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Efficient Irrigation and Water Conservation

Evidence from South India

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Abstract

Widespread adoption of efficient irrigation technologies, including drip irrigation, has been proposed as a means of limiting groundwater overexploitation, especially in the intensively farmed and water-stressed South Asia region. This paper reports on a randomized controlled trial conducted in the Indian state of Andhra Pradesh to evaluate the potential productivity and water-saving benefits of smallholder drip irrigation. A group of well-owners was encouraged to adopt drip irrigation through a subsidy scheme, whereas a control group was left to its own devices. The results indicate that, after three years, the drip group shifted into more remunerative and irrigation reliant crops, enjoyed higher agricultural revenue, and transferred (primarily through cash sales) more of its groundwater to adjacent plots. In terms of groundwater pumping, which has zero marginal price in this setting, there is precisely zero difference between the drip and control groups. The evidence thus suggests that drip adoption in South India, while increasing irrigation efficiency, will not save groundwater.

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Efficient Irrigation and Water Conservation: Evidence from South India*

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1 Introduction

Rapid depletion of groundwater is an emerging threat to agriculture-led rural development, especially in the densely populated and semi-arid regions of South Asia. In the face of water scarcity, sustaining the increased agricultural intensification that has steadily raised rural living standards since the dawn of the Green Revolution must involve improvements in irrigation efficiency. Indeed, the potential for new and relatively cheap irrigation technologies to alleviate growing global water stress has been hailed by scientists, economists, and policy makers alike (Postel et al., 2001; Tilman, 1999; Foley et al., 2011). One of the principal means by which the government of India is addressing its own looming groundwater crisis is through the promotion of agricultural water-use efficiency on a large scale. Massive government resources are being invested in a program that offers millions of smallholders 50%-90% subsidies on drip and sprinkler irrigation systems, technologies that promise to increase crop productivity while simultaneously reducing per acre water requirements.

The extent of government investment in these technologies stands in contrast to the paucity of experimental evidence on their actual performance when used by smallholder farmers, especially in regards to water conservation. It is not uncommon for technologies that are proven in agronomic trials or in modern commercial farms to fail to achieve the same result in the smallholder, low income farming context. Moreover, even if small farmers realize the technology's potential to improve water-use efficiency, such improvement need not necessarily reduce overall water consumption, especially if farmers face zero marginal cost for irrigation. In a context where agricultural land remains idle or underutilized, as is the case in much of India during the dry season, and especially where groundwater markets are active, farmers may adjust their water application along the extensive margin to leave overall groundwater pumping unchanged.

We implemented a randomized controlled trial in the Indian state of Andhra Pradesh with well-owners who did not previously own a drip system to measure the impact of drip irrigation adoption on water use and sales, cultivation patterns and agricultural revenue. As far as we are aware, our results provide the first experimental evidence on the benefits of drip irrigation to smallholder farmers and on the extent of water conservation. Farmers in Andhra Pradesh can receive up to a 90% government subsidy on their first installation of drip irrigation, a system that typically costs around USD 1,000 per acre. We offered randomly selected households assistance with filing the paperwork and an additional 10% subsidy that reduced the cost of the equipment to zero, requiring them only to finance the necessary land preparation costs to install the system.

This encouragement design led to modest take-up, with about 35% of treated households adopting drip, an increase of only 16 percentage points (p.p.) over the control sample, which was also eligible for the state subsidy. Despite this limited compliance, we estimate significant shifts in cropping patterns and positive impacts on agricultural revenue on the treated reference plot (a plot with a functioning well in which the drip system is installed). By contrast, we do not find any reduction in pumping from the reference well, and this zero effect is precisely estimated. We do find, however, an increase in irrigation provided by the reference well to adjacent plots, particularly through water sales. When electricity for running groundwater pumps is free at the margin, as is the case in Andhra Pradesh (and much of India, for that matter), rather than conserving water farmers prefer to maximize pumping and sell the excess water to adjacent plots.

Our results add to the numerous agronomic and observational studies that investigate the performance of drip irrigation, some of which are set in developing countries (e.g., Narayanamoorthy, 2004; Sezen et al., 2006; Kumara and Palanisamib, 2010, and work cited therein). These studies often find shifts in cropping patterns, higher yields and higher water productivity, but are mostly based on small samples and do not deal with selection bias. Specifically, farmers who take up drip irrigation may be more likely to be wealthier, more progressive and risk-taking and, therefore, may cultivate more intensively and extensively even in the absence of drip. An exception is Burney et al. (2010), who address selection using difference-in-differences to find substantial consumption and nutritional impacts of collective systems of drip irrigation in two villages in Benin. Critically, however, no developing country study of drip irrigation considers farmer responses along the extensive margin and particularly the role of groundwater markets, which are pervasive across South Asia and India in particular (Saleth, 2014). We are also not aware of any prior experimental evaluations of drip irrigation.

Multiple studies have assessed whether water-saving technology can arrest groundwater depletion in the US context, mostly using integrated hydrological-economic-agricultural models calibrated on river basins (Ward and Pulido-Velazquez, 2008; Peterson and Ding, 2005; Huffaker and Whittlesey, 2003; Scheierling et al., 2006; Huffaker and Whittlesey, 2000). Other, principally theoretical work, considers the interaction between water markets and the adoption of water-saving technologies; but it too is confined exclusively to the US context (Carey and Zilberman, 2002; Dridi and Khanna, 2005). In an important study, Pfeiffer and Lin (2014) use panel data from Kansas to find that adoption of water-efficient center pivot irrigation led to an increase in groundwater use through both a decrease in fallow and a shift to more water-intensive crops. Groundwater markets, however, are not relevant in this setting.

