Using the parameters from Salcedo and Gutierrez (2013), presented in Appendix A, we simulated the model for 100 periods, varying the value of γ from 0 to 0.8 in increments of 0.1 to analyze the behavior of the water users and its impact on the pumping and height to the water table as a function of the level of subsidy. Figure 1 demonstrates that there is a steady increase in the height of the water when the level of subsidy increases, thereby demonstrating that there is a strong connection between the state variable and the level of subsidy.

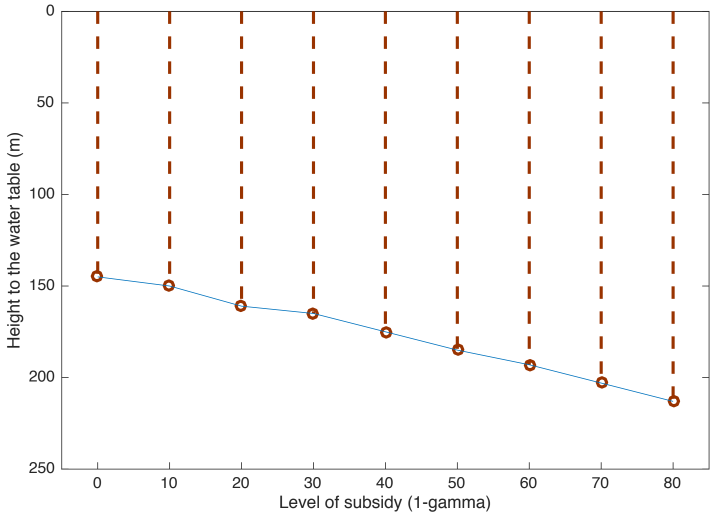

Figure III.1. Relationship between level of subsidy and height of the water table.

For our analysis, we focus on four scenarios: Status quo ($\gamma = 0.2$), reduction ($\gamma = 0.5$), elimination ($\gamma = 1$), and decoupling the subsidy ($\gamma = 1$ and a cash transfer equivalent to the average subsidy received in the past i periods). In the latter case, the optimization problem is updated to include the decoupling factor, and it is represented by:

$$\max_{u_t} \sum_{t=1}^{\infty} a^t J \left[\delta J u_t - u_t \left(\frac{\gamma P_E \xi}{(\bar{X} - x_t) AS}\right)\right] - C_0 + \phi\,, \quad (5)$$

where

$$\phi = \frac{\sum_{k=t-i}^{t} \frac{u_k \gamma P_E \xi}{(\bar{X} - x_k) AS}}{i}.$$

In comparison with Equation 3, with the respective Bellman equation, we obtain:

$$V(x_t) = \max_{u_t} \left[J \delta u_t - u_t \left(\frac{\gamma P_E \xi}{(\bar{X} - x_t) AS}\right) - C_0\right] + \phi + \alpha V[x_{t+1}]. \quad (6)$$

In this case, the decoupling factor $\frac{\sum_{k=t-i}^{t} \frac{u_k \gamma P_E \xi}{(\bar{X} - x_k) AS}}{i}$ is calculated for all $t \in [1, i]\ \forall\, i > 1$.

The hypothesis tested in the field experiments predicted that changing the subsidy structure by eliminating the subsidy, reducing the subsidy, or giving users a transfer equivalent to the average subsidy they received in past periods would result in a decrease in the individual requests that lead to a higher steady state of the height to the water table.

Figure 2 portrays a comparison between status quo, subsidy reduction from 80% to 50%, and decoupling with a 15-period lag for calculating the average decoupling factor.[9] Decoupling accomplishes the highest steady state of the height of the water table, which suggests it to be a viable policy intervention.

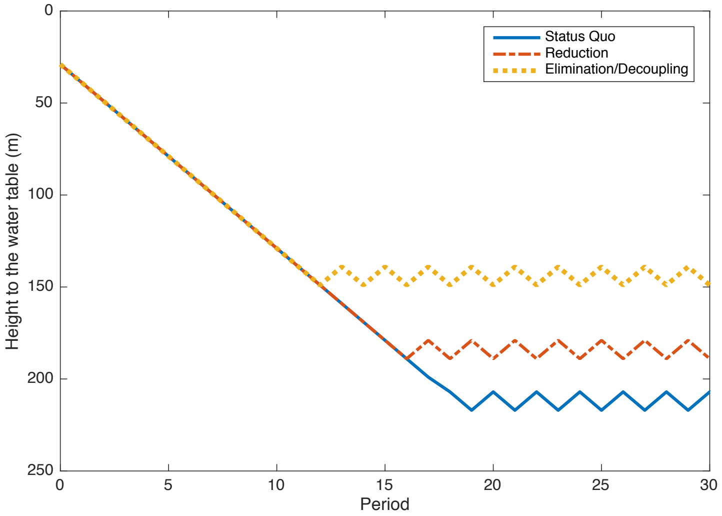

Figure III.2. Steady state of the height of the water table under different policy interventions.

We observe that the steady state forms a periodic wave rather than a horizontal line; this is explained by the extraction path, where after reaching a certain depth, the users change from extracting zero units to extracting 10, as shown in Figure 3.

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[9] The results for the elimination scenario are exactly the same as in the decoupling scenario, since in the optimization problem, the decoupling factor (which is a constant) is dropped from the first order conditions. For a more detailed explanation of the choice of the length of the lag, please refer to Tellez Foster et al. (2016a).

