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Impact Evaluation of a Solar Powered Drip Irrigation Intervention in Eastern Yemen

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ABSTRACT

Groundwater irrigation supports agricultural production and local food security in arid regions, however costs and accessibility of fuel for pumping are a challenge in conflict-affected contexts. Solar-powered drip irrigation technology can support smallholder farmers in such settings. In this study we estimated the impacts of subsidized solar-powered drip irrigation systems on smallholder farmers' production decisions and household food security via a clustered randomized control trial in eastern Yemen. We found that farmers in the treatment group were significantly less likely to cultivate cereals, more likely to cultivate horticultural crops, and more likely to sell a higher share of their harvests at market during the first season post-intervention. These results provide causal evidence on the impact of solar drip irrigation systems on shifting smallholder farmers' crop production toward higher-value crops. We did not find significant impacts on household food security within the short-term post-intervention period that the analysis covered. These findings also provide preliminary support for investments in solar and drip irrigation technology in Yemen, while acknowledging that more research is needed to address potential negative externalities.

INTRODUCTION

In arid regions that rely on local agricultural production for food security, lack of reliable and sufficient access to water for irrigation is a critical issue. This challenge is compounded in fragile, conflict-affected zones such as Yemen where access to energy (i.e., diesel and electricity) required to pump groundwater is highly unpredictable and prohibitively costly.

Solar energy offers an alternative, renewable energy source for powering irrigation pumps (Lefore, Closas and Schmitter, 2021). By reducing dependency on diesel fuels to pump groundwater, solar-powered irrigation systems lower and stabilize production costs, potentially leading to greater food production and improved food and nutrition security. A study by Buisson *et al.* (2024) in Bangladesh found that farmers who adopted solar-powered irrigation pumps had more profitable agricultural production and higher food security scores, compared to the farmers who were still relying on diesel pumps for irrigation. These benefits were largely driven by lower costs of irrigation and labor.

At the same time, solar irrigation facilitates potential overexploitation of groundwater resources (Closas and Rap, 2017; Balasubramanya *et al.*, 2024). Qualitative interviews reported that the high rate of adoption of solar irrigation in Yemen has incentivized unsustainably high rates of groundwater extraction, and therefore should be combined with policies and technologies that encourage water conservation (Colburn *et al.*, 2025). Drip irrigation is the most well-known technology that improves water use efficiency in Yemen, however the costs of installation are high. In addition, key informants mentioned that farmers lacked knowledge about the best way to implement these systems (Colburn *et al.*, 2025).

Despite the long-term cost savings from reduced fuel needs, the initial investment costs for both solar panels and drip irrigation tubing are high, limiting adoption by smallholder farmers with limited access to credit. As such, combining provision of solar-powered pumping of groundwater with drip irrigation infrastructure is a potential solution to addressing water access challenges while limiting overuse. When bundled together these innovations can improve agricultural outcomes by enabling smallholder farmers to grow higher-value crops, increase their yields, and bolster food security (Hartung and Pluschke, 2018). Solar powered drip irrigation has been shown in Benin to significantly increase production and dietary diversity, household income, and nutritional intake (Burney *et al.*, 2010; Alaofè *et al.*, 2016).

The objective of this study was therefore to determine how access to more reliable and cost-efficient irrigation systems, such as solar-powered drip irrigation, impacts agricultural practices and food security in a fragile and water-scarce setting. We conducted a clustered Randomized Control Trial (RCT) in Hadhramaut, an arid governorate of eastern Yemen, where we randomly selected and assigned wells to treatment and control groups. The wells that were randomly assigned to the treatment group were equipped with solar panels and solar-powered water pumps, and well operators received technical support in exchange for their commitment to supply water to smallholder farmers. The smallholder farmers who were connected to these wells were assigned to the treatment group and received drip irrigation systems.

Our study makes two main contributions to literature. First, we estimated rigorously the effect of solar-powered drip irrigation on smallholder agriculture using a randomized impact evaluation. Studies by Burney *et al.* (2010) and Alaofè *et al.* (2016), while assessing the effects of solar drip irrigation systems, relied on estimation using matched-pair comparison between two villages in the treatment and two villages in the control group. A recent systematic review by Yavuz *et al.* (2025) did not identify other studies that evaluated the impact of solar-powered and drip irrigation combined. Gupta (2019) used a quasi-experimental difference-in-difference approach to evaluate the effects of adoption of solar-powered pumps only, and Fishman, Giné and Jacoby (2023) implemented a randomized controlled trial to study causal impacts of adopting drip irrigation systems only. Similarly, Dyer and Shapiro (2023) implemented a randomized controlled trial in Kenya to study the impact of distributing manual-powered irrigation pumps, in comparison to no irrigation.