Grafton et al. (2018) have recently written of the "paradox of irrigation efficiency," part of which is that water-saving technologies lower the shadow price of water at the farm-level. In the context of India, Fishman et al. (2015) show that the positive cultivation response has the potential to greatly mitigate the groundwater-saving impact of drip adoption, but, as noted, there is virtually no evidence on the magnitude of this response in practice. As far as we are aware, our study provides the first evidence of this kind. It suggests that in the absence of other incentives, such as a price on water usage and/or for the electricity to pump water, subsidizing technologies like drip irrigation can be an effective strategy for the expansion of irrigation, but not for conserving water or arresting the decline of groundwater tables.

2 Context and Conceptual Framework

India is the world's largest user of groundwater (Aeschbach-Hertig and Gleeson, 2012). Groundwater irrigation covers more than half of the total irrigated area, is responsible for 70% of production, and supports some 50% of the population (Langseth and Stapenhurst, 1998; Shah, 2010). However, there is growing evidence that over-extraction of groundwater is depleting aquifers across the country (Rodell et al., 2009; Tiwari et al., 2009; Pahuja et al., 2010; Shah, 2009). While the efficient way to manage the resource would be to price the use of water (and the energy used to pump it), political and technical constraints often prohibit pricing, especially in developing countries. In India, groundwater is neither regulated nor priced, and even the electricity used for pumping is heavily subsidized and often priced at a flat tariff, if at all (Badiani et al., 2012; Fishman et al., 2016).

In lieu of pricing, India rations power for pumping (Ryan and Sudarshan, 2020) and has moved to the promotion and subsidization of water-efficient cultivation technologies. India's National Mission on Sustainable Agriculture (NMSA) is perhaps the largest such program in the world, offering 50%-90% subsidies on drip and sprinkler irrigation, technologies that promise to increase crop productivity and simultaneously reduce per acre water requirements. In the study areas, the NMSA is implemented through the Andhra Pradesh Micro Irrigation Project (APMIP) with the assistance from the government of India and state government.[1] In particular, the central government provides 40% of the cost of the drip system, contingent on an additional 10% or more being offered by state governments. There is considerable variation in the level of subsidy across states. Andhra Pradesh offers a subsidy of 50%, resulting in a total subsidy of 90%. The maximum amount that farmers can receive depends on their landholdings. For the smallest total landholding category (< 10 acres), the maximum is 100,000 Rs. per farmer, which at current prices allows for a 2-acre drip system, depending on various factors including the crop grown. Farmers who have already applied for the subsidy in the past are ineligible to receive additional subsidies for a period of 10 years.

A drip system is made up of evenly spaced emitters along parallel laterals (rubber hoses) where water flows near the crops' roots, rather than to the entire field (see Figure 1 for a schematic). This system has several benefits, including irrigation efficiency (crop yield per unit of water applied) which can increase by as much as a factor of two or more; stable levels of soil moisture which enhance plant growth and yields; limited weed growth, potentially reducing labor costs; and fertilizers that can be applied directly into the water flow ("fertigation"), enhancing yields and reducing labor costs. All of these benefits, if realized, can contribute to higher profits per acre as well as to reducing per acre water requirements.

Although groundwater extraction in rural India is not priced, it is constrained by the number of hours per day with available electrical power to run the pump; power is rationed to agriculture in most Indian states (Ryan and Sudarshan, 2020), including in Andhra Pradesh. Well-owners and their neighbors may therefore be forced to leave some of their land fallow in the dry season, or to cultivate crops with low water requirements. As drip adoption improves irrigation efficiency, this water constraint may be relaxed and farmers may adjust by cultivating more of their land previously left fallow, by switching to more water-intensive crops, or by transferring water to neighboring plots via sales or other arrangements (Giné and Jacoby, 2020). While these behavioral responses would increase the income of the drip adopter (as well as, possibly, that of the neighboring farmers), they may not lead to a reduction in overall groundwater pumping, especially when the farmer lacks incentives to do so.

In sum, the impact of drip irrigation on overall water use remains an open empirical question, and one with substantial practical implications for India's agriculture and the state of its groundwater resources.[2]

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[1] As stated in its website, the goal of APMIP is to "improve the economic conditions of the farmers by conserving water, bringing additional area into cultivation with the available water resources, enhancing the crop productivity and production, quality, facilitating judicious usage of ground water, saving in power consumption and cost of cultivation."

[2] Drip irrigation is likely to reduce the magnitude of return flows, unused irrigation water that percolates back into the aquifer (Maréchal et al., 2003). Due to reductions in return flows, even if groundwater extraction is unchanged, the net effect on groundwater balance may be negative, although this depends on aquifer characteristics (Grafton et al., 2018).