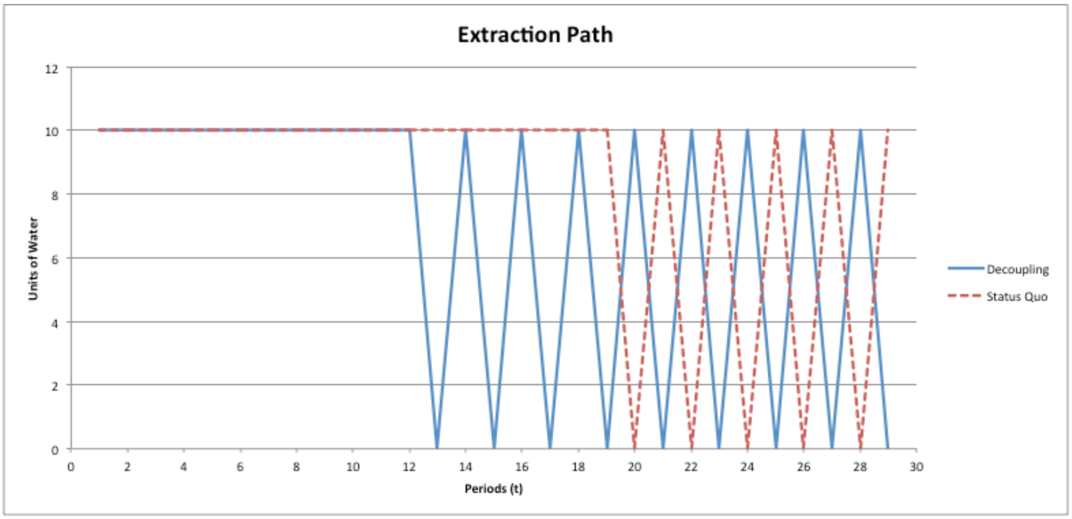


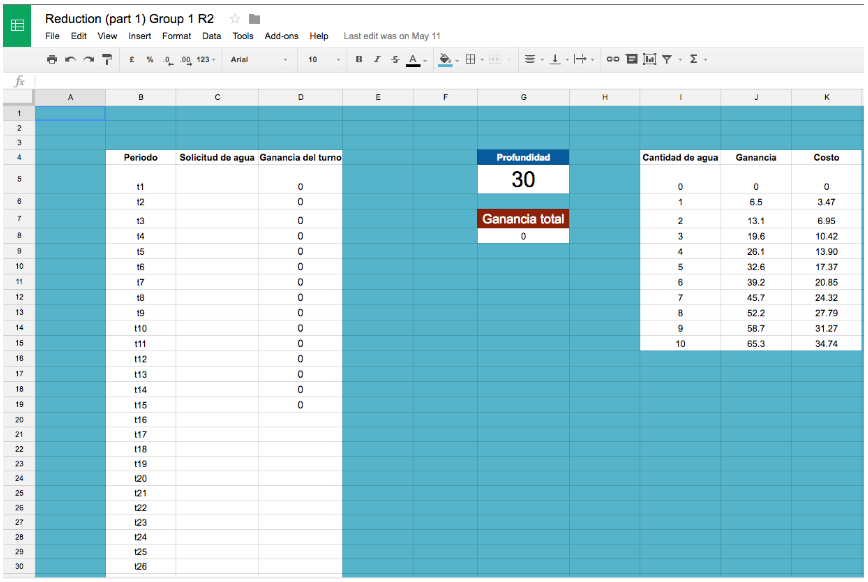
Figure III.3. Extraction path.

4 Field Experiments

To test the hypothesis stated in the previous section, we designed an experiment to be implemented in the city of León, Guanajuato with farmers who were recruited with the help of the local water authority and the School of Economics at the National Autonomous University of Mexico. We recruited a total of 84 farmers, who were randomly assigned to groups of 6. The experiment was divided into two parts: all the subjects participated in the Status Quo condition in Part 1, and then proceeded to participate in the policy intervention (Elimination, Reduction, or Decoupling) in Part 2. The subjects in the control group participated in the Status Quo condition in both parts of the experiment. Communication between group members was not allowed.

Each group member was assigned a separate computer. Subjects were given time to read and understand instructions. This phase was followed by a short oral summary of the instructions, after which participants' questions were answered. Sessions lasted no more than two hours, including check-in and payment.

A simple version of a programmed smart sheet using the Google docs platform was presented in this experiment. Subjects were presented with a computer screen that exhibited a space to submit their request for each period. In addition, they were informed of the current depth of the aquifer, the accumulated earnings (measured in tokens), and the potential profit for every possible request at the current depth of the aquifer and the cost associated with it. See Figures 4 and 5.



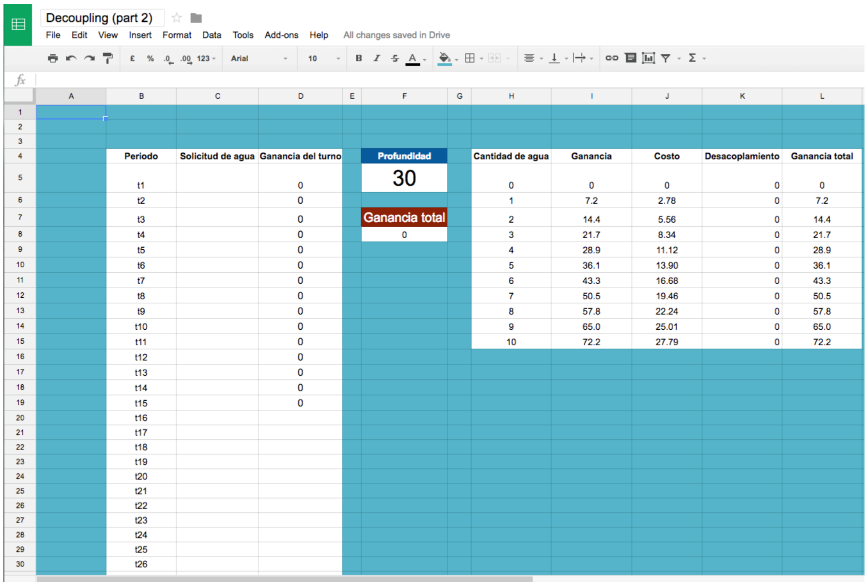
Periodo	Solicitud de agua	Ganancia del turno
t1		0
t2		0
t3		0
t4		0
t5		0
t6		0
t7		0
t8		0
t9		0
t10		0
t11		0
t12		0
t13		0
t14		0
t15		0
t16		
t17		
t18		
t19		
t20		
t21		
t22		
t23		
t24		
t25		
t26		

Profundidad: 30

Ganancia total: 0

Cantidad de agua	Ganancia	Costo
0	0	0
1	6.5	3.47
2	13.1	6.95
3	19.6	10.42
4	26.1	13.90
5	32.6	17.37
6	39.2	20.85
7	45.7	24.32
8	52.2	27.79
9	58.7	31.27
10	65.3	34.74

Figure III.4. Participant's screen.



