Over-drilling: Local Externalities and the Social Cost of Electricity Subsidies in South India

Jesús Bueren[1] Xavier Giné[2] Hanan Jacoby[2] Pedro Mira[3]

[1]EUI

[2]World Bank

[3]CEMFI

Introduction

- A groundwater revolution has unfolded across the Asian subcontinent in recent decades.
- Groundwater is now the dominant source of irrigation in India, allowing widespread dry-season cultivation that has helped sustain rural income growth and poverty reduction.
- Many Indian states, however, provide electricity free of charge to farmers for running their pumps, thereby inflating the returns to well-drilling.

Introduction

- Drilling a borewell is costly.
  - Drilling for subsidies: farmers sink wells that would not otherwise be economically viable.
- Groundwater is a common property resource.
  - Pumping imposes negative externality on nearby wells lowering their discharge and increasing failure probabilities: coordination failure.
- Aquifer-wide externalities are largely absent in our setting.
  - Shallow hard-rock aquifer highly localized spatially.

This Paper

- We quantify the social cost of electricity subsidies in south India and compute an optimal drilling tax that maximizes social welfare.
- For this purpose, we develop and estimate a structural model in which:
    - Neighboring farmers play a dynamic discrete investment game.
    - Farmers are connected through a network defined by a map of adjacent agricultural plots in the locality
    - We estimate model using 5 years of panel data on well drilling, failure, success and flow in two districts of Andra Pradesh and Telangana.

This Paper

Preliminary Results

- We use the model to assess the changes in social welfare in a counterfactual economy where electricity subsidies were to be removed:
    1. If electricity subsidies were removed the social value of land would almost double.
    2. Due to the negative externality, the optimal tax on having a well is found to be around 150% the cost of electricity.
    3. The number of functioning wells would decrease by 40%.

Literature

- Studies quantifying the social costs of common ressources externalities.

  Ryan and Sudarshan (2020), Huang and Smith (2014),

- Empirical literature on network games has consisted on static applications.

  Acemoglu et al. (2015), König et al. (2017), Xu (2018)

  $\Rightarrow$ A static model could not account for low drilling success rate and well failure + transitional dynamics

Model

Output

- Let output from a plot be:

$$y(q, a) = \theta q^{\gamma} a^{1-\gamma}$$

  where q is flow and a is area.

- **Adjacency**: set of plots contiguous to a given plot.
  - flow is a random variable whose pdf varies with the number of wells in the adjacency.

The Model
Drilling Decision

- Let $V^i(n, \sigma_n; \sigma_A, \sigma_x)$ be the value function for a plot in a map.
  - $n \in \{0, 1, 2\}$ denotes the number of wells farmer i owns.
  - σ_n denotes the number of wells in each plot if the map not owned by farmer i.
  - σ_A denotes the size of each plot.
  - σ_x denotes the adjacency matrix.
- Let's denote:

  N: total number of functioning wells in the adjacency (including n)

The Model

Drilling Decision: $n = 0$

- A farmer (plot-owner) with $n = 0$ may decide not to make a drilling attempt with payoff:

$$\bar{v}^{i}_{d=0}(n = 0, \sigma_n) + \varepsilon_{d=0}$$

or may decide to make a drilling attempt with payoff:

$$\bar{v}^{i}_{d=I}(n = 0, \sigma_n) + \varepsilon_{d=I},$$

where ε_d are the econometric error or the taste shock observed by the farmer but not by the econometrician.

- We assume that the ε_d are iid across choices and time

The Model

Drilling Decision: $n = 0$

- The payoff of not drilling when $n = 0$ is given by:

$$\begin{aligned}\bar{v}^i_{d=0}(n=0,\sigma_n) =& \beta\mathbb{E}\Big[V^i(n'=0,\sigma'_n)\Big] \\ =& \beta\sum_{\sigma'_n} F(\sigma'_n|\sigma_n, n=0)V^i(n=0,\sigma'_n),\end{aligned}$$

where β is the discount factor and $F(\sigma'_n|\sigma_n, n)$ captures the farmer's beliefs about the probability that the state of the map will be σ'_n conditional on σ_n and n.