Second, we conducted this work in a conflict-affected area where rigorous quantitative research on agriculture is scarce. Previous studies, such as Burney *et al.* (2010) and Alaofè *et al.* (2016), showed evidence on the benefits of solar drip irrigation in Benin, which at that time was considered an economically and politically stable context. High adoption rates of solar irrigation have been observed in conflict-affected contexts and rigorous evidence on the impacts of adoption of such technologies is lacking (Aklan and Lackner, 2021). Understanding the effects of more reliable and efficient irrigation on local food production in a country suffering from extreme food insecurity, is an urgent humanitarian priority.

We found that smallholder farmers in Hadhramaut provided with access to solar powered drip irrigation technology shifted their production choices in favor of greater probability of horticultural crop production in the first season after receiving the inputs, resulting in a higher share of crops sold at market. This result provides support for the effectiveness of subsidizing smallholder technology adoption in fragile settings to increase local production of higher value horticultural crops. While our study observed only crop outcomes in the first season after the intervention, the strong impacts on crop choice and production for the market suggest the potential for eventual downstream impacts on farmer incomes, food security, and local market linkages as farmers increasingly take advantage of the benefits of these complementary irrigation technologies.

BACKGROUND

Yemen is facing one of the world's worst humanitarian crises, driven by over a decade of conflict which has compounded longstanding vulnerabilities. Almost half of the population, approximately 17 million people, was estimated to face food insecurity in 2025, including five million expected to face emergency levels of food insecurity (UNOCHA, 2025). While the international community has mobilized to provide humanitarian support and food distribution, experts from both Yemen and international NGOs have increasingly called for investment in local food systems and local production to provide a sustainable solution (Al-Sakkaf, Harper and Thorpe, 2024; Ecker *et al.*, 2023; World Bank, 2022).

Under the current conflict conditions, it is estimated that more than half of Yemen's population depends on agriculture for their livelihoods (FAO, nd). With an annual rainfall of less than 600 mm in most areas and no permanent lakes or rivers, two-thirds of the value of agricultural production relies on irrigation with groundwater (World Bank, 2010).

Wheat and sorghum are important staple food crops and are widely cultivated by smallholder farmers, primarily to meet household consumption needs (Darbyshire, 2020; Nanga, Wadie and Manni, 2025). While these cereals are important for supplying staple calories, their production costs are high by global standards due to limited economies of scale and high capital costs (SMEPS, 2022). Producing higher value horticultural crops has much greater potential to increase smallholder income and food and nutrition security but requires higher inputs.

Groundwater overexploitation is a major challenge in Yemen, particularly in the area surrounding the capital city of Sana'a where water tables have fallen to depths of up to 1,000 m and agricultural production is no longer viable in some areas (Mubarak *et al.*, 2017). The study areas in this paper are situated in the eastern part of Yemen within the catchment area of Wadi Hadhramaut where well depths are relatively shallow, recharge rates are higher and extraction rates are lower compared to Sana'a, although still higher than sustainable (Iskander, 2022).

Groundwater irrigation in Yemen largely relies on diesel-powered pumps to lift water from wells for agricultural use. Diesel prices in Yemen have been highly volatile since the onset of the conflict, with prices in Hadhramaut occasionally reaching up to 15 times pre-crisis levels (Aklan and Lackner, 2021). In spite of Hadhramaut being an oil-producing governorate, Yemen continues to be a major importer of refined petroleum products due to a lack of operating refineries. Local transport and distribution costs and taxes represent about two-thirds of the cost of diesel and are highly sensitive to disruptions caused by the conflict and rent-seeking (ACAPS, 2021).

Given the insecurity of diesel access and the near absence of public electricity provision, combined with the country's abundant sunlight, solar power has rapidly been adopted for agricultural and household use. The use of solar-powered irrigation systems has grown as farmers seek cost-effective and more reliable energy sources for irrigation in the context of fuel shortages and high diesel prices. Fieldworkers from our implementing partner, a Yemeni development agency,[1] had observed high take-up rates of solar irrigation technology by better-off farmers in Hadhramaut. Smallholder farmers, however, have been slower to adopt this technology due to the high initial costs. This observed discrepancy inspired the design of the intervention tested in this study.

METHODS

Intervention locations

The intervention took place at the level of individual wells each serving multiple smallholder farmers. We worked closely with our implementing partner to identify areas suitable for the project, eligible wells and smallholder farmers. Eligibility conditions at the well level were that the well operator has not received similar support before, the well operator had been providing water for

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[1] The implementing partner for this study is anonymized in this working paper. The study authors hope to be able to acknowledge the implementing partner properly in the future.

agriculture to five to nine smallholder farmers, the well is permanent and not at risk of being exhausted, the depth of the well did not exceed 150 meters, and the well operator was willing to participate in 80/20 subsidy scheme (more details in the next section). Smallholder farmers were eligible to be enrolled in the study if they were connected to an eligible well with a water transmission network from the well to the farm, they were intending to cultivate crops in the upcoming planting season (December 2023), they owned 0.25 – 2 hectares (0.6 – 4.9 acres) of agricultural land, and were willing to commit to the intervention conditions during the upcoming agricultural season and throughout duration of the project. A sample of wells to receive the intervention was randomly drawn from a list of eligible wells across five districts in Hadhramaut governorate (Al Qatn, Tarim, Sah, Sayun, and Ghayl Bin Yamin).