Periodo	Solicitud de agua	Ganancia del turno
t1		0
t2		0
t3		0
t4		0
t5		0
t6		0
t7		0
t8		0
t9		0
t10		0
t11		0
t12		0
t13		0
t14		0
t15		0
t16		
t17		
t18		
t19		
t20		
t21		
t22		
t23		
t24		
t25		
t26		

Profundidad: 30

Ganancia total: 0

Cantidad de agua	Ganancia	Costo	Desacoplamiento	Ganancia total
0	0	0	0	0
1	7.2	2.78	0	7.2
2	14.4	5.56	0	14.4
3	21.7	8.34	0	21.7
4	28.9	11.12	0	28.9
5	36.1	13.90	0	36.1
6	43.3	16.68	0	43.3
7	50.5	19.46	0	50.5
8	57.8	22.24	0	57.8
9	65.0	25.01	0	65.0
10	72.2	27.79	0	72.2

Figure III.5. Participant's screen for decoupling condition.

The procedures are summarized below.

Part 1

Condition 1: Status quo (no change of subsidy).

All subjects participated in this condition. They were instructed to extract groundwater (from zero to 10 meters) to be pumped from the aquifer. The height of the water table was set at 30 meters for the first period. After period 1, each subject could inspect the current height of the water table for each period in the main screen and the potential profit for each of the possible water requests. After the group members submitted their requests, the water table was updated and they were asked to submit new requests independently. Because the extraction game was played under an infinite time horizon, each round was terminated randomly with a conditional probability of 15% contingent on reaching this round. At the end of the session, subjects were paid anonymously, contingent on their performances, and dismissed from the laboratory.

Part 2

Condition 2: Elimination of the subsidy.

Subjects were asked to perform the same task as in Part 1, with the same conditional probability of termination. In this condition, the value of γ was set equal to one, thereby implying the complete elimination of the subsidy.

Condition 3: Reduction of the subsidy.

In this condition, the value of γ was set equal to 0.5, meaning that the new subsidy was only 50% of the pumping costs. Subjects performed the same task as in Part 1, with the same conditional probability of termination.

Condition 4: Decoupling (elimination of the subsidy and transfer of payment).

In this condition, subjects participated in Part 1, then were informed that the average subsidy received during the first 15 periods would be their decoupling factor. Each subject was informed individually, and all were informed collectively that the subsidy in Part 2 would be removed ($\gamma = 1$). Then, they were asked to perform the same task as in Part 1 with the same conditional probability of termination.

Condition 5: Control.

In Condition 5, the subjects performed the same task as in Part 1. After the random termination of that part of the experiment, they proceeded to participate in Part 2 with the same level of subsidy ($\gamma = 0.2$), until it was randomly terminated.

Results

The results of the field experiment are summarized in this section. We do not compare the behavior in part 1 across all conditions; rather, the analysis is conducted by comparing the behavior of the groups in Part 1 of each condition with the behavior of groups in part 1 of the control condition.

Elimination

For the elimination condition, 18 farmers were assigned randomly to three groups of six members each. Subjects were given time to read the instructions at their own pace, followed by a brief oral summary of the instructions and a short question-and-answer period. This procedure was followed in all conditions.

In this section, we compare the behavior of groups in the status quo condition (Part 1) and the elimination condition (Part 2). Figure 6 indicates that the mean total request per group in the elimination condition is consistently lower than the one in the status quo condition; subjects understood quickly that the costs increased after the subsidy was eliminated and consequently played more conservatively than they did in the first period.

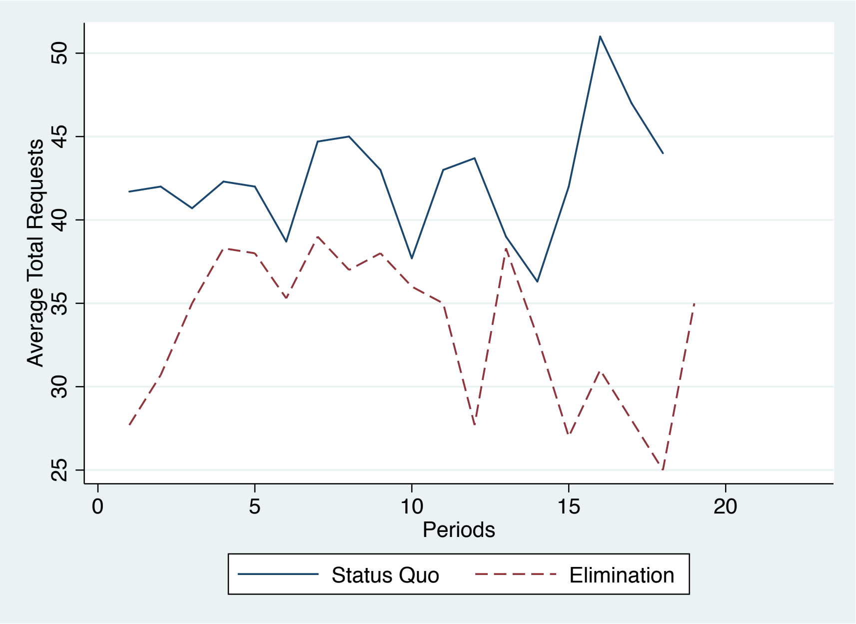


Figure III.5. Mean individual requests per group.

A *t*-test was performed to test the hypothesis that the mean request in the status quo and elimination conditions would be the same. The test indicated that the difference between the mean is statistically significant ($t = 5.97$, $p < 0.001$). Note that this is not a measure of the magnitude of the treatment effect, which will be discussed in later sections.

The effects of the extraction decisions shown in Figure 6 are reflected in the height of the water table. Figure 7 demonstrates that the value of the height of the water table under the status quo gradually increases from 30 meters to about 100 meters, whereas the height of the water table in the elimination condition fluctuates between 30 and 50 meters.

