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

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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: 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 4,000 Rupees more expensive than the cost of electricity but with small quantitative welfare effects.
    3. The number of functioning wells would decrease by 40%.
    4. The current steady-state is socially dynamically inefficient as there are welfare gains during the transition to the counterfactual economy where farmers are required to pay the optimal drilling tax.

Literature

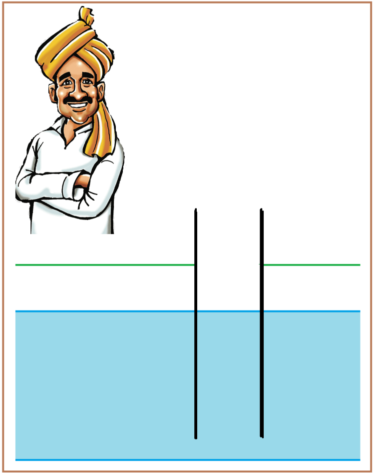
- Studies quantifying the social costs of common ressources externalities.

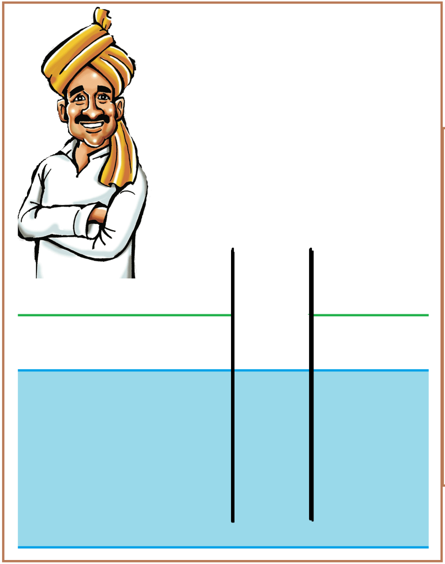
  Ryan and Sudarshan (2020), Huang and Smith (2014),

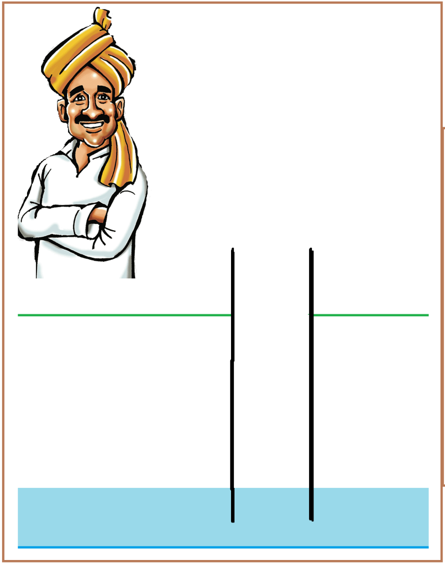
- Empirical literature on network games has consisted on static applications.

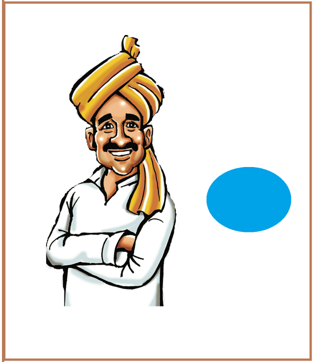
  Acemoglu et al. (2015), König et al. (2017), Xu (2018)