The Model

Drilling Decision: $n = 0$

- There is time to build in drilling investment so even if successful no discharge and output will occur until the next period.

- The payoff of drilling when $n = 0$ is given by:

$$\begin{aligned}\bar{v}^i_{d=I}(n=0,\sigma_n) =&\pi_s\Big(-c_s+\beta\mathbb{E}\Big[V(n'=1,\sigma'_n)\Big]\Big)+\\&(1-\pi_s)\Big(-c_d+\beta\mathbb{E}\Big[V(n'=0,\sigma'_n)\Big]\Big),\end{aligned}$$

  where c_s and c_d are the drilling cost of a successful and unsuccessful attempt, respectively ($c_s > c_d$).

- Therefore, we can write the beginning of period value function as:

$$\begin{aligned}V^i(n=0,\sigma_n) = \mathbb{E}\max\Big\{&\bar{v}^i_{d=0}(n=0,\sigma_n)+\varepsilon_{d=0},\\&\bar{v}^i_{d=I}(n=0,\sigma_n)+\varepsilon_{d=I}\Big\}\end{aligned}$$

The Model

Drilling Decision $n = 1$

- The choice specific value function when $n = 1$ is by:

$$\begin{aligned}\bar{v}^{i}_{d=0}(n=1,\sigma_n) = &\mathbb{E}[y(q,a)|N] - \cancel{c_e} + \\ &\beta\Big(\pi_f(N)\mathbb{E}\Big[V^i(n'=0,\sigma_n')\Big] + \\ &(1-\pi_f(N))\mathbb{E}\Big[V^i(n'=1,\sigma_n')\Big]\Big)\end{aligned}$$

The Model

Drilling Decision $n = 1$

- The choice specific value function when $n = 1$ is by:

$$
\begin{aligned}
\bar{v}^i_{d=0}(n=1,\sigma_n) =& \mathbb{E}[y\big(q,a\big)|N] - \cancel{c_e} + \\
& \beta\Big(\pi_f(N)\mathbb{E}\Big[V^i(n'=0,\sigma'_n)\Big] + \\
& (1-\pi_f(N))\mathbb{E}\Big[V^i(n'=1,\sigma'_n)\Big]\Big) \\
\bar{v}^i_{d=I}(n=1,\sigma_n) =& \mathbb{E}[y\big(q,a\big)|N] - \cancel{c_e} - c_s\pi_s - c_d(1-\pi_s) + \\
& \beta\Big(\pi_f(N)(1-\pi_s)\mathbb{E}\Big[V^i(n'=0,\sigma'_n)\Big] + \\
& ((1-\pi_f(N))(1-\pi_s) + \pi_f(N)\pi_s)\mathbb{E}\Big[V^i(n=1,\sigma'_n)\Big] + \\
& (1-\pi_f(N))\pi_s\mathbb{E}\Big[V^i(n=2,\sigma'_n)\Big]\Big)
\end{aligned}
$$

The Model

Drilling Decision $n = 1$

- The choice specific value function when $n = 1$ is by:

$$
\begin{aligned}
\bar{v}^i_{d=0}(n=1,\sigma_n) =& \mathbb{E}[y(q,a)|N] - \cancel{c_e} + \\
& \beta\Big(\pi_f(N)\mathbb{E}\Big[V^i(n'=0,\sigma'_n)\Big] + \\
& (1-\pi_f(N))\mathbb{E}\Big[V^i(n'=1,\sigma'_n)\Big]\Big) \\
\bar{v}^i_{d=I}(n=1,\sigma_n) =& \mathbb{E}[y(q,a)|N] - \cancel{c_e} - c_s\pi_s - c_d(1-\pi_s) + \\
& \beta\Big(\pi_f(N)(1-\pi_s)\mathbb{E}\Big[V^i(n'=0,\sigma'_n)\Big] + \\
& ((1-\pi_f(N))(1-\pi_s) + \pi_f(N)\pi_s)\mathbb{E}\Big[V^i(n=1,\sigma'_n)\Big] + \\
& (1-\pi_f(N))\pi_s\mathbb{E}\Big[V^i(n=2,\sigma'_n)\Big]\Big)
\end{aligned}
$$