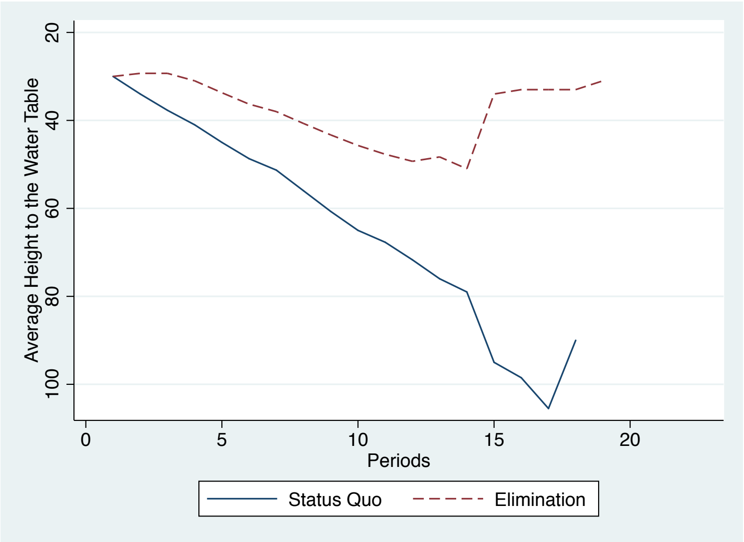


Figure III.6. Mean height of the water table (in meters).

Reduction

In the reduction condition, the subjects were instructed to perform the same task as they did previously, except in this condition, they were faced with a reduction in the subsidy level from 80% to 50%. Figure 8 demonstrates that the effect of the reduction to 50% of the subsidy is considerably weaker. This sensitivity to the change in subsidy level is confirmed by a *t*-test ($t = -0.81$, $p > 0.2$), which shows that the difference in requests between the first and second parts of the experiment is not statistically significant.

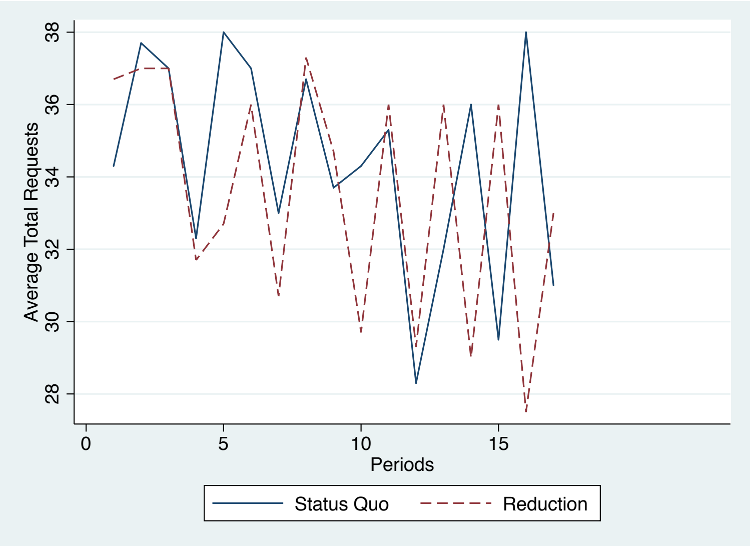


Figure III.7. Mean individual requests (reduction condition).

Figure 9 indicates that the lower requests had only a minor effect on the height of the water table. Under reduction, the height of the water table is lower.

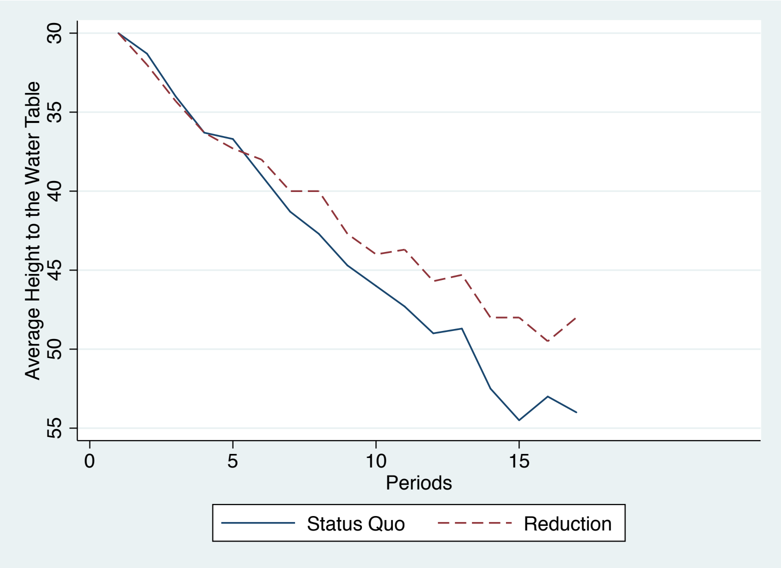


Figure III.8. Mean height of the water table (reduction condition).

Decoupling

The decoupling condition was performed in the same manner as in the previous two conditions; however, after completing Part 1, the subjects were informed of the size of the individual decoupling factor and then proceeded to play Part 2, where the subsidy was completely eliminated and replaced by cash transferred.

Figure 10 depicts the mean total request by the group. It shows that the requests under the decoupling condition are consistently lower than under the status quo condition. The difference between the two mean requests is statistically significant ($t = -2.42$, $p < 0.001$). The extraction values under this condition meet the theoretical predictions presented in the previous sections more closely than those under any other condition.

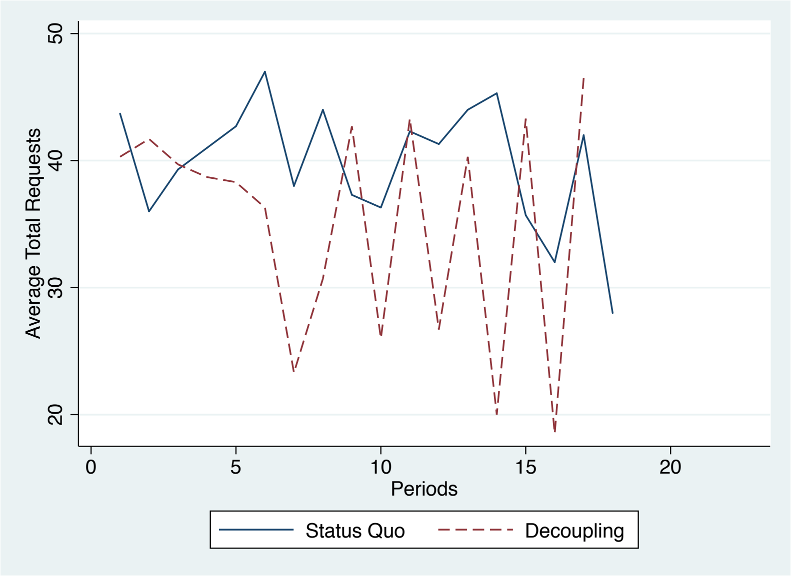


Figure III.9. Mean individual requests (decoupling condition).