3 Experimental Design and Empirical Strategy

3.1 Intervention and Mode of Delivery

Commercial suppliers certified by the government can sell drip equipment to farmers at regulated prices and be eligible for the subsidy. To apply for the subsidy, the farmer must present several documents, including a certificate of land ownership and a legal electricity connection for the pump, at the local AP-MIP office. The application process is often facilitated by the supplier. Once the farmer pays the remaining 10% of the cost of the drip system and the application is approved, the farmer prepares the land and the drip supplier installs the equipment. Land preparation entails digging trenches for the (underground) main and submain lines, the cost of which amounts to roughly 60 USD on a 2-acre drip system. Finally, once the government verifies the installation, the remaining 90% of the costs are transferred directly to the supplier.

Our study was conducted in three districts of Andhra Pradesh (Anantapur, Kadapa, and Guntur) and was carried out in cooperation with Jain Irrigation (JI), the largest provider of drip irrigation in India. The intervention consisted in offering help with the subsidy application and an additional subsidy to cover the remaining 10% of the farmer share to a randomly selected group of farmers with a functioning well but without a drip system.

3.2 Sample and Data

The first step was to identify a sample of borewell owners eligible for the AP-MIP subsidy program. Eligible farmers had to own less than 10 acres of land, not to have had already received the subsidy in the past ten years, and had to have official proof of land ownership (land passbook) and a legal electricity connection for the borewell. We started in villages with active groundwater markets from the 2012 Groundwater Markets Survey (henceforth GMS; see Giné and Jacoby, 2020), but subsequently expanded the sample to include additional villages in Anantapur and Kadapa (also pre-screened for having significant numbers of borewell owners and groundwater market activity). We administered a filter survey to 2,192 farmers in all, identifying 1,699 eligibles.[3] Due to budget constraints, however, our study sample only includes 862 eligible farmers located in 32 sub-districts. These farmers were randomized into control and treatment groups, stratified by district. Because of the high cost of the treatment, the control group was designed to be about 20% larger than the treatment group.

A baseline survey was administered in mid-2016 among the sample of 862 eligible farmers; immediately after finishing the survey, enumerators revealed the respondent's treatment status by means of a pre-assigned scratch-card. The survey covered agricultural production on the reference plot over the previous dry (rabi) season, including area irrigated, crops grown, investment in various inputs (including seeds, fertilizer and labor), yields, revenue, hours of borewell operation (if one is present on the plot) and details of water transactions with adjacent plots. An endline survey along similar lines was administered in August 2019.

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[3] In addition to the administrative eligibility criteria, we also excluded respondents with multiple irrigated plots (about 15% of borewell owners) because they might have chosen to use the subsidy to install drip irrigation using a well other than the reference borewell.

In order to account for the localized nature of groundwater markets (the vast majority of water transactions occur between adjacent plots), the unit of analysis for the study is the adjacency of the reference borewell, that is, the reference plot itself (a plot with a well where the drip system could be installed) and the plots adjacent to it, as illustrated by the area within the red double thin lines in Figure 2. As in the GMS survey, data was collected from the owner of the reference borewell on his reference plot (the red cell) as well as on water transfers to any of the adjacent plots (orange cells). No information was collected on the outer ring of plots (yellow cells). According to our baseline survey data, there is an average of 4 plots per adjacency and 2.5 borewells, including those on the reference plot. Excluding the reference plot, around 65% of plots in the adjacency are cultivated in the dry season and around 50% have a functioning borewell.

Of the 862 farmers interviewed at baseline, we were able to re-interview 843 at endline. This low attrition rate (less than 3%) did not differ significantly by treatment status or other farmer attributes. Note, finally, that although 3 years elapsed between collection of baseline and endline data, not all of the farmers who adopted drip irrigation due to our intervention necessarily used it for 3 rabi seasons as there were often significant delays in assembling the paperwork for the government subsidy.[4]

Table 1 presents descriptive statistics and balance checks for the study sample, including characteristics of farmers, their reference plots, and their borewells. Column 1 reports the mean characteristics for all study subjects. Farmers average about 50 years of age, have 4.3 years of education, and own about 3.6 acres of land in total. Average reference plot area is about 2.3 acres, virtually all of which was cultivated (and thus irrigated) during the dry season of 2015-16. The average reference borewell has a depth of about 395 feet and has a 10 HP pump (modal pump has 7.5 HP). About 75% of the reference wells are individually owned, with the rest co-owned by other farmers, who are usually relatives.

Except for plot area, the rest of the owner and plot characteristics are balanced across the control and treatment groups. The pipe width of reference wells from farmers in the control group appears to be larger than that in the treatment group, but while the difference is statistically significant, it is small. Reference wells in the treatment group also appear to be deeper than those in the control group by 33 feet. We follow Bruhn and McKenzie (2009) and include these two characteristics that are imbalanced as control variables in our regressions.

3.3 Estimation

Treatment effects are estimated using the following specification:

$$Y_{i1} = \alpha T_i + X_i\prime\beta + \gamma Y_{i0} + \epsilon_i, \tag{1}$$

where Y_{i1} refers to an outcome of borewell, plot or adjacency i at endline, T_i is a treatment dummy that takes value 1 if the owner of the reference plot i was offered help with the paperwork application and the additional subsidy for a drip system, X_i is a vector of plot or well characteristics, including those with imbalance, and Y_{i0} is the value of the outcome at baseline. Controlling for baseline outcomes, as in equation (1), is more general than a difference-in-differences specification.