$$
V^i(n=1,\sigma_n) = \mathbb{E}\max\Big\{\bar{v}^i_{d=0}(n=1,\sigma_n) + \varepsilon_{d=0}, \bar{v}^i_{d=I}(n=1,\sigma_n) + \varepsilon_{d=I}\Big\}
$$

The Model

Drilling Decision $n = 2$

- When $n = 2$, no investment decisions are made so the value function is directly given by:

$$
\begin{aligned}
V^i(n = 2, \sigma_n) = & \mathbb{E}[y\big(q_1 + q_2, a\big)|N] - 2\cancel{c_e} + \\
& \beta\Big((1 - \pi_f(N))^2 \mathbb{E}\Big[V(n' = 2, \sigma_n')\Big] + \\
& 2(1 - \pi_f(N))\pi_f(N)\mathbb{E}\Big[V(n = 1, \sigma_n')\Big] + \\
& \pi_f(N)^2 \mathbb{E}\Big[V(n' = 0, \sigma_n')\Big]\Big)
\end{aligned}
$$

The Model

Drilling Decision

- The decision rule as perceived by the econometrician is characterized by the Conditional Choice Probability function (CCP) as:

$$
\begin{aligned}
CCP^i(n,\sigma_n) =& Pr(d^i = 1|n,\sigma_n) \\
=& Pr(\bar{v}_0^i(n,\sigma_n) + \varepsilon_0 < \bar{v}_I^i(n,\sigma_n) + \varepsilon_I) \\
=& \frac{\exp(\bar{v}_I^i(n,\sigma_n)/\rho)}{\exp(\bar{v}_I^i(n,\sigma_n)/\rho) + \exp(\bar{v}_0(n,\sigma_n)/\rho)},
\end{aligned}
$$

with type-I extreme value distributed shocks where ρ is the scale parameter.

The Model

Equilibrium

- Let $F(\sigma_n'|\sigma_n, n)$ denotes the beliefs about the evolution of the state of the map.
- Let $CCP^i(n, \sigma_n)$ be a choice probability function for farmer i.
- $\tilde{F}(\sigma_n'|\sigma_n, n, CCP)$ be the one period ahead law of motion for the state induced by the CCP vector of all farmers, $\pi_f(N)$, and π_s.

The Model

Equilibrium

- A Markov-perfect equilibrium is:
  - A vector of CCPs for all farmers.
  - A vector of beliefs on the future evolution of the state of the map.

such that:

  - Given beliefs, CCP^i is the solution of farmer i's dynamic game.
  - Beliefs are correct: $F(\sigma'_n|\sigma_n, n) = \tilde{F}(\sigma'_n|\sigma_n, n, CCP)$

The Model

Adjacency Equilibrium

- We make three assumptions for computational tractability:

  1. Limited information: farmers only observe:
     - Own wells
     - Number of neighbors and wells around them
     - Area
  2. Conditional on plot's fixed characteristics, n and N, farmer's beliefs do not depend on their specific location in the map.
  3. Beliefs about N' are consistent with the steady-state of the game.

$\Rightarrow$ We can prove existence of an adjacency-equilibrium

Computing the Equilibrium

- Inputs: production function parameters, flow, failure, and success probabilities, and adjacency matrix.

    1. Initialization: Assign initial well ownership and CCP_0 for every type.
    2. Start of iteration k: Using CCP_{k-1}, π_s, π_f, we simulate a time series of well drilling decisions, successes and failures until the steady state is reached.
    3. From the steady state simulation, obtain the one period ahead transition matrix $\tilde{F}(N'|N, n, CCP_{k-1})$.
    4. Use $\tilde{F}$ to compute the new CCP_k by value function iteration.
    5. If $||CCP_k - CCP_{k-1}||$ are closed enough, done. Otherwise go to 2.