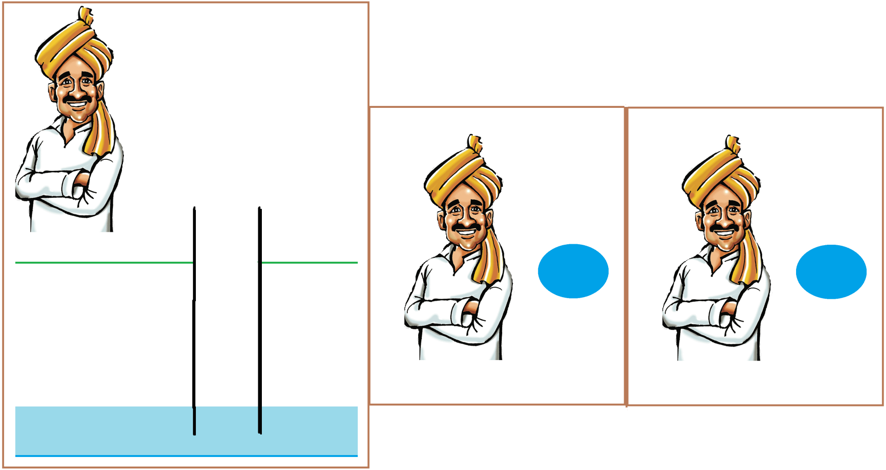
  $\Rightarrow$ A static model could not account for low drilling success rate and well failure + transitional dynamics

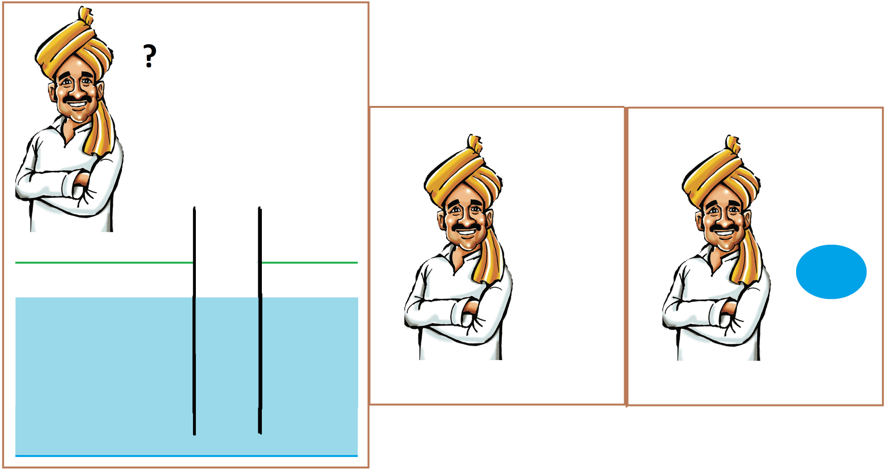


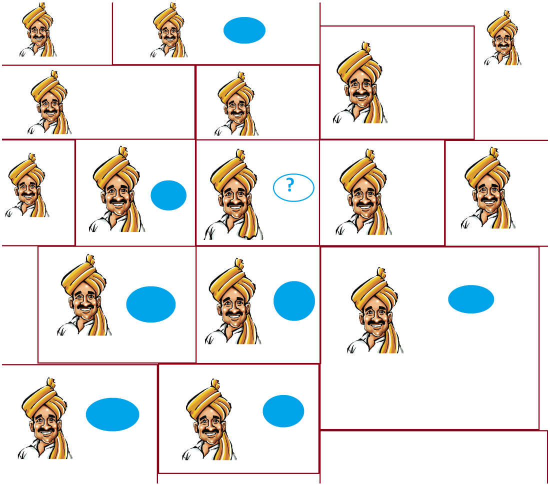












Model
Output

- Let output from a well owned by a farmer 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 and aquifer quality.

The Model

Drilling Decision

- Let $V(X)$ be the value function for a plot in a map.
  - X denotes the state of each plot in the map.
  - Each plot in the map can be heterogeneous along four dimensions:
    1. Area
    2. Number of neighbors
    3. Aquifer quality
    4. Number of wells (up to two)
  - Let's denote:

    n: number of wells in each plot

    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:

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

or may decide to make a drilling attempt with payoff:

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

where $\varepsilon_{n,d}$ are the econometric error or the taste shock observed by the farmer but not by the econometrician.