Experimental design and intervention

We implemented a clustered randomized controlled trial (RCT),[2] where we randomly selected and assigned 41 eligible wells (clusters) in the following way: i) 16 wells (eight shallow wells below 40 meters, and eight deep wells above 40 meters) were randomly assigned to the treatment group, and ii) 25 wells were randomly assigned to the control group. From the control group, the five wells geographically closest to the treatment wells were removed from the main control sample due to potential for spillover effects. As such, the study enrolled 41 well operators and 253 smallholder farmers that were connected to randomly selected and assigned wells. The assignment of these farmers to treatment, control, and spillover groups matched the random assignment of wells, i.e., smallholder farmers connected to a treatment well were assigned to the treatment group, smallholder farmers connected to a control well were assigned to the control group, and smallholder farmers connected to a spillover well were assigned to the spillover group.

Well operators and respective smallholder farmers that were randomly assigned to the treatment group were provided with financial grants and technical support, as the two components of the intervention. Financial grants of up to $18,000 were provided to each well operator to procure solar panels and solar-powered water pumps in return for a commitment to provide water to four to 10 smallholder farmers. Smallholder farmers were provided with grants of up to $1,200 and involved in a purchasing process organized by the implementing partner to procure a drip irrigation system for 0.5 hectares (1.2 acres) of farming land The financial grants followed a matching grant scheme of 80/20 (80 percent project subsidy, 20 percent beneficiary contribution) to ensure sustainability and ownership of the assets.

The technical support component of the intervention was in the form of a two day long technical training through agronomists and linking the beneficiaries with input suppliers and microfinance institutions. Well operator beneficiaries were trained about the components and operation of solar-powered water pumps, advantages and disadvantages of different types available in the market, maintenance, and safety and security measures during installation and operation. The training also emphasized the importance and methodology of linking solar-powered pumps to a drip irrigation network. Smallholder farmers received training on drip irrigation system installation and

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[2] This RCT was registered as AEARCTR-0012388.

maintenance, modern agricultural techniques, irrigation scheduling, proper fertilization and integrated pest management especially for vegetable crops, an overview of crops that can be grown in the region and the importance of crop diversity, and good harvest and post-harvest practices.

The wells and their respective well operators, as well as smallholder farmers connected to those wells, that were randomly assigned to control and spillover groups did not receive financial grants nor technical support.

According to implementing partner's project reporting, compliance with the randomization was perfect. However, only 71 out of 91 (78 percent) farmers in the treatment group reported owning a drip irrigation system during endline data collection.

Data

Data were collected in two survey waves through in-person interviews with 220 households.[3] The baseline survey was conducted in November 2023 prior to the planting season and before the intervention took place. The endline data were collected approximately one year later, in November 2024, following the completion of harvest from the respective planting season. Both survey rounds gathered information on household characteristics and crop production.

Our working sample consists of 190 households at baseline and endline, where 99 households are from the control group and 91 are from the treatment group. Namely, the endline survey targeted the same 220 households from baseline, however five households refused to participate which led to attrition rate of approximately two percent. In addition, smallholder farmers who were connected to three control wells did not cultivate any crops in the seasons before and after the baseline survey. These farmers therefore did not meet the study eligibility criteria and as such are excluded from the analysis.

Variables

We focused on the outcomes that were likely to be directly affected by the adoption of irrigation technology, given that our data captured immediate, shorter-term, effects of the intervention, i.e., the effects of using a solar-powered drip irrigation system for the first time during only one cropping season. We first looked at the outcome variables that reflected farmers' production choices to cultivate annual crops or forgo planting altogether during the season. Notably, in this context leaving land fallow approximately every other cropping season is a common practice. We defined variables for production decisions: i) *Grew any annual crops* as a binary variable that takes the value of one if a smallholder farmer grew any annual crops during the respective planting season and zero otherwise, and ii) *Grew any vegetables* that takes the value of one if a farmer grew any vegetables during respective cropping seasons, and the value of zero if he did not. Horticultural crops are more suitable for drip irrigation systems than field crops given the higher production value per unit of land area.

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[3] We also surveyed 33 households from the spillover group. These households are not a part of the analysis in this paper.