This periodic request changes in Figure 10 are reflected in the height of the water in Figure 11. This figure shows that the trend stabilizes after period 5 at 60 meters, whereas the height of the water table in the status quo condition follows the trend, as in the previous two treatments (compare Figures 7, 9, and 11).

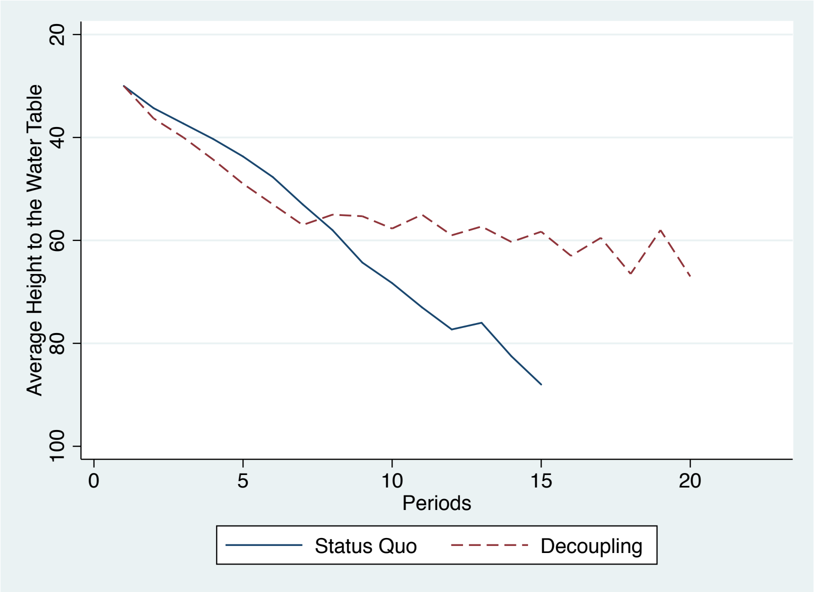


Figure III.10. Mean height to the water.

Quantifying Policy Intervention Effectiveness

To analyze the effects of the policy interventions quantitatively, we employ the difference in differences method, following the analysis conducted in Tellez Foster et al. (2016b). This technique often is used in the literature to analyze the effect of treatment across populations. It compares the behavior of individuals before and after receiving treatment to a counterfactual population. The model estimated is represented by:

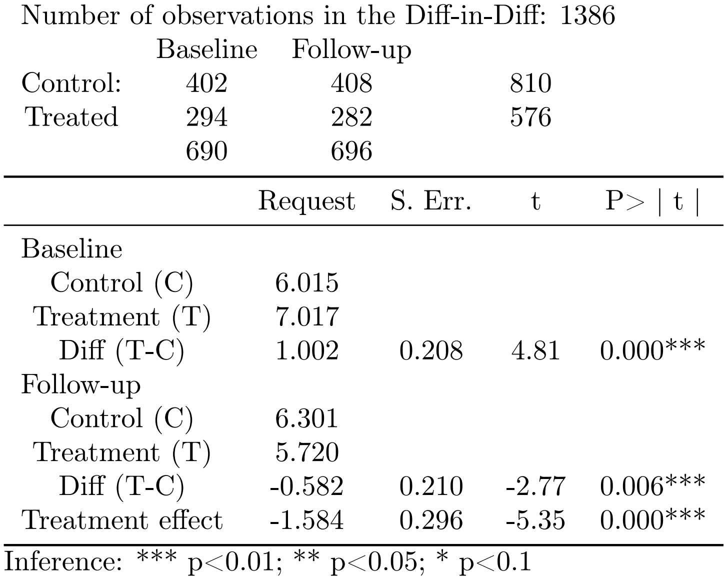
$$\Delta u = \beta_1\, Pretreatment + \beta_2\, Post - treatment + \beta_3\, Interaction\ term\ (pre * post),$$

where Δu is the change in the requests for groundwater after the treatment is applied, β_1 is the estimator for the status quo condition, β_2 is the treatment estimator, and β_3 is the relevant estimator in obtaining the final effect of the treatment.

The treatment effects for the three conditions is presented in Tables 1, 2, and 3 below:

Table III.1

Difference in Differences Estimation (Elimination)



Number of observations in the Diff-in-Diff: 1386

	Baseline	Follow-up	
Control:	402	408	810
Treated	294	282	576
	690	696	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	6.015			
Treatment (T)	7.017			
Diff (T-C)	1.002	0.208	4.81	0.000***
Follow-up				
Control (C)	6.301			
Treatment (T)	5.720			
Diff (T-C)	-0.582	0.210	-2.77	0.006***
Treatment effect	-1.584	0.296	-5.35	0.000***

Inference: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

We observe that the reduction per period per individual is 1.5 units of water. This confirms our hypothesis that the sign of the effect is negative. The effect we observe in elimination is the greatest among all the treatments, which also coincides with the theoretical predictions made by Tellez Foster et al. (2016b).

Table III.2

Difference in Differences Estimation (Reduction)

Number of observations in the Diff-in-Diff: 1386

	Baseline	Follow-up	
Control:	402	408	810
Treated	276	270	546
	678	678	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	6.015			
Treatment (T)	6.395			
Diff (T-C)	0.380	0.206	1.85	0.065**
Follow-up				
Control (C)	6.301			
Treatment (T)	5.722			
Diff (T-C)	-0.579	0.206	-2.81	0.005***
Treatment effect	-0.959	0.291	-3.29	0.001***

Inference: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

For reduction we expected a smaller effect, following the theoretical predictions presented above. Reducing the subsidy from 80% to 50% resulted in the requests being reduced by an average of less than one unit only. However, the cumulative effect demonstrates an increase in the height to the water table, as shown in the previous section.