Data

- Seven year retrospective panel survey for the states of Andhra Pradesh and Telangana on :
  - Borewell functioning (flow)
  - Failure
  - Drilling attempts
  - Well drilling around each plot
- The sample consists of 1,052 farmers.
- Geolocalized plot level data for contructing the adjacency matrix.

Estimation

- We estimate the model using a two-step procedure.
  - Step 1: Estimate all the first-step parameters using conventional panel-data econometrics.
  - Step 2: Estimate the second-step parameters using the equilibrium CCPs and the steady state distribution of wells taking first-step parameters as given.

Estimation

- We have described the algorithm that we would use to compute an equilibrium given the second-step parameters.
- For each set of parameters, we need to solve for the equilibrium algorithm, recover the CCPs, beliefs and steady state distribution of wells and compute the likelihood
- Given first-step parameters and $\tilde{F}_k$, obtain an estimate of $\Omega_p = [\theta, \rho, \gamma]$ using:

$$\hat{\Omega}_k = \arg\max_{\Omega} \mathcal{L}(X, \Omega), \tag{1}$$

where,

$$\mathcal{L}(X, \Omega) = \prod_{i=1}^{N} p(d_i^T, n_i^T, N_i^T | \Omega)$$

$$p(d_i^T, n_i^T, N_i^T | \Omega) = p(n_1, N_1 | \Omega) \prod_{t=2}^{T} p(d_t | n_t, N_t, \Omega).p(N_t | N_{t-1}, n_{t-1}, \Omega)$$

Second Stage Parameters

θ	γ	ρ
17.3	0.21	12.9
(-)	(-)	(-)