Second, we generated outcome variables that captured the effects of drip irrigation system adoption on annual crop production: i) *Total cultivated land (acres)* is a sum of all land area under annual crop production during the respective season, ii) *Land under vegetables as a share of total cultivated land*[4] is a percentage of cultivated land devoted to cultivation of vegetables, from total cultivated land during the respective season, iii) *Crop count* reflects the number of different annual crops a household grew during respective seasons, iv) *Total crop production (USD real)* is the total volume of annual crop harvest from respective planting seasons, quantified at the corresponding prices obtained from self-reported sales data,[5] v) *Total crop production per acre (real USD/acre)* is *Total crop production* per acre of land, vi) *Total vegetable production (real USD)* is the total volume of vegetable harvest quantified at the corresponding self-reported prices, and similarly, vii) *Total cereal production (real USD)*[6] is the total volume of cereal harvest quantified at the corresponding self-reported prices, viii) *Total crop sales (real USD)* represents total volume of sold produce at self-reported prices, and ix) *Total crop sales as a share of total crop production* is a percentage of the value of total crop production that was sold by smallholder farmers in our sample, calculated as the value of Total crop sales in USD divided by the value of Total crop production in USD. To account for skewness in the data, we transformed land and crop production variables using inverse hyperbolic sine.

Third, to measure the potential impact of our intervention on household food security we used the Household Dietary Diversity Score (HDDS) and the reduced Coping Strategy Index (rCSI). The HDDS represents the total number of food groups consumed by a household over a given reference period. In our study, consumption was measured using a 24-hour recall of consuming food items from 12 food groups: cereals; roots and tubers; vegetables; fruits; meat, poultry, and offal; eggs; fish and seafood; legumes and nuts; dairy; oils and fats; sugar and honey; and spices and condiments. Each food group was assigned a score of one if consumed over the previous 24 hours, or zero if not consumed. Accordingly, the HDDS ranges from zero to 12. The rCSI is a weighted indicator of household food insecurity that measures household behaviors in response to insufficiency of food or money for food, based on a recall of past seven days. It considers the frequency and severity of five coping strategies that the household had to employ in the seven days prior to the survey, namely: relying on less preferred or less expensive food, borrowing food or relied on help from friends or relatives, reducing the number of meals eaten daily, reducing portion size of meals, and restricting adult consumption to ensure that small children can eat. The RCSI score ranges from zero to 56, with higher scores indicating more severe food insecurity.

Summary statistics and balance check

Table 1 shows that baseline household characteristics were balanced between households randomly assigned to the control and treatment groups, on average. The household heads were on average 47 years old and had completed roughly eight years of schooling, indicating incomplete

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[4] The vegetables category includes potatoes, tomatoes, onions, watermelon, melon, scallions, okra, eggplants, carrots, zucchini, chili peppers, bell peppers, leeks, radishes, watercress, garlic, and pumpkin.

[5] We imputed prices for those farmers who did not sell any crops.

[6] The cereals category includes wheat, sorghum, and Levantine corn.

basic education. The households comprised of around nine members, on average. About 93 percent of households owned livestock, while 15 and six percent owned a tractor and a tractor-pulled plow respectively, on average.

Table 1. Descriptive statistics (pre-intervention period)

Variable	All	Control	Treatment	Significance diff. in means
Household head age (years)	46.71	46.64	46.79	–
	(0.93)	(1.23)	(1.40)	
Household head education (years)	7.84	7.56	8.15	–
	(0.37)	(0.51)	(0.53)	
Household size (persons)	8.83	8.87	8.79	–
	(0.45)	(0.56)	(0.72)	
Ownership of livestock (yes = 1)	0.93	0.95	0.91	–
	(0.02)	(0.02)	(0.03)	
Ownership of tractors (yes = 1)	0.15	0.14	0.16	–
	(0.03)	(0.04)	(0.04)	
Ownership of tractor-pulled plow (yes = 1)	0.06	0.05	0.07	–
	(0.02)	(0.02)	(0.03)	
Sample size	190	99	91	190

Notes: Reporting Mean and Standard Deviation in parentheses. For indicator variables we report %. Significance for the difference in means: Not statistically significant (–) p>0.01, *** p<0.01, ** p<0.05, * p<0.1.

Most of the outcome variables measured at baseline were also balanced between the control and treatment groups on average, as shown in table 2. The exceptions were the *Total crop production* and the *Total crop production per acre* variables, as farmers who were randomly assigned to the treatment group seemed to report higher values of crop production compared to the control group, on average.

Post-intervention, statistically significant differences between control and treatment groups emerged across almost all outcomes of interest. Nearly all households continued to grow annual crops (93 percent overall), with a significantly higher rate among treatment group farmers (99 percent) relative to controls (88 percent), on average. The difference was much sharper for cultivation of vegetables, as 95 percent of farmers in the treatment group reported growing vegetables compared to 38 percent of farmers who were randomly assigned to the control group, on average. Correspondingly, the average share of cultivated land allocated to vegetables was significantly larger in the treatment group (79 percent) compared to the control group (27 percent).