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[4] Because of endogeneity concerns, we do not exploit variation in number of seasons of experience with drip in our analysis; that said, it may contribute to heterogeneity in treatment effects.

The parameter α in equation (1) represents the "Intent-to-Treat" (ITT) effects, the average impacts and responses to the *offer* of drip irrigation installation. In addition to the ITT, we also estimate the impact of the treatment on the treated (ToT) by applying instrumental variables to equation (1), i.e., instrumenting drip adoption with T_i. The ToT represents the average impact of drip adoption on those who took it up.

4 Results

We begin by examining the impacts of the intervention on outcomes related to cultivation on the reference plot, we then turn to the same outcomes in adjacent plots, then to pumping intensity and finally to revenues on the reference plot.

4.1 Reference Plot Cultivation

Panel A of Table 2 reports estimates of the specification in (1) for several outcomes related to cultivation. Each row corresponds to a separate regression. Column 1 reports the mean value of the outcome in the control group, Column 2 reports the ITT estimate, while Column 3 reports the ToT (IV) estimate.

The take-up of the drip offer was underwhelming. As reported in the first row of Table 2, about 20% of the control group (all of whom were eligible for the 90% government subsidy) had installed a drip system in the reference plot by the time the endline survey was collected. Treatment still resulted in a 16 percentage point (p.p.) increase in the adoption of drip irrigation in the reference plot and a similar proportionate increase in reference plot area covered by drip irrigation (row 2). Although drip installation may enable farmers to avoid having to leave their plots fallow because of water scarcity, we do not find that treatment reduced the incidence of leaving reference plots fallow (row 3). There is, however, a *decrease* in the likelihood that the reference plot was fully cultivated, a mechanical consequence of the fact that, in 40% of cases, the drip system did not fully cover the area of the plot.

In response to the offer of drip, we find that farmers shift towards crops more amenable to efficient irrigation, particularly high-value horticultural crops that are reliant on steady soil moisture, such as tomatoes. Treated farmers are twice as likely to plant such crops in the reference plot.

4.2 Adjacent Plots

In panel B of Table 2, we report treatment effects related to cultivation on plots surrounding the reference plot. About 14% of these plots have drip installed in the control group, and treatment reduces this likelihood by 3 p.p. This decrease could potentially reflect reduced motivation to invest in water efficiency given greater water availability from the reference well, or, alternatively, the increased saliency of a potential future subsidy through AP-MIP given proximity to a beneficiary. At any rate, the coefficient is small and insignificant in the IV specification.

A central question of this study is whether any water saved on the reference plot might be used to irrigate adjacent plots. As with reference plots, we do not find evidence that adjacent plots were more or less likely to be left fallow (or to be fully cultivated), which indicates that drip irrigation in the reference plot did not affect the extensive margin of cultivation in the adjacency. However, we do find significant increases in the likelihood that an adjacent plot is irrigated by a "treated" reference well. Whereas 37%

of adjacent plots in the control group are irrigated by the reference well, this rate increases by 7 p.p. in the treatment group, and by 53 p.p. as a result of drip installation (IV estimate). The adjacency area irrigated by the reference well increases by 0.16 acre as a result of treatment, and by 1.2 acres as a result of drip installation (IV). Given the zero estimated extensive margin effect, we may interpret the additional irrigation received by adjacent plots as an increase in the frequency of watering.

In our study area, water is transferred to adjacent plots under various arrangements, including sales in informal water markets, co-ownership of wells by adjacent land owners, and sometimes leasing of adjacent land. Water is sold to only 4% of adjacent plot owners in the control group, but treatment increases sales by 3 p.p. and installing drip irrigation by 22 p.p. (IV). There is also a commensurate increase in revenue from water sales in the treatment group. Even though most water transfers in the control group (22%) occur through the joint ownership of wells or other arrangements (11%), neither category of transfers responds significantly to treatment.

4.3 Overall Water Use

Does the installation of drip irrigation conserve water? We have seen evidence of an increase in irrigated area, suggesting that whatever water is saved on the reference plot is at least partially applied elsewhere. To assess the overall impact on groundwater use, we would ideally measure the volume of water pumped on both treated and control plots. Since such volumetric metering is impractical, however, we use the duration of pump operation as a proxy for overall water extraction.

Treatment effects on pumping behavior are shown in Table 3. Farmers report that they have 30 days of electricity service per month during the rabi season, but that it is limited to 8 hours per day, consistent with the rationing practices of local power utilities. On average, respondents in the control group operate their pump for 16 of these 30 days and, on these days of operation, report about 3.3 hours of "saving" during which the pump is not on even though electricity is available. Respondents do not use their pump on the remaining days of the month because of lack of water in the well or pump malfunction. There is, on average, only 0.3 day of "saving" in which farmers do not operate the pump even though both electricity and water are available (and their pump is working). Anecdotal evidence suggests this is also the reason that farmers do not use the entire 8 hours available to them per day: wells tend to dry up after being pumped for several hours, and water flow only recovers after a long pause in pumping.

Treatment has no impact on any of the above measures of pump usage. Coefficients are small and confidence intervals are tight. For example, there is a difference of about 0.5 (s.e. 0.7) day of pumping between control and treatment, compared to the control mean of 16 days. The difference in the number of hours without pumping is 0.5 hour, compared to a mean value of 3.7, but the confidence interval is wider (s.e. 0.2).