- We assume that the $\varepsilon_{n,d}$ are iid across choices and time

The Model

Drilling Decision: $n = 0$

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

$$\begin{aligned}\bar{v}_{n=0,d=0}(X) =&\beta\mathbb{E}\Big[V(X')|n'=0\Big]\\ =&\beta\sum_{X'}F(X'|X,n'=0)V(X'),\end{aligned}$$

where β is the discount factor and $F(X'|X,n')$ captures the farmer's beliefs about the probability that the state of the map will be X' conditional on X 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:

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

  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:

$$V_{n=0}(X) = \mathbb{E}\max\Big\{\bar{v}_{n=0,d=0}(X) + \varepsilon_{n=0,d=0}, \bar{v}_{n=0,d=I}(X) + \varepsilon_{n=0,d=I}\Big\}$$

The Model

Drilling Decision $n = 1$

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

$$
\begin{aligned}
\bar{v}_{n=1,d=0}(X) =& \mathbb{E}[y\big(q,a\big)|u,N] + \\
& \beta\Big(\pi_f(N)\mathbb{E}\Big[V(X')|n'=0\Big] + \\
& (1-\pi_f(N))\mathbb{E}\Big[V(X')|n'=1\Big]\Big) \\
\bar{v}_{n=1,d=I}(X) =& \mathbb{E}[y\big(q,a\big)|u,N] - c_s\pi_s - c_d(1-\pi_s) + \\
& \beta\Big(\pi_f(N)(1-\pi_s)\mathbb{E}\Big[V(X')|n'=0\Big] + \\
& ((1-\pi_f(N))(1-\pi_s) + \pi_f(N)\pi_s)\mathbb{E}\Big[V(X')|n'=1\Big] + \\
& (1-\pi_f(N))\pi_s\mathbb{E}\Big[V(X')|n'=2\Big]\Big)
\end{aligned}
$$

$$
V_{n=1}(X) = \mathbb{E}\max\Big\{\bar{v}_{n=1,d=0}(X) + \varepsilon_{n=1,d=0}, \bar{v}_{n=1,d=I}(X) + \varepsilon_{n=1,d=I}\Big\}
$$

The Model

Drilling Decision $n = 2$

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

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

The Model

Drilling Decision

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

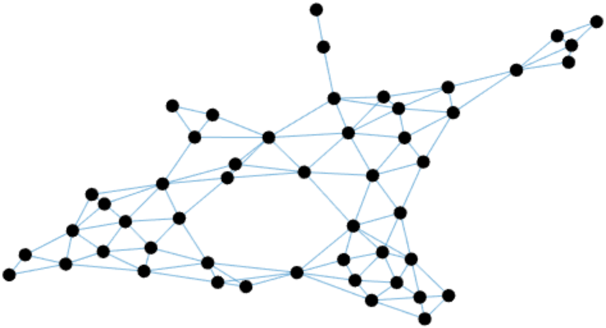
$$\begin{aligned} CCP_n(X) =& Pr_n(d = 1|X) \\ =& Pr(\bar{v}_{n,0}(X) + \varepsilon_{n,0} < \bar{v}_{n,I}(X) + \varepsilon_{n,I}) \\ =& \frac{\exp(\bar{v}_{n,I}(X)/\rho)}{\exp(\bar{v}_{n,I}(X)/\rho) + \exp(\bar{v}_{n,0}(X)/\rho)}, \end{aligned}$$

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

The Model

Equilibrium

- Map processing delivers a symmetric $G \times G$ adjacency matrix A where G is the number of plots in a village.
- $A_{i,j}$ is equal to one if plots i and j are neighbors and 0 otherwise.
- At any given period the state of each plot is $n_i \in \{0, 1, 2\}$ and let X denote the full state of the map.
- Let $CPP_i(X)$ be a choice probability function for farmer i.
- Let $F(X'|X)$ denotes the beliefs about the evolution of the state of the map and $\tilde{F}(X'|X, CCP)$ be the one period ahead law of motion for the state induced by the CCP, $\pi_f(N)$, 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 is the solution of farmer i's dynamic game.
  - Beliefs are correct: $F(X'|X) = \tilde{F}(X'|X, CCP)$

The Model

Adjacency Equilibrium

- Even though the externality is localized to adjacent plots, correctly forecasting N requires farmers knowing the state of the whole map.
- We make three assumptions for computational tractability:

1. Limited information: farmers only observe:
    - Own wells
    - Number of neighbors and wells around them
    - Area
    - Aquifer quality
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

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 CCP approach taking first-step parameters as given.
- First-step parameters include: failure/success probabilities π_s, $\pi_f(N)$, and pdf of flow q as a function of N.