Table III.3

Difference in Differences Estimation (Decoupling)

Number of observations in the Diff-in-Diff: 1386

	Baseline	Follow-up	
Control:	408	402	810
Treated	252	318	570
	660	720	

	Request	S. Err.	t	P> | t |
Baseline				
Control (C)	6.301			
Treatment (T)	7.369			
Diff (T-C)	1.068	0.208	5.12	0.000***
Follow-up				
Control (C)	6.015			
Treatment (T)	5.874			
Diff (T-C)	-0.141	0.258	-0.54	0.586
Treatment effect	-1.208	0.331	-3.65	0.000***

Inference: *** $p<0.01$; ** $p<0.05$; * $p<0.1$

The treatment effect in the decoupling condition is close to the one calculated for the elimination treatment. It also shows the expected negative sign and it is close to the theoretical prediction that stated the same effect for elimination and decoupling conditions.

Robustness of the Results

Comparing the results of the laboratory experiments presented in Tellez Foster et al. (2016b) with the results of the field experiments presented in this paper leads to a more comprehensive understanding of how policy interventions affect water requests and, consequently, in the height of the water. Table 4 presents the treatment effect of the three conditions, calculated using the difference in differences method.

Table III.4

Comparison of Treatment Effect: Laboratory vs Field Experiments

Condition	Laboratory	Field
Elimination	-0.789 (0.342)***	-1.584 (0.296)***
Reduction	-1.534 (0.310)***	-0.959 (0.291)***
Decoupling	-2.015 (0.272)***	-1-208 (0.331)***

(S. Err) ***p<0.01; **p<0.05; *p<0.1

Table 4 demonstrates that in both sets of experiments (laboratory and field) the sign of the treatment is negative, as predicted in the theoretical model. However, differences in the magnitude of the effect must be analyzed carefully. The strongest effect observed among the laboratory experiments was for the decoupling condition, followed by the reduction and the elimination conditions. Among the experiments conducted in the field, the elimination of the subsidy had the greatest effect, and the reduction had the smallest. Analyzing how the magnitude of the treatment effect varies across different populations, the plausible explanation for the difference in behavior could be explained by the experience that farmers have had with the problema; therefore, their behavior was closer to what was predicted by the theoretical model.

Although the purpose of this paper is not to investigate the differences between laboratory and field experiments, it will present analysis comparing the two sets of experiments.

Comparing Results with Previous Studies

This section compares the results of the experiments conducted in the field with those obtained in laboratory experiments in Tellez et al. (2016(b)). The treatment effect resulted in the expected sign for all conditions and in both student and farmer populations. However, we observe that farmers' behavior follows the predictions of the theoretical model closely, which could be explained by the prior knowledge that farmers bring to the experiment.

Analyzing Free-Riding Behavior

One of the measures in which students and farmers' behavior differ is in free riding the conservation efforts of others. Figure 12 demonstrates the number of periods that a participant requested above the average request of the group as a percentage of the total number of periods. The graphs indicate that students in the laboratory were more prone to request above the average, free riding the efforts of other participants to preserve the resource.

Free-riding behavior was not affected by the treatment, and the graphs below show that students consistently made requests over the average, undermining the efforts of other players to preserve water. On the other hand, farmers were less likely to free ride the efforts of others in conserving water. The figure demonstrates that the number of requests above the group average for farmers is significantly lower than those of students. A *t*-test was conducted to assess the statistical significance of the mean difference between field and laboratory participants, showing that in a two-tailed test, the mean difference is not zero with a *p* value of 0.0042. Meanwhile, in a single-tailed test, the *p* value for a difference less than 0 was 0.0021. These results confirm that the free-rider behavior for the field experiments statistically were significantly lower than the behavior shown by participants in the laboratory.