4.4 Revenue

Turning finally to the direct benefit of drip, while there is no effect of treatment on total reference plot area cultivated, we do find an increase in revenue. Table 4 reports results for various measures of revenue based on the inverse hyperbolic sine (IHS) transformation.[5] Whether it is measured in total or per acre terms, and whether it includes water sales or not, revenue increases significantly due to treatment. While the IV estimates are marginally insignificant at the 10% level, the estimated ToT effects are very large, e.g., about a 150% increase in revenue per acre. Since these estimated impacts include the effect of crop shifting, they cannot be compared to estimates from the agronomy literature for a fixed set of crops. We emphasize that the confidence interval for this estimate is wide and thus we cannot exclude substantially smaller or larger impacts. By contrast, there is no evidence of higher or lower input costs (total investment) on the plot, suggesting that drip installation was profitable for adopters.[6]

Farmers' own assessments of the benefits of drip irrigation at endline are consistent with these results. As reported in Table 6, the mean farmer believes that drip irrigation can result is an about 40% increase in yields, but no substantial reduction in cultivation costs. Perhaps surprisingly, these assessments do not differ between control and treatment farmers, potentially owing to the rather widespread diffusion of the technology in the area.

5 Discussion and Conclusion

We implemented a field experiment in the Indian state of Andhra Pradesh to experimentally evaluate the performance of a heavily promoted water saving technology on cultivation, water use and water markets. We find that the adoption of drip irrigation shifts cropping patterns to more remunerative and irrigation reliant crops, and thereby increases revenue on the plot with drip. Although we do not measure groundwater extraction or use directly, we find increased transfers of water from the treated plot to adjacent plots, primarily through water sales. Because we find no evidence of reductions in pumping, it appears that drip irrigation allows farmers to reduce water usage on the treated plots and to transfer excess water to adjacent plots. More generally, we conclude that, in settings where both groundwater itself and the electricity required to extract it are unpriced, and in which cultivation is severely constrained on the extensive margin, the adoption of water-saving technologies is not likely to result in much water saving.

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[5] Such a transformation is appropriate as it seems more natural to expect drip to have a roughly proportional, rather than linear, effect on revenue across a variety of crop types with different levels of baseline revenue, and because the data contains zeros.

[6] When costs of cultivation are separated into different components (land preparation, seeds, fertilizer, labor, etc.), we find no statistical differences in any of the components except for tractor costs in land preparation, which are lower among those offered drip (p-value is 0.089, results not shown).