First-step

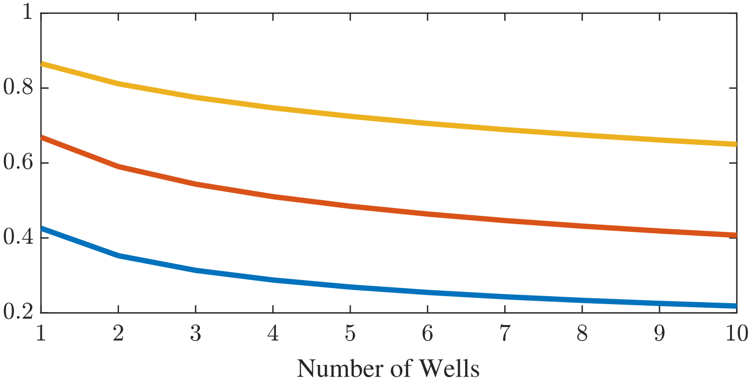


Figure 1: Expected flow with number of functioning wells in the adjacency

Second Stage Parameters

- We follow a CCP estimation strategy for the dynamic discrete choice model which embeds a solution algorithm.
- We first describe the solution algorithm for computing the adjacency equilibrium given both first and second stage parameters.
- Then, we cover the full estimation algorithm.

Solution Algorithm

- Inputs: first and second step parameters + adjacency matrix.
    1. Initialization: Assign initial well ownership and CCP_0 for every type.
    2. Start of iteration k: Using the first-step parameters and CCP_{k-1} for every type, 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 $\tilde{F}(N'|N, n, n', CCP_{k-1})$.
    4. Use parameters and $\tilde{F}$ 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.

Estimation Algorithm

- 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 and beliefs and compute the likelihood
- Given first-step parameters and $\tilde{F}_k$, obtain an estimate of $\Omega_p = [\theta, \rho, \gamma]$ using:

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

where,

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

Second Stage Parameters

θ	γ	ρ
17.3	0.21	12.9
(-)	(-)	(-)

