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Impact of irrigation pump ownership on farm productivity in rice-wheat cropping systems of Nepal Terai

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ABSTRACT

Groundwater irrigation is critical for supporting food security, rural livelihoods, and economic development in the Eastern Indo-Gangetic Plains (EIGP) of South Asia. However, groundwater resources in the EIGP remain underutilized due to farmers' reliance on expensive diesel pumps for accessing water. This study uses primary household survey data from the Terai region of Nepal to analyse the drivers of variability in irrigation access costs across farms, and how these cost variabilities influence agricultural outcomes. We employ an endogenous switching regression model to assess the impacts of pump ownership on farm productivity and profitability. Our findings show that pump ownership reduces irrigation costs rice and wheat cultivation, the region's two major crops, by 72 % and 76 %, respectively, and increases rice and wheat productivity by 37 % and 20 %, respectively. Our findings provide empirical evidence of the positive impact of technology ownership on agricultural productivity and highlight the opportunities for policy interventions focused on improving performance of existing technologies for enabling long-term sustainable intensification of irrigated agriculture in the EIGP.

1. Introduction

Globally, 1.2 billion (about one in six people) live in areas with water shortages and scarcity, with almost half residing in South Asia [1]. As 60 % of rural households in the region depend on agriculture for their livelihood, access to water for irrigation is critical in supporting food security for millions of resource-poor households. The impacts of climate change and climate variability are projected to have severe consequences for agriculture in South Asia, including increased variability in rainfall patterns, increased average temperatures, and increased frequency and/or severity of extreme weather events [2].

Irrigation is a key means for farmers to adapt to the risks posed by water scarcity, drought, and climate change. While surface water

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is used to support irrigation across many parts of South Asia, including in the Terai region of Nepal, water supplies from rivers and canals are highly seasonal and dependent on monsoon rainfall during summer months. Inadequate investment in construction and maintenance of surface water infrastructure, such as dams and canals, further reduces reliability and cost-effectiveness of surface water supply for distributed irrigation [3,4]. As a result, farmers in South Asia primarily rely on groundwater, accessed via diesel and electric pumps, as a more consistent and reliable water supply source for irrigation.

Despite the importance of groundwater for agriculture in South Asia, farmers face substantial variability in the costs of accessing groundwater for irrigation, even when using similar pumping technologies within comparable farming systems. This cost heterogeneity represents a critical constraint to agricultural productivity and rural livelihoods across the region. Subsidized rural electrification for groundwater pumping has enabled substantial increases in agricultural output in the Western Indo-Gangetic Plains (WIGP) of Pakistan and India [5]. However, groundwater in the Eastern Indo-Gangetic Plains (EIGP) of India and Nepal is relatively under-utilised, with groundwater extraction rates only a fraction of estimated development potential [6].

Farmers' reliance on expensive diesel or gasoline fuel for pumping is one of the most frequently cited reasons for the low levels of groundwater irrigation in the EIGP. Over 80 % of the installed irrigation pump horsepower in the EIGP comes from diesel pumps [7,8]. However, beyond the general reliance on expensive diesel fuel, irrigation costs vary dramatically between farmers, with some paying several times more than others for equivalent irrigation services. Understanding the drivers of this irrigation cost variability is essential for designing effective interventions to improve agricultural productivity in the EIGP. Low levels of groundwater utilisation in the EIGP limit crop production outside the rainy season, and reliable management of risks posed by rainfall variability. These factors contribute to chronic agricultural productivity and yield gaps in the EIGP, resulting in some of the highest rates of rural poverty and food insecurity found across South Asia and globally [9].

Various solutions have been proposed to improve access to and utilisation of groundwater for irrigation in the EIGP [10–12]. Given a considerable proportion of the Terai and wider EIGP lacks direct connections to electric grids in comparison to the rest of the IGP, increasing levels of rural electrification could provide a means to lower costs of groundwater pumping. However, structural constraints to electrification in the Terai region and wider EIGP, such as the cost of providing electricity and limited incentives for utilities to supply power, currently are major barriers to expanding electricity access for irrigation [13]. At the same time, future expansion of rural electrification is also dependent on the completion of upstream hydropower projects [14]. Large-scale expansion of rural electrification in the Terai therefore will require significant investments in capital-intensive infrastructure and regulation, which will likely take several decades to deliver at scale.

Alternative proposals have focused on opportunities for investment in upscaling alternative groundwater pumping technologies, such as solar-based irrigation systems. However, scaling up solar irrigation systems in the EIGP to date has been constrained by several technical and economic challenges, such as high upfront capital costs, limited local maintenance services, limited mobility to serve fragmented plots, and the risk of excessive withdrawal in weakly regulated regions [15,16]. By 2021, approximately 2000 solar irrigation pumps (SIPs) ranging from 1 to 5 horsepower have been installed in Nepal, predominantly in the Terai region. The majority of these installations were facilitated by high levels of subsidization [12]. This suggests that without such high levels of subsidization, the adoption of these solar irrigation pumps would likely have been much lower, and substantial long-term investment is required for wider adoption.