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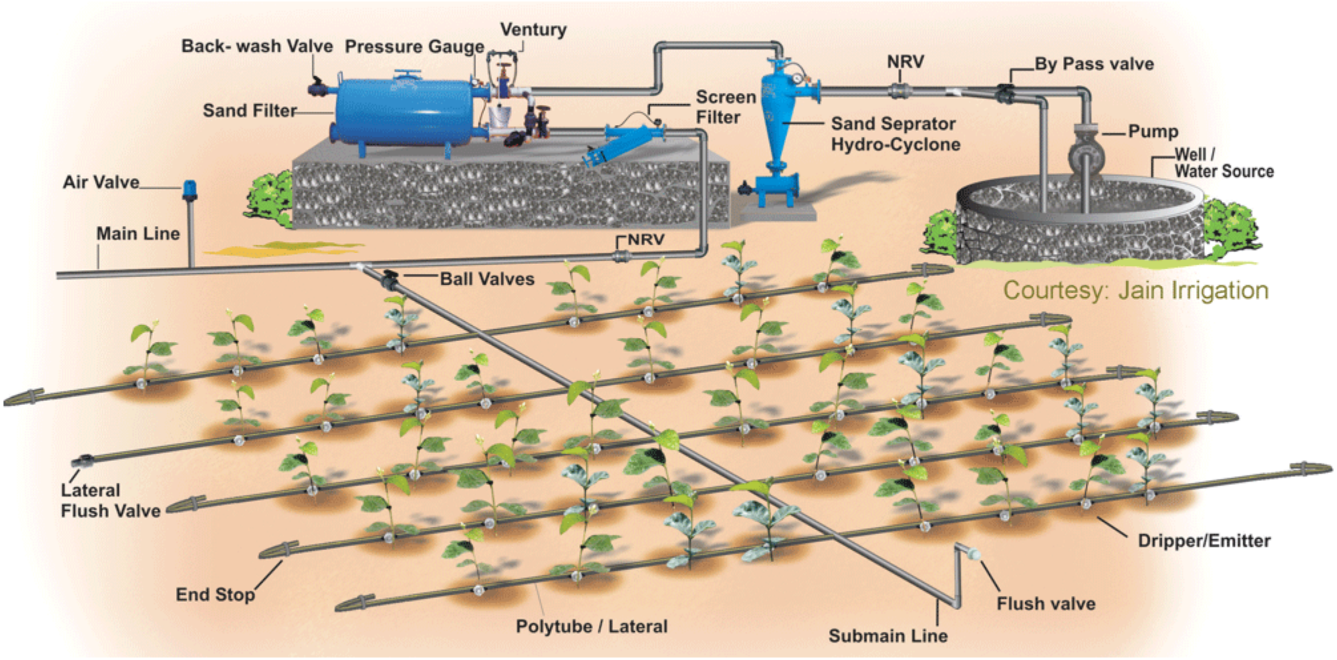
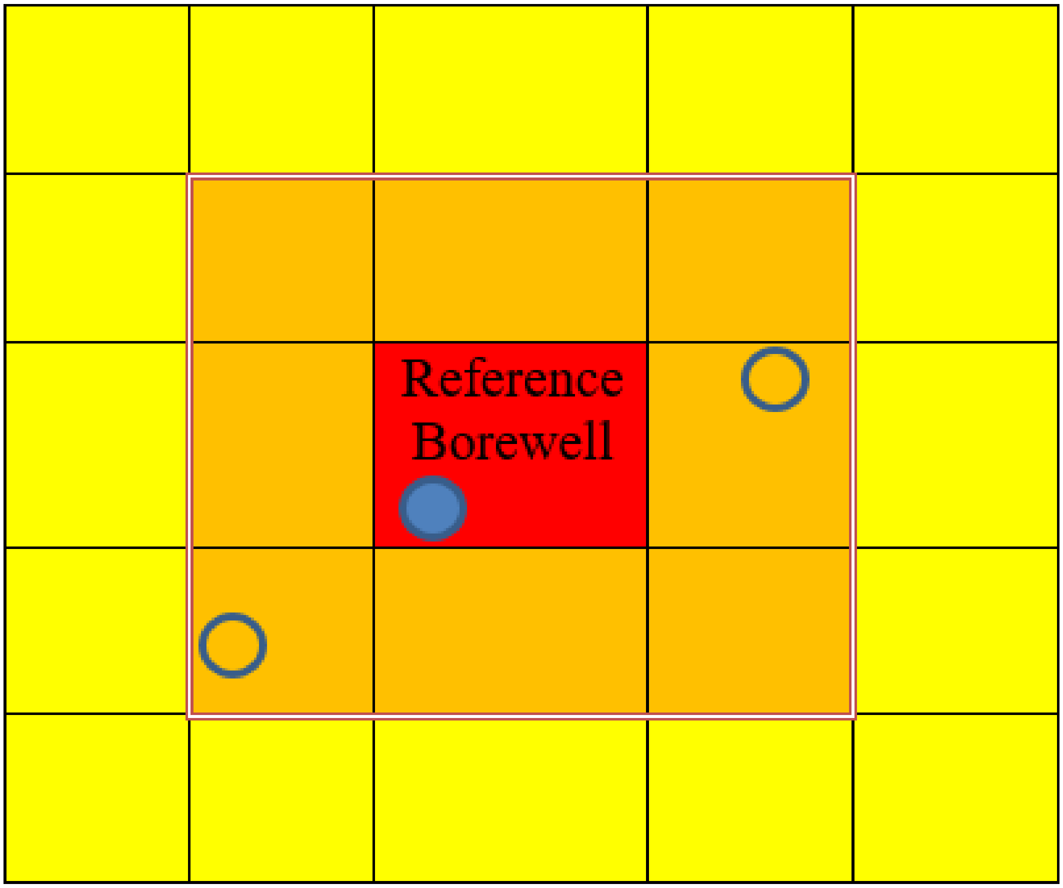
Figures and Tables



Notes: Diagram shows the main line, submain line and laterals. The main line and submain line are installed underground, while the laterals are above the surface.

Figure 1: A drip irrigation system



Notes: The reference plot, in which the reference well (solid blue circle) is located, is marked in red. The adjacency includes contiguous plots to the reference plot, marked in orange. Some of those plots may also have their own wells (hollow blue circles). Data on plots further away (marked in yellow) are not collected.

Figure 2: Schematic Representation of the Unit of Analysis

Table 1: Balance Checks

	(1) All	(2) Control	(3) Treatment	(2)=(3) P-value
Gender of plot owner (1=male)	0.788	0.781	0.796	0.934
Age of plot owner	49.27	49.70	48.60	0.298
Plot owner is forward caste (1=yes)	0.498	0.466	0.537	0.111
Years of education of plot owner	4.331	4.302	4.366	0.866
Total landholdings of plot owner	3.627	3.705	3.532	0.155
Plot owner grows traditional crops (1=Yes)	0.586	0.607	0.560	0.114
Plot owner grows new crops (1=Yes)	0.236	0.223	0.251	0.852
Plot area (acres)	2.286	2.370	2.184	0.002***
Share of plot area cultivated in Rabi 2015-16	0.964	0.959	0.971	0.269
Number of functional wells in the plot	1.030	1.030	1.029	0.725
Number of functioning wells in the adjacency (exc. ref plot)	1.549	1.612	1.474	0.11
Well is individually owned (1=Yes)	0.749	0.761	0.733	0.283
Well flow at start of Rabi 2015-16	0.977	0.978	0.977	0.617
Well intra flow in Rabi 2015-16	0.350	0.355	0.344	0.268
Well pipe width	2.363	2.380	2.343	0.089*
Well depth of well	395.2	380.2	413.2	0.014**
Well pump HP	10.41	10.26	10.58	0.495
Observations	843	461	382	
F-test of joint significance (p-value)				0.033**
F-test, number of observations				840

Notes: Mean values of baseline variables, marked on the left hand side, are reported for the full (Column 1), control (Column 2), and treatment (Column 3) samples. Column 4 reports p-values of T-test comparing the control and treatment samples. Fixed effects at district level are included in the estimation regression. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 2: Impact of a Drip System on Cultivation and Water Sales