Table 1: Estimated second-step parameters

Second Stage Parameters

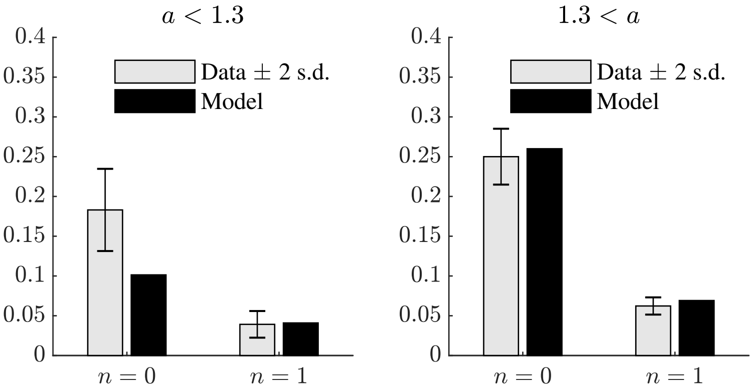


Figure 2: Drilling propensities: model vs data

Second Stage Parameters

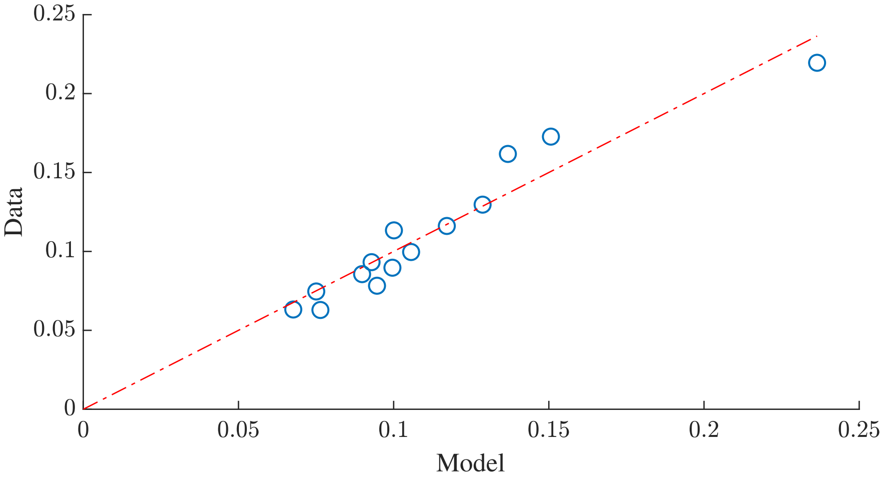


Figure 3: Drilling propensities across villages: model vs data

Second Stage Parameters

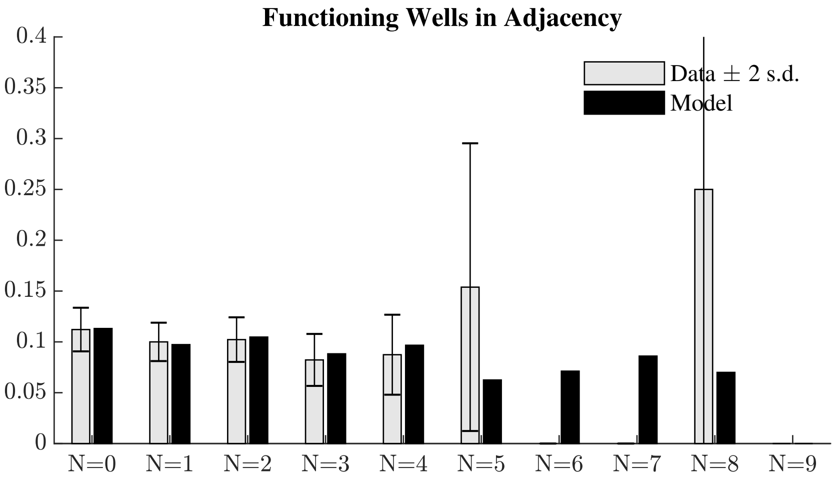


Figure 4: Drilling propensities: model vs data

Second Stage Parameters

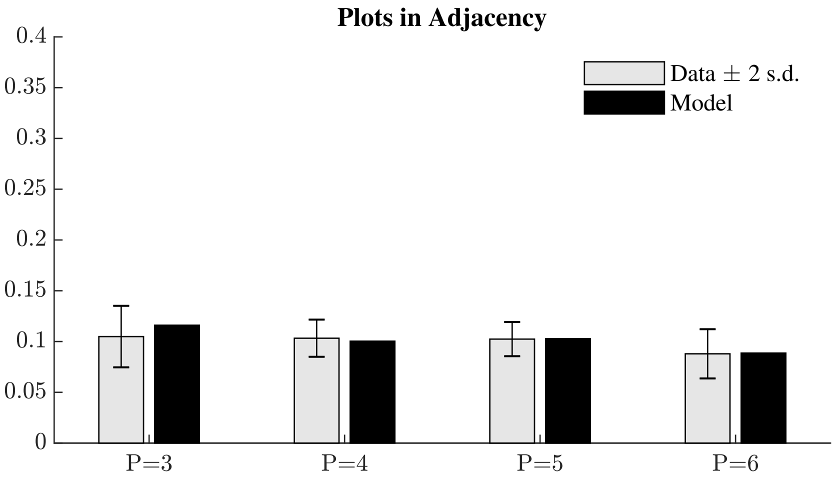


Figure 5: Drilling propensities: model vs data

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

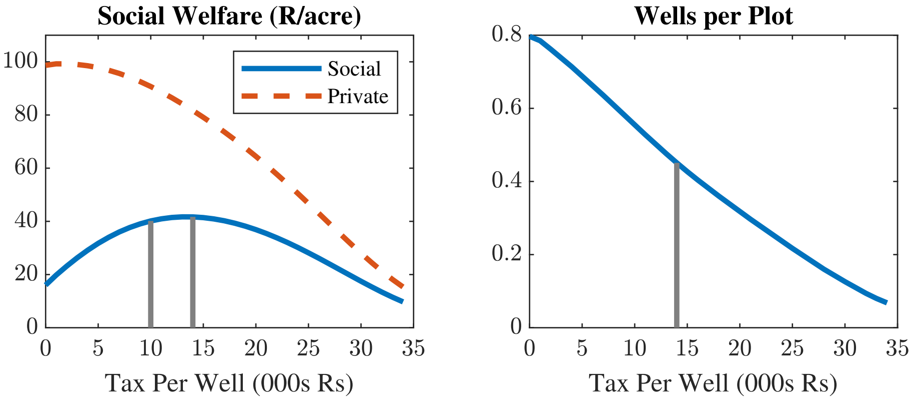


Figure 6: Social welfare (000s Rs per acre) as a function of yearly tax per functioning well

Transitional Dynamics

- We now compute how long it takes for the ground water economy to transition to the new steady state under the counterfactual optimal drilling tax.
- For this purpose we solve for the transition using a shooting algorithm.

Transitional Dynamics

Shooting on beliefs