These differences appear to reflect changes in cropping choices rather than expansion in land use. The number of different annual crops cultivated by farmers in both groups was on average lower in post-intervention period compared to pre-intervention, but farmers in the treatment group cultivated a significantly higher number of crops than control group farmers post-intervention, on average. Production outcomes further reflect this shift in cropping patterns. While the value of total crop production was similar across the two groups, farmers in the treatment group achieved significantly higher value of crop production per acre compared to farmers in the control group on average. The value of vegetable production was significantly higher, whereas the value of cereal production was significantly lower for farmers in the treatment group, compared to control group on average. The farmers in the treatment group also reported significantly higher value of total crop sales compared to the control group on average, as well as the share of crops sold in the market in terms of the value of production.

Descriptively, we found that the households in the treatment group were more food secure compared to households in the control group. Namely, the HDDS was significantly higher, and reliance on negative coping strategies as measured by the rCSI was significantly lower among the treatment group households compared to the control group on average.

Table 2. Outcome variables for pre- and post- intervention periods

	Pre-intervention				Post-intervention			
Variable	All	Control	Treatment	Significance diff. in means	All	Control	Treatment	Significance diff. in means
Grew annual crops (yes = 1)	0.91	0.88	0.93	–	0.93	0.88	0.99	***
	(0.02)	(0.03)	(0.03)		(0.02)	(0.03)	(0.01)	
Grew vegetables (yes = 1)	0.75	0.73	0.78	–	0.65	0.38	0.95	***
	(0.03)	(0.04)	(0.04)		(0.03)	(0.05)	(0.02)	
IHS Total cultivated land	1.55	1.56	1.53	–	1.17	1.30	1.03	**
	(0.05)	(0.08)	(0.07)		(0.05)	(0.09)	(0.06)	
Land under vegetables as a share of total cultivated land (%)	0.33	0.31	0.35	–	0.52	0.27	0.79	***
	(0.02)	(0.03)	(0.03)		(0.03)	(0.04)	(0.04)	
Crop count	2.21	2.13	2.29	–	1.29	1.19	1.41	**
	(0.09)	(0.13)	(0.13)		(0.05)	(0.07)	(0.07)	
IHS Total value of crop production	7.32	7.05	7.63	*	6.89	6.77	7.03	–
	(0.17)	(0.27)	(0.21)		(0.17)	(0.28)	(0.18)	
IHS Total value of crop production per acre	6.50	6.17	6.86	**	6.58	6.25	6.93	**
	(0.15)	(0.23)	(0.18)		(0.15)	(0.26)	(0.16)	
IHS Total value of vegetable production	5.38	5.15	5.64	–	4.79	3.07	6.67	***
	(0.24)	(0.33)	(0.34)		(0.27)	(0.40)	(0.23)	
IHS Total value of cereal production	5.52	5.75	5.26	–	3.43	5.02	1.70	***
	(0.23)	(0.30)	(0.34)		(0.27)	(0.36)	(0.32)	
IHS Total value of crop sales	6.09	5.85	6.34	–	5.85	5.23	6.52	***
	(0.23)	(0.34)	(0.30)		(0.24)	(0.38)	(0.26)	
Total crop sales as a share of total crop production (%)	0.53	0.54	0.52	–	0.66	0.54	0.79	***
	(0.03)	(0.04)	(0.04)		(0.03)	(0.04)	(0.03)	
HDDS (0-12)	7.47	7.55	7.38	–	8.43	8.09	8.79	**
	(0.16)	(0.21)	(0.24)		(0.15)	(0.23)	(0.19)	
rCSI (0-56)	7.93	7.52	8.38	–	6.03	6.81	5.19	*
	(0.74)	(1.06)	(1.03)		(0.48)	(0.72)	(0.63)	
Sample size	190	99	91	190	190	99	91	190

Notes: Variable total cultivated land is inverse hyperbolic sine transformation of total cultivated land area in acres. The variables total crop production, total crop production per acre, total vegetable production, total cereal production, and total crop sales represent inverse hyperbolic sine transformation of real USD values. HDDS stands for Household Dietary Diversity Score. rCSI stands for reduced Coping Strategies Index. Reporting Mean and Standard Deviation in parentheses. For indicator variables we report %. Significance for the difference in means: Not statistically significant (–) $p>0.01$, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

EMPIRICAL STRATEGY

We estimated if the random assignment of farmers to control or treatment group at the well level (intention to treat) had an impact on the set of outcomes using the Analysis of Covariance (ANCOVA) as follows:

$$Y_{fw}^{t} = \alpha + \beta Treatment_{w} + \delta Y_{fw}^{t-1} + \boldsymbol{\gamma}'\boldsymbol{X_{fw}} + \varepsilon_{fw} \tag{1}$$

Where the variable Y^t is the outcome of interest for farmer f from well w at time period t, i.e., post-intervention. The variable $Treatment$ represents random assignment of farmers to experimental groups at the well level and takes a value of one if a farmer was assigned to treatment group and zero if a farmer was assigned to control group. Baseline household characteristics (household head age, household head education, household size, indicator variable for livestock ownership, indicator variables for ownership of productive assets) are included in vector $\boldsymbol{X}$.