	(1) Dep. variable among control group	(2) (ITT)	(3) (IV)	(4)
	Mean *SD*	Coef. Std. Error	Coef. Std. Error	N. Obs.
Panel A: Reference Plot				
Plot has drip irrigation (1=Yes)	0.195	0.158***		843
	0.397	(0.030)		
Plot Area Under Drip (incl. 0)	0.376	0.209***	1.335***	843
	0.866	(0.058)	(0.182)	
Plot was left fallow in Rabi 2018-19 (1=Yes)	0.193	-0.001	-0.004	843
	0.395	(0.028)	(0.176)	
Plot is fully cultivated (1=Yes)	0.646	-0.062*	-0.395*	843
	0.479	(0.033)	(0.222)	
Plot had area cultivated under new crops (1=Yes)	0.085	0.098***	0.742**	622
	0.280	(0.028)	(0.289)	
Area cultivated under new crops	0.171	0.186***	1.381**	622
	0.630	(0.059)	(0.569)	
Area cultivated under traditional crops	1.245	-0.068	-0.516	622
	1.293	(0.085)	(0.633)	
Panel B: Adjacent plots				
Plot has drip irrigation (1=Yes)	0.135	-0.030*	-0.220	2,574
	0.341	(0.018)	(0.162)	
Plot Area Under Drip (incl. 0)	0.302	-0.083*	-0.611	2,574
	0.922	(0.045)	(0.405)	
Plot was left fallow in Rabi 2018-19 (1=Yes)	0.234	0.009	0.066	2,574
	0.481	(0.028)	(0.214)	
Plot is fully cultivated (1=Yes)	0.637	-0.040	-0.296	2,574
	0.423	(0.025)	(0.185)	
Ref. well provides irrigation (1=Yes)	0.371	0.071**	0.526**	2,574
	0.483	(0.030)	(0.263)	
Ref. well provides irrigation through water sales (1=Yes)	0.041	0.031*	0.225*	2,574
	0.198	(0.016)	(0.130)	
Ref. well provides irrigation through JO (1=Yes)	0.224	0.037	0.271	2,574
	0.417	(0.025)	(0.197)	
Ref. well provides irrigation through other schemes (1=Yes)	0.107	0.003	0.021	2,574
	0.309	(0.022)	(0.165)	
Hyp. sine transformation of revenue from water sales	0.331	0.276**	2.027*	2,574
	1.617	(0.132)	(1.105)	
Area irrigated by reference well	0.813	0.162**	1.193*	2,574
	1.316	(0.077)	(0.650)	
Area irrig. by ref. well through sales	0.071	0.091**	0.669**	2,574
	0.401	(0.039)	(0.332)	
Area irrig. by ref. well through JO	0.498	0.062	0.454	2,574
	1.122	(0.059)	(0.445)	
Area irrig. by ref. well through other schemes	0.244	0.008	0.057	2,574
	0.814	(0.056)	(0.413)	

Notes: Estimated impacts of treatment for outcomes indicated on the left. Column 1 reports the mean (and s.d.) value of the outcome in the control group. Column 2 reports ITT estimates. Column 3 reports impacts on the treated using an IV specification. All regressions control for unbalanced baseline variables (area of reference plot, the pipe width and the depth of the reference well), district fixed effects and the value of the dependent variable at baseline. In panels A, C and D, the sample consists of all farmers, and robust standard errors are reported in parentheses. In Panel B, the sample includes all adjacent plots and standard errors are clustered at the adjacency level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3: Impact of a Drip System on Water Pumping

	(1) Dep. variable among control group	(2) (ITT)	(3) (IV)	(4)
	Mean *SD*	Coef. Std. Error	Coef. Std. Error	N. Obs.
Days with electricity	30.09	-0.085	-0.539	843
	0.881	(0.058)	(0.382)	
Days pumping	15.77	-0.478	-3.113	843
	10.02	(0.700)	(4.641)	
Days not pumped due to pump malfunction or lack of water	15.92	0.417	2.658	843
	8.919	(0.612)	(3.977)	
Days saving	0.281	0.039	0.251	843
	1.202	(0.078)	(0.512)	
Hours with electricity	8.203	0.027	0.174	843
	0.810	(0.061)	(0.382)	
Share of months farmer used all hours with available electricity	0.387	0.003	0.021	843
	0.449	(0.031)	(0.199)	
Hours saving	3.369	-0.047	-0.299	843
	2.922	(0.206)	(1.303)	

Notes: Estimated impacts of treatment for outcomes indicated on the left. Column 1 reports the mean (and s.d.) value of the outcome in the control group. Column 2 reports ITT estimates. Column 3 reports impacts on the treated using an IV specification. All regressions control for unbalanced baseline variables (area of reference plot, the pipe width and the depth of the reference well), district fixed effects and the value of the dependent variable at baseline. In panels A, C and D, the sample consists of all farmers, and robust standard errors are reported in parentheses. In Panel B, the sample includes all adjacent plots and standard errors are clustered at the adjacency level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4: Impact of a Drip System on Reference Plot Revenue