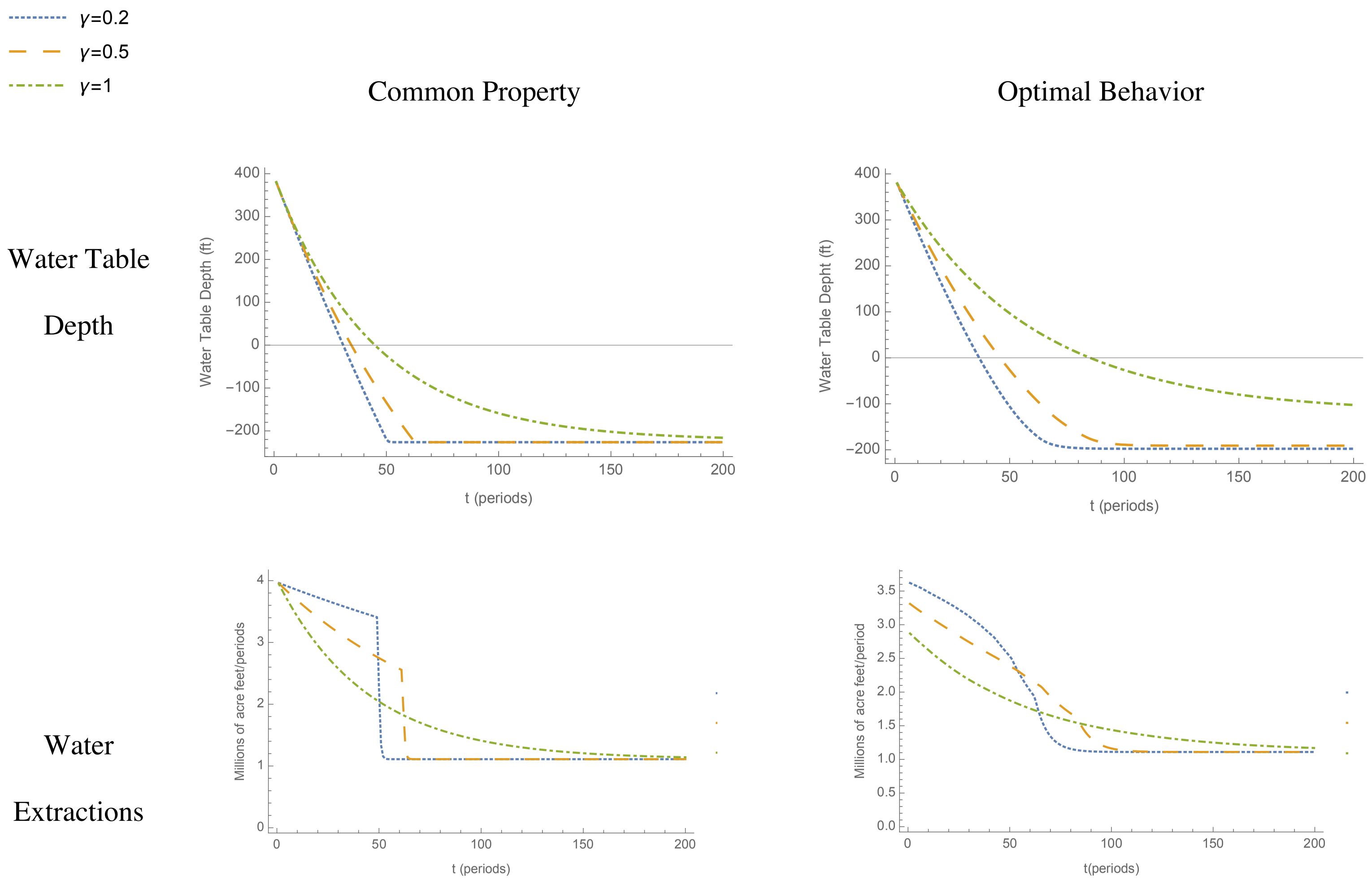


Figure I.7. Sensitivity analysis for Kern aquifer under common property, optimal behavior scenarios.

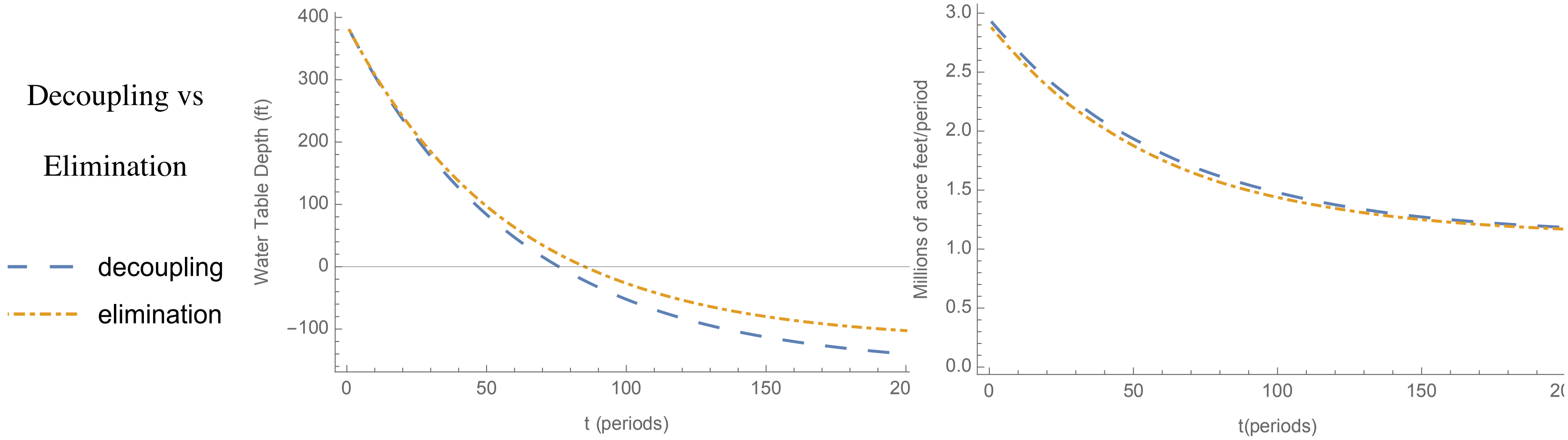
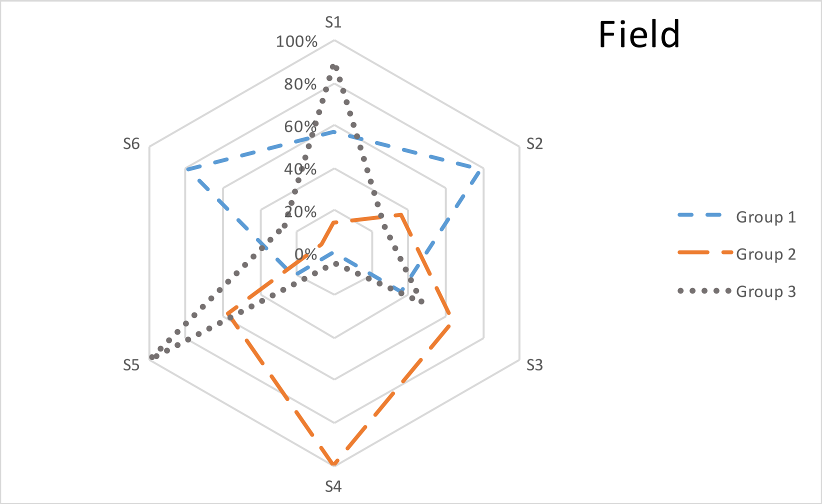


Figure I.7.1. Sensitivity analysis for Kern aquifer: Decoupling and full elimination scenarios.

Elimination



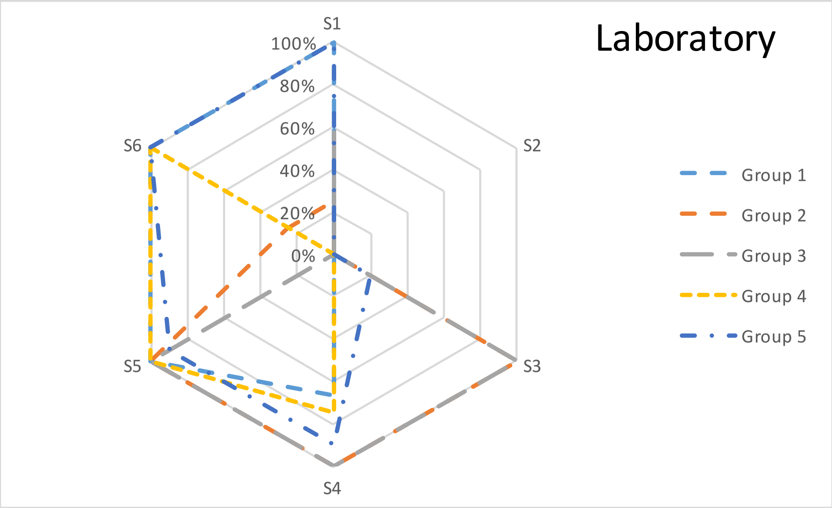


Figure III.12. Percentage of periods of individual requests exceeding the group average.