Table 1: Estimated second-step parameters

Second Stage Parameters

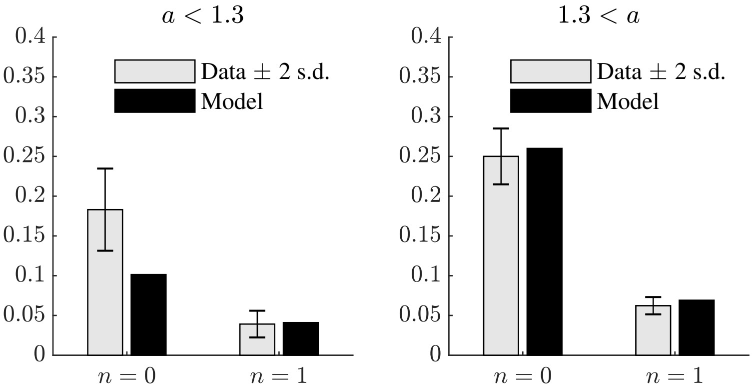

Figure 1: Drilling propensities: model vs data

Second Stage Parameters

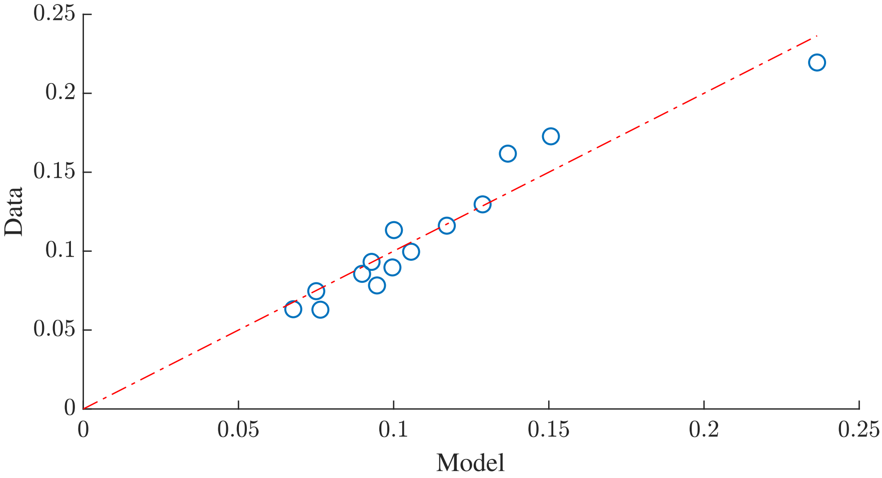

Figure 2: Drilling propensities across villages: model vs data

Second Stage Parameters

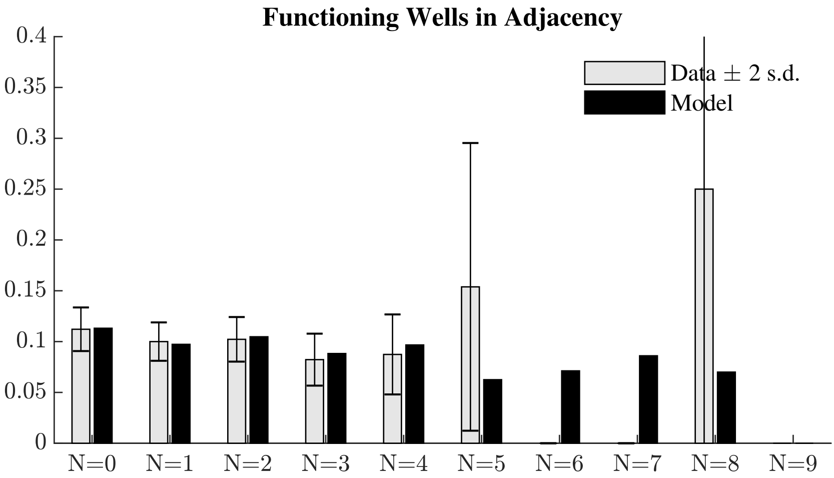

Figure 3: Drilling propensities: model vs data

Quantifying the welfare costs of electricity subsidies

- Given our estimates, we consider the following counterfactual:
- Suppose the government imposed a yearly tax T per functioning well, with tax revenues redistributed to farmers as a lump-sum.
- For every T, we need to solve the new equilibrium as farmer's drilling choices are affected by taxation.
- We compute the social welfare per acre of land taking into account the unsubsidized electricity cost of dry-season pumping e.

$$\text{Social Welfare} = \text{output value} - \text{drilling cost} - e$$

- When $T = e$, we recover the social welfare per acre when farmers internalize the electricity cost; compare to benchmark $T = 0$.

Quantifying the welfare costs of electricity subsidies

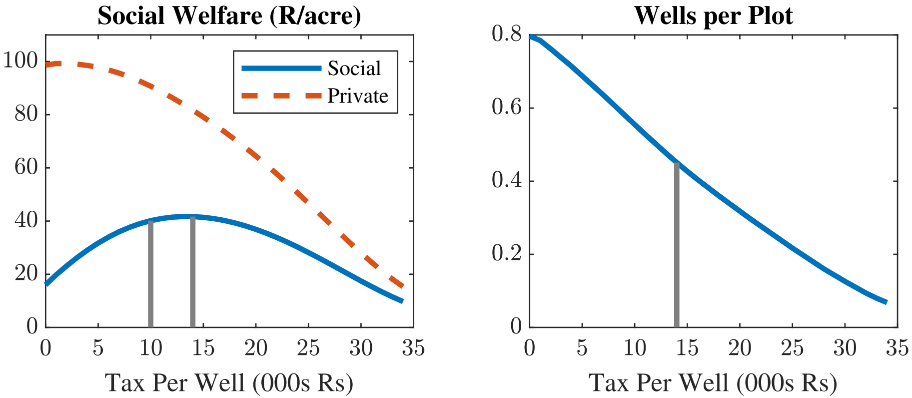

Figure 4: Social welfare (000s Rs per acre) as a function of yearly tax per functioning well