	(1) Dep. variable among control group	(2) (ITT)	(3) (IV)	(4)
	Mean *SD*	Coef. Std. Error	Coef. Std. Error	N. Obs.
Plot area cultivated (IHS)	1.129	0.009	0.058	843
	0.677	(0.019)	(0.121)	
Revenue (000s rupees; IHS)	3.972	0.174*	1.100	843
	2.479	(0.100)	(0.679)	
Revenue per acre (000s rupees)	3.424	0.147*	0.926	843
	2.150	(0.089)	(0.596)	
Revenue, inc. water sales (000s rupees; IHS)	4.256	0.209*	1.328	843
	2.740	(0.127)	(0.866)	
Total investment on plot (000s rupees; IHS)	3.336	0.108	0.684	843
	1.920	(0.066)	(0.442)	

Notes: Estimated impacts of treatment for outcomes indicated on the left. Column 1 reports the mean (and s.d.) value of the outcome in the control group. Column 2 reports ITT estimates. Column 3 reports impacts on the treated using an IV specification. All regressions control for unbalanced baseline variables (area of reference plot, the pipe width and the depth of the reference well), district fixed effects and the value of the dependent variable at baseline. In panels A, C and D, the sample consists of all farmers, and robust standard errors are reported in parentheses. In Panel B, the sample includes all adjacent plots and standard errors are clustered at the adjacency level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 5: Farmers' Assesements

	(1) N	(2) Mean	(3) SD	(4) P10	(5) P50	(6) P90
Panel A. Full Sample						
Expected yield difference: drip vs. no drip system (quintals/acre)	843	8.91	28.93	0.00	5.00	15.00
Expected percentage change in yield	843	0.41	1.02	0.00	0.25	0.80
Expected cost difference: drip vs. no drip system (000 rupees/acre)	843	-3.93	16.25	-13.00	-2.00	5.00
Expected percentage change in cost	843	0.02	0.95	-0.33	-0.13	0.27
Panel B. Controls						
Expected yield difference: drip vs. no drip system (quintals/acre)	461	10.05	31.20	0.00	5.00	20.00
Expected percentage change in yield	461	0.39	0.77	0.00	0.25	0.75
Expected cost difference: drip vs. no drip system (000 rupees/acre)	461	-3.26	16.22	-10.00	-2.00	5.00
Expected percentage change in cost	461	0.04	0.99	-0.38	-0.11	0.33
Panel C. Offered Drip						
Expected yield difference: drip vs. no drip system (quintals/acre)	382	7.53	25.91	0.00	5.00	10.00
Expected percentage change in yield	382	0.44	1.26	0.00	0.25	0.80
Expected cost difference: drip vs. no drip system (000 rupees/acre)	382	-4.72	16.28	-15.00	-2.00	5.00
Expected percentage change in cost	382	0.00	0.89	-0.33	-0.15	0.25

Notes: Summary statistics of farmers' subjective assessments of drip irrigation, for the entire, control and treatment samples (panels A, B and C, respectively).

Table 6: Variable definitions

Variable	**Definition**
Traditional crops	Paddy, cotton, groundnut, pulses, and leafy vegetables
New crops	Red chili, green chili, tomato and flowers
Plot Area Under Drip (incl. 0)	Plot area irrigated by a drip system (0 means no area irrigated area in the ploy)
Plot was left fallow in Rabi 2018-19 (1=Yes)	Plot was not used, neither totally or pacially, to grow any crop
Plot had area cultivated under new crops (1=Yes)	Plot was used to grow new crops. See below definition of new crops
Area cultivated under new crops	In acres
Area cultivated under traditional crops	In acres
Ref. well provides irrigation (1=Yes)	=1 if well in the reference plot provides irrigation to the non-reference plot
Ref. well provides irrigation through water sales (1=Yes)	=1 well in the reference plots provides irrigation through a water sale arrangement
Revenue from water sales	Revenue of reference plot owner from selling water to other plot owners in the adjacency
Area irrigated by reference well	In acres
Plot area cultivated	In acres
"Revenue (000s rupees)"	Revenue, in thousand rupees (only revenues from production sales)
Revenue per acre (000s rupees)	Revenue per acre, in thousand rupees (only revenues from production sales)
Revenue, inc. water sales (000s rupees)	Revenue inc. water sales, in thousand rupees
Total investment on plot (000s rupees)	Total investment on plot, in thousand rupees
Days with electricity	Mean monthly number of days with available electricity (from October 2018 to March 2019)
Days pumping	Mean monthly number of days pumped in month (from October 2018 to March 2019)
Days with pump malfunction	Mean monthly number of days not pumped due to pump malfunction or lack of water (from October 2018 to March 2019)
Days saving	Mean monthly number of days with available electricity less days pumped and less days with pump malfunction
Hours with electricity	Mean monthly number of hours with available electricity in a typical day (from October 2018 to March 2019)
Months all hours with available electricity were used	Share of the six months that all hours with available electricity were used (from October 2018 to March 2019)
Hours saving	Mean monthly hours per day pump was off when electricity was available (from October 2018 to March 2019)
Expected yield difference: drip vs. no drip system (quintals/acre)	Difference between expected yield with drip system less expected yield without drip
Expected percentage change in yield	Expected percentage change in yield with drip system compared with yield without drip
Expected cost difference: drip vs. no drip system (000 rupees/acre)	Difference between expected costs with drip system less expected costs without drip
Expected percentage change in cost	Expected percentage change in cost with drip system compared with yield without drip