In an analysis of how many average free riders per group we find per condition, we define a free rider as a participant that requests above the average group request for 50% or more of the periods. Table 5 demonstrates that students partake in free-riding behavior consistently more than farmers do. This reinforces that the experience farmers possess is reflected in their decisions, even in abstract settings such as that of this experiment.[10]

Table III.5

Average Number of Participants Free Riding Per Condition

Condition	Laboratory	Field
Elimination	3.6	2.7
Reduction	3.4	2.3
Decoupling	3.5	2

Conclusions and Policy Implications

This paper sheds light on the behavioral changes of groundwater users under different policy interventions in the context of perverse subsidies to electricity. Its conclusions on the implications of policy modifications are presented in this section.

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[10] We are unable to test this hypothesis because of restrictions of the HHRRB on collecting personal data of participants.

Predicted Behavior vs. Observed Behavior

We found several trends in the number of requests and height of water table variables by comparing the behavior of subjects under the status quo condition and the policy interventions. All three interventions resulted in a reduction in the requests per period. Although hypotheses predicted that elimination and decoupling would accomplish the same result, we found that elimination had a greater effect, followed closely by decoupling with a 0.3 units of difference. Reduction of the subsidy resulted in the smallest effect, with less than one unit on average per period.

In all cases, subjects demonstrated an understanding of the consequences of changing the subsidy structure and acted consequently, and users' strategies were more aggressive in the first part of the experiment before they adopted more conservative strategies after the treatment is applied.

Policy Implications

Changes in the institutional arrangements of water management are slow and costly; they often face resistance from decision-makers and users. The results derived from these experiments, both in the laboratory and in the field, provide an efficient and cost-effective method of analyzing the effects of policy interventions before they are applied.

We observe some outstanding differences in the magnitude of the treatment effect between laboratory and field experiments for two particular treatments: elimination and reduction. In the case of laboratory results, we observe a larger effect for the latter, with an average reduction of more than one unit per period, as compared with a reduction of less than one unit for the elimination treatment. For the field results, the magnitude of the effect seems to be reversed, with elimination showing a reduction of about 1.5 units per period and for the reduction treatment a decrease of less than one unit per period. This adds to the discussion presented above about the differences in the behavior of students and farmers and opens the discussion to considering the unobserved factors that influence this behavior. These questions are subject to further research.

Our research has demonstrated that changing the subsidy structure for groundwater extraction has significant effects on the extraction levels and consequent height of the water table. The three policy interventions investigated in the present study prove to have the desired effect; namely, a reduction in the requests for groundwater. As expected, elimination of the subsidy produced the strongest effect. However, as discussed in Muñoz et al. (2006) and Tellez Foster et al. (2016b), eliminating the subsidy is not politically feasible. Reducing the subsidy produces a limited effect (less than one unit per period on average), and its implementation most likely would face the same political difficulties. Decoupling the subsidy has an effect close to the one observed in the Elimination condition without the averse political difficulties. Therefore, we propose decoupling as an alternative policy intervention in overcoming the political obstruction.

General Conclusions

These essays help to shed light on the negative consequences of perverse subsidies to energy for pumping groundwater. The experience in many countries that have implemented the aforementioned subsidies have demonstrated overexploitation of their groundwater resources. Mukherji & Shah (2005) demonstrated how the implementation of such policies is followed by an increase in the number of wells and the amount of water pumped from aquifers for irrigation. This is proven true for countries in South Asia, such as India and Pakistan, and for China, Spain, and in Mexico.

In Mexico, a subsidy to electricity for pumping groundwater was implemented in 2004 and led to the same results. Out of the 600 major aquifers in Mexico, more than 100 have an extraction/recharge rate greater than one, meaning they fall under the classification of overexploited.

The first essay outlined a theoretical model that simulates the behavioral responses of groundwater users under different subsidy structures. This model uses real geological and economic data from two aquifers: one in Leon, Guanajuato, Mexico and the other in Kern County, California. Results of the computer simulations demonstrated that eliminating and decoupling the subsidy produced the most effective response among groundwater users, with pumping reduced and height of the water table stabilized. Reducing the subsidy, meanwhile, led to the least effective response.

Essay 2 detailed a set of laboratory experiments and a simplified theoretical model that experimentally proved the hypothesis posed in Essay 1. We tested three different policy interventions: eliminating and reducing the subsidy, and decoupling it from electricity. The experiments conducted at the Behavioral Laboratory at UCR with undergraduate students demonstrate that the decoupling intervention has the greatest effect in reducing pumping and keeping the height of the water table shallow, followed by reduction, then elimination. These results differ from the theoretical predictions, however all of them had the expected sign in the negative effect calculated.

Essay 3 introduces a set of field experiments similar to those introduced in Essay 2, and it tests the hypothesis drawn from the theoretical model developed in Essay 2. These experiments, conducted with farmers in the city of Leon, Guanajuato, Mexico, revealed that elimination and decoupling produced the greatest effect, while the effect of reduction was minimal. These results are more in line with the theoretical predictions than those observed in the laboratory, possibly because the farmers possessed prior experience with groundwater scarcity. However, in both the laboratory and the field, decoupling the subsidy from the electricity price clearly represented a feasible alternative to traditional policy interventions, and it reduced the social and political costs of implementing changes in the subsidy structure.

Policy Implications

The results obtained from the three essays that compose this work demonstrate that modifying electricity subsidies reduces withdrawals from aquifers. Along with testing traditional policy interventions—reduction and elimination—we tested an innovative new policy, first suggested by Muñoz et al. (2007), that involves decoupling the electricity subsidy and introducing in its place a lump sum calculated using the average consumption over a predetermined period of time. This modification could be as effective as eliminating the subsidy while circumventing the political complications of doing so, making it a feasible policy intervention that could help stabilize overexploited aquifers.

We recognize that no policy change is a panacea, and complementary policies that send the correct signals to stakeholders must accompany policy modifications in order to improve the efficiency water resource use.

Looking Forward

Our explanation of the challenges energy subsidies pose for groundwater extraction could be complemented by variations and additions to the theoretical model and the experimental design. Future work could explore farmers' crop and irrigation technology choices when facing a change in the subsidy, changes in pumping habits when introducing a stochastic recharge rate, and adaptations of the model and experimental setup in studying other cases like India, Pakistan, China, and Spain.

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