We ran separate regression for each outcome of interest Y^t, and we included lagged outcome variable measured pre-intervention, Y^{t-1}, as an additional control on the right-hand side. We clustered standard errors at the well level, to match the level of randomization.

RESULTS

The results from equation (1) are presented in table 3. We note from columns 1 and 2 that the farmers who were connected to the wells that were randomly assigned to treatment group were on average 11 and 56 percentage points more likely to decide to cultivate annual crops and vegetables post-intervention respectively, compared to the farmers who were connected to control group wells.

Our results show a clear shift from cereal to vegetable production for the farmers who were randomly assigned to the treatment group. Namely, the farmers who were connected to the wells with solar-powered pumps allocated a significantly higher share of cultivated land to production of vegetables (column 4), while the total cultivated land area remained statistically indistinguishable from that cultivated by farmers in the control group on average (column 3).

The value of total crop production reported by farmers in the treatment group was not statistically significantly different from the value reported by the control group farmers on average, as shown in columns 6 and 7. But farmers in treatment group had a statistically significantly higher value of vegetables production (column 8) and, almost symmetrically, statistically significantly lower production of cereals (column 9) compared to the control group farmers on average.

Column 10 of table 3 shows that the farmers in both groups did not have statistically distinguishable total value of crop sales. However, when we looked at the value of crop sales as a share of the value of total crop production in column 11, we found that the share of crops sold at market in the treatment group was on average 25 percentage points higher than the share of crops sold by farmers in the control group in terms of the value of production.

We do not find a statistically significant impact of the intervention on household dietary diversity score or reduced coping strategies index.

Table 3. The impact of random assignment to control or treatment group on the outcomes of interest

Panel A Variables	(1) Grew annual crops (yes = 1)	(2) Grew vegetables (yes = 1)	(3) Total cultivated land (IHS)	(4) Vegetable land share	(5) Crop count	(6) Total value of crop production (IHS)	(7) Total value of crop production per acre (IHS)
Treatment (yes = 1) ($\hat{\beta}$)	0.11**	0.56***	–0.27	0.51***	0.22	0.17	0.70
	(0.05)	(0.08)	(0.19)	(0.09)	(0.15)	(0.52)	(0.42)
Lagged outcome var.	–0.04	0.02	0.38***	0.21**	–0.01	0.08	–0.08
	(0.06)	(0.06)	(0.09)	(0.10)	(0.04)	(0.08)	(0.09)
Household controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.83***	0.51**	0.40*	0.33	1.27***	5.84***	6.74***
	(0.15)	(0.23)	(0.23)	(0.25)	(0.28)	(1.22)	(1.47)
Observations	190	190	190	190	190	190	190
R-squared	0.07	0.37	0.26	0.37	0.07	0.09	0.07

Notes: Results from equation (1). Variable total cultivated land in column 3 is inverse hyperbolic sine transformation of total cultivated land area in acres. The variables total crop production (column 6) and total crop production per acre (column 7) represent inverse hyperbolic sine transformation of real USD values. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Panel B Variables	(8) Total value of vegetable production (IHS)	(9) Total value of cereal production (IHS)	(10) Total value of crop sales (IHS)	(11) Crop sales share of production	(12) HDDS	(13) rCSI
Treatment (yes = 1) ($\hat{\beta}$)	3.54***	–3.19***	1.19	0.25***	0.71	–1.54
	(0.63)	(0.91)	(0.76)	(0.08)	(0.56)	(1.28)
Lagged outcome var.	0.08	0.32***	0.16	0.06	0.08	0.11
	(0.07)	(0.10)	(0.10)	(0.07)	(0.10)	(0.07)
Household controls	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.82**	2.88*	5.30**	0.56**	7.71***	9.91**
	(1.63)	(1.48)	(1.94)	(0.26)	(0.90)	(3.77)
Observations	190	190	190	190	190	190
R-squared	0.31	0.31	0.12	0.14	0.08	0.18

Notes: Results from equation (1). The variables total vegetable production (column 8), total cereal production (column 9), and total crop sales (column 10) represent inverse hyperbolic sine transformation of real USD values. HDDS stands for Household Dietary Diversity Score. rCSI stands for reduced Coping Strategies Index. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

DISCUSSION AND CONCLUSION

This study focused on evaluating short-term, immediate, effects of adopting solar-powered drip irrigation systems on smallholder farmers' productivity and household food security in fragile and water-scarce contexts. Specifically, we conducted an RCT in eastern Yemen to measure the impacts.