1. Solve the model for the initial and the final state and recover $V_{t=0}(X)$ and $V_{t=final}(X)$
2. Set a large number of periods for the transition to take place ($t_{final} = 500$)
3. Make a guess of the beliefs $F_k(X'|X, t)$.
4. From $t = final$ to $t = 1$, by backwards induction, solve for $V_{k,t-1}(X)$ and $CCP_{k,t-1}(X)$ given $V_{k,t}(X')$ and $F_{k-1,t}(X'|X, t)$.
5. Simulate the transition and compute $F_{k,t}(X'|X, CCP_{k,t})$.
6. If $||CCP_{k,t} - CCP_{k-1,t}||$ is small enough for all t, done. Otherwise go to 3.

Transitional Dynamics

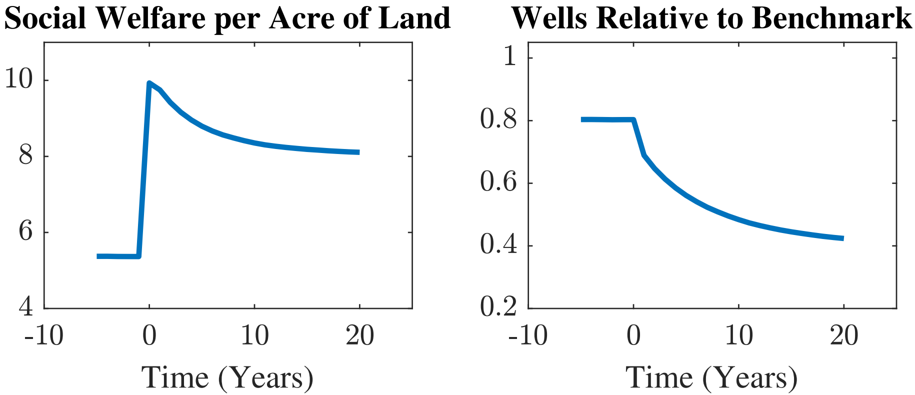


Figure 7: Transition between benchmark economy and economy with paid electricity

Conclusions

- Preliminary estimates imply large welfare losses from drilling subsidies:
  - Drilling subsidies decrease social welfare by around 20,000 Rupees per acre.
- It takes around 5 years to cover half of the distance to the new steady state.
- There are no social welfare losses over the transition as wells are a sunk cost.