Our analysis underscored three major insights. First, farmers in the treatment group were 11 percentage points more likely to cultivate annual crops compared to farmers in the control group, on average. This result was supported by the self-reported reasons for not planting annual crops collected in the endline survey. Namely, of the 12 farmers in the control group who did not cultivate any annual crops post-intervention, the majority of farmers (75 percent) cited fuel costs and frequent power outages, with respect to the availability of water for irrigation, as the main reason for not planting annual crops.[7]

Second, although we found strong evidence in support of farmers in the treatment group shifting towards higher value horticultural crops and away from cereals, we did not find significant impacts on the total value of crop production. As seen in table 2, the number of different crops cultivated by each farmer in both experimental groups decreased post-intervention compared to pre-intervention period. However, the crop count for treatment farmers was significantly higher than the number of different crops cultivated by farmers in the control group post-intervention, on average. Most notable shift for treatment group farmers was from cultivating cereals and onions pre-intervention to cultivation of other vegetables post-intervention, while farmers in the control group continued to cultivate predominantly cereals and onions. In addition, field supervisors at our implementing partner noted that inputs were delivered somewhat late in the planting period due to logistical challenges, and that some farmers may have decided to keep land fallow instead of planting it too late in the season.

Third, we did not detect impacts on household food security outcomes, despite finding strong impacts on decisions to cultivate annual crops, and specifically higher-value crops, which are important precursors of improved food security.

Descriptive patterns in the data (as seen in table 2) and anecdotal reports provide suggestive evidence that the full impact of the intervention could be realized beyond short-term, through future and additional cropping seasons. The field supervisors clarified that the shift towards growing vegetables was due to smallholder farmers perceiving horticultural crops as benefitting more significantly from the new irrigation technology. However, farmers generally planted these horticultural crops for the first time and therefore may have experienced challenges throughout the production process, including marketing.

Our study is limited by only looking at the first season after the intervention, during which farmers were still benefiting imperfectly from the new irrigation system. The delays in the distribution of inputs and the need for learning by doing with horticultural crops suggest that eventual impacts on the total value of production and household food security may be higher than seen in the first season post-intervention. Thus, our results likely underestimate the benefits of adopting improved irrigation technology.

Another limitation of our study is that we did not estimate the effects of installing solar drip irrigation on groundwater depletion. Groundwater in Yemen is, and has been, extracted beyond its recharge rates and previous studies have linked depletion of water resources and water crisis with the ongoing conflict (Weiss, 2015; Varisco, 2019; Al-Saidi, 2020). The farmers in our sample, especially in the treatment group, switched to cultivating vegetables while farmers in the control group predominantly grew cereals.

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[7] One farmer from the treatment group did not plant annual crops due to personal reasons.

We did not measure water footprints of such production decisions. It is possible that farmers with solar drip irrigation used water at a higher rate than when relying on diesel, primarily due to the lower cost of water and possibly due to cultivation of more water-intensive crops (Closas and Rap, 2017; Hartung and Pluschke, 2018; Gupta, 2019). The use of drip irrigation systems, although improving water use efficiency, does not imply water savings. Future research should assess rigorously the impacts of solar drip irrigation on water depletion and propose solutions that could regulate solar irrigation in Yemen.

Still, this study is unique in collecting detailed quantitative information on smallholder agriculture and irrigation use in eastern Yemen in the context of the ongoing conflict. Given the paucity of research on smallholder production in fragile and arid settings, the findings may be applicable in other similar contexts. Overall, the results provided preliminary evidence in favor of expanding investments in solar and drip irrigation technology in Yemen to improve smallholder production and possibly enhance food security. The crop choice among smallholder farmers in our sample was limited and determined by lack of ability to adopt improved irrigation systems pre-intervention. Our study showed the potential of adoption of solar and drip irrigation technology to cause shifts towards higher value horticultural production for the market. However, our intervention was relatively costly, and the gains to smallholder farmers and wider community should be weighed against the investments and potential overextraction of groundwater resources. An accurate cost-effectiveness analysis would require measuring economic returns for smallholder farmers beyond the first season, as the long-term benefits of eliminating ongoing fuel costs could outweigh the upfront investment.

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APPENDIX

ROBUSTNESS CHECKS

As a robustness check, we conduct the analysis using Probit model for the indicator outcome variables (columns 1 and 2 of table 3), and Hurdle model for production outcome variables (columns 3-10 of table 3).

We employ Probit model to estimate the two production decisions, to cultivate annual crops and vegetables post-intervention, made by farmer f who was randomly assigned to treatment or control group at the well w level as follows:

$$P_{fw} = \alpha + \beta Treatment_{w} + \boldsymbol{\gamma}'\boldsymbol{X_{fw}} + \varepsilon_{fw} \qquad \text{(A.1)}$$

We run two separate regressions, one for each production decision P that is equal to one if a farmer decided to plant annual crops (and to plant vegetables in the second regression) post-intervention, and zero otherwise. The variable $Treatment$ and the vector of controls $\boldsymbol{X}$ remain as explained for equation (1). We cluster standard errors at the well level, to match the level of randomization.

Next, we model farmer f's production as a result of two decisions: the farmer f first has to decide whether or not to cultivate annual crops, and then after deciding to cultivate an annual crop, the farmer decides what crop to plant and how much. Namely, 93 percent of farmers in our sample decided to cultivate annual crops, out of which 65 percent decided to plant vegetables (table 2). Therefore, crop production in the sample is characterized by a corner solution. To deal with this issue we estimated a two-equation Hurdle model that treated each farmer's decisions as two consecutive decisions. Following Cragg (1971), we used the lower limit of zero to bind the dependent variable and obtain the selection model (i.e., first equation):

$$d_{fw} = \begin{cases} 1, & \delta Treatment_{w} + \boldsymbol{\theta}'\boldsymbol{X_{fw}} + \mu_{fw} > 0 \\ 0, & otherwise \end{cases} \qquad \text{(A.2)}$$

where the variable $Treatment$ and vector $\boldsymbol{X}$ remain as explained for equation (1), and μ_{fw} is a standard normal error term. The production variable V is observable only if $d = 1$, so the exponential outcome model (i.e., second equation) can be specified as:

$$V_{fw} = \exp(\delta Treatment_{w} + \boldsymbol{\theta}'\boldsymbol{X_{fw}} + \nu_{fw}) \qquad \text{(A.3)}$$

We run eight separate regressions for eight production outcome variables.

Based on the results from Probit specification in appendix table A.1, the impact of our intervention on farmers' decision to cultivate annual crops and vegetables remained high and significant. The farmers connected to treatment wells were about 14 and 48 percentage points more likely to cultivate annual crops and vegetables post-intervention respectively, compared to farmers connected to control wells on average. These results are generally in agreement with our main results in table 3.

Table A.1. Impact of intervention on production decision, robustness check (Probit)

Variables	(1) Grew annual crops (yes = 1)	(2) Grew vegetables (yes = 1)
Treatment (yes = 1) ($\hat{\beta}$)	0.14**	0.48***
	(2.18)	(13.11)
Household controls	Yes	Yes
Observations	190	190

Notes: Results from equation (A.1). Reporting Probit marginal effects. z-statistics in parentheses. *** p<0.01, ** p<0.05, * p<0.1

The results from Hurdle model are outlined in table A.2. We found that the Hurdle model provided coefficient estimates that were generally lower in magnitude compared to the coefficient estimates from ANCOVA specification. In terms of the statistical significance, the results mainly remained unchanged compared to ANCOVA results in table 3. However, the coefficient estimate on the *Total crop production per acre* variable became statistically significant at the 90 percent significance level, providing suggestive evidence that the farmers who were randomly assigned to the treatment group had a significantly higher value of crop production per acre post-intervention, compared to the control group farmers on average.

Table A2. Impact of intervention on agricultural production, robustness check (Hurdle model)

Panel A					
Variables	(1) Total cultivated land (IHS)	(2) Vegetable land share	(3) Crop count	(4) Total value of crop production (IHS)	(5) Total value of crop production per acre (IHS)
Treatment (yes = 1) ($\hat{\delta}$)	–0.17	0.26***	0.18	0.41	0.70*
	(0.22)	(0.08)	(0.16)	(0.50)	(0.38)
Household controls	Yes	Yes	Yes	Yes	Yes
Observations	380	380	380	380	380

Notes: Results from equation (A.3). Variable total cultivated land in column 1 is inverse hyperbolic sine transformation of total cultivated land area in acres. The variables total crop production (column 4) and total crop production per acre (column 5) represent inverse hyperbolic sine transformation of real USD values. Reporting Hurdle model marginal effects. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Panel B				
Variables	(6) Total value of vegetable production (IHS)	(7) Total value of cereal production (IHS)	(8) Total value of crop sales (IHS)	(9) Crop sales share of production
Treatment (yes = 1) ($\hat{\delta}$)	1.98***	–1.84***	0.85	0.09
	(0.52)	(0.70)	(0.61)	(0.08)
Household controls	Yes	Yes	Yes	Yes
Observations	380	380	380	380

Notes: Results from equation (A.3). The variables total vegetable production (column 6), total cereal production (column 7), and total crop sales (column 8) represent inverse hyperbolic sine transformation of real USD values. Reporting Hurdle model marginal effects. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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