Given the challenges of upscaling alternative irrigation pumping systems and technologies, improving the efficiency and performance of the millions of existing diesel pump irrigation systems across the region could help support near-term advances in groundwater irrigation affordability in the EIGP. This could also complement and aid future transitions to alternative technologies powered by renewable energy to support growth in low carbon irrigation infrastructure through either direct grid supplies (e.g. rural electrification) or distributed pumping systems (e.g. solar pumps). There is growing evidence that several diesel pump irrigation systems in the EIGP have extremely low water delivery to fuel consumed, meaning that these pumps deliver a relatively small amount of water per unit of fuel consumed [17–20]. Furthermore, pump rental costs contribute to increased irrigation costs for farmers, further exacerbating the financial burden on those who do not own their pumps [18,19]. These inefficiencies increase irrigation costs for farmers and, in turn, reduce the potential benefits of groundwater use for farmers.

The substantial heterogeneity in irrigation access costs observed across farmers in the EIGP stems from multiple factors, with pump ownership emerging as a key determinant according to recent research in the region [18,19]. Identifying the underlying causes of this cost variability and its impacts on irrigation practices and agricultural production outcomes is critical to better understand and identify key entry points to intensify agricultural production and reduce poverty across the Terai region. However, to date, there has been little research that has focused explicitly on quantifying the extent and underlying reasons for disparities in groundwater access and costs in the EIGP, as well as the cascading impacts of this variability on irrigation practices and agricultural production outcomes. This limits the capacity of governments and donors to target interventions aimed at improving groundwater access and supporting sustainable intensification of irrigation as a climate adaptation measure in water abundant but under-irrigated land use systems of the EIGP such as the Terai.

To answer these questions, we combine detailed microeconomic data from household surveys and a series of semi-structured interviews from Rupandehi and Kapilvastu districts in the Terai region of Nepal. These districts were selected as they are representative of rice-wheat smallholder farming systems across the EIGP, where most farmers irrigate their crops using groundwater and pumps. Diesel pumps are the *modus operandi* for pumping groundwater due to limited rural electrification, and these districts represent an ideal case study to explore opportunities for improving cost-effectiveness of existing diesel pump irrigation systems as a means to support irrigation-led intensification of agriculture production and dependent livelihoods.

To address the limited understanding of irrigation cost heterogeneity and its agricultural impacts in the EIGP, this paper aims to: (1) analyse the drivers of variability in irrigation costs across farms and how these irrigation cost variabilities influence agricultural practices, and (2) explore the impacts of pump ownership – one of the main drivers of irrigation cost variability according to ongoing research in the region– on farm productivity and profitability.

Our analysis provides insights into the factors that lead to differences in irrigation access costs, how these disparities affect irrigation practices, and how irrigation costs and practices, in turn, impact heterogeneities in low land productivities. Our findings contribute to national and regional policy debates in the EIGP on sustainable intensification of irrigated agriculture, including directly to Nepal's National Planning Commission strategy to increase productivity and profitability of cereal production systems [21] and to Nepal's 2019 Irrigation Masterplan [22]. In particular, we identify several key technology and policy pathways for intensifying appropriate use of irrigation through reducing the overall costs and variability of groundwater access for farmers. Our findings highlight opportunities to revitalise existing diesel pump irrigation systems, which could help provide immediate support to goals of poverty reduction, food security, and livelihood improvement for over 500 million people [6]across the EIGP.

2. Background and data

2.1. Study area

About two-thirds of the population in Nepal depend on agriculture for their livelihood, which also accounts for one-third of the nation's GDP and more than half of its exports [23]. Over 80 % of Nepal's agricultural land area is concentrated in the fertile alluvial plains of the southern Terai. Despite making up only 23 % of Nepal's overall land area, the Terai region sustains 68 % of the country's rice production[24]. Nepal's ability to address food and nutritional security and support livelihoods of its rapidly growing population is heavily conditioned on agricultural productivity in the Terai.

Farming systems in the Terai are smallholder dominated, with most of the production centered on the dominant rice-wheat cropping rotation found across much of South Asia. Landholdings in the Terai are small, much like the rest of the country, and has been gradually decreasing for the last three decades[25]. Rice and wheat account for over 90 % of all food grain production. Rice is cultivated during the rainy season (June–October), while wheat is cultivated during the dry season (November–March) after the monsoon following the rice harvest. Both rice and wheat are typically irrigated: 75 % of rice and 81 % of wheat farmers in the Terai used irrigation between 2016 and 2017 [26]. Irrigation for wheat is required due to the lack of rainfall during the dry winter season, while for rice, irrigation serves for timely crop planting to protect against dry spells during the monsoon while also meeting large water demands of rice relative to other cereal crops[4]. However, substantial variability in irrigated areas exist across the Terai, with smaller proportions of land irrigated in poorer districts in the far west and eastern region, both during the monsoon *kharif* and dry winter seasons [4,27]. Similarly, where land is irrigated, the water applied is insufficient to meet full crop water requirements, in part due to economic constraints posed by lack of access to affordable irrigation water supplies [28].

As a result of limited irrigation access and use, agricultural productivity in the Terai and the wider EIGP remains considerably lower than in other more intensively irrigated parts of South Asia. For example, cereal production in the Terai is half as productive as the adjacent Indian states of Punjab and Haryana [29]. In this context, understanding the factors limiting access to groundwater in the region will be essential to support cost-effective intensification of groundwater irrigation in the Terai.

2.2. Data

This study utilises on-farm survey data collected from two districts in the Nepal Terai region between June and August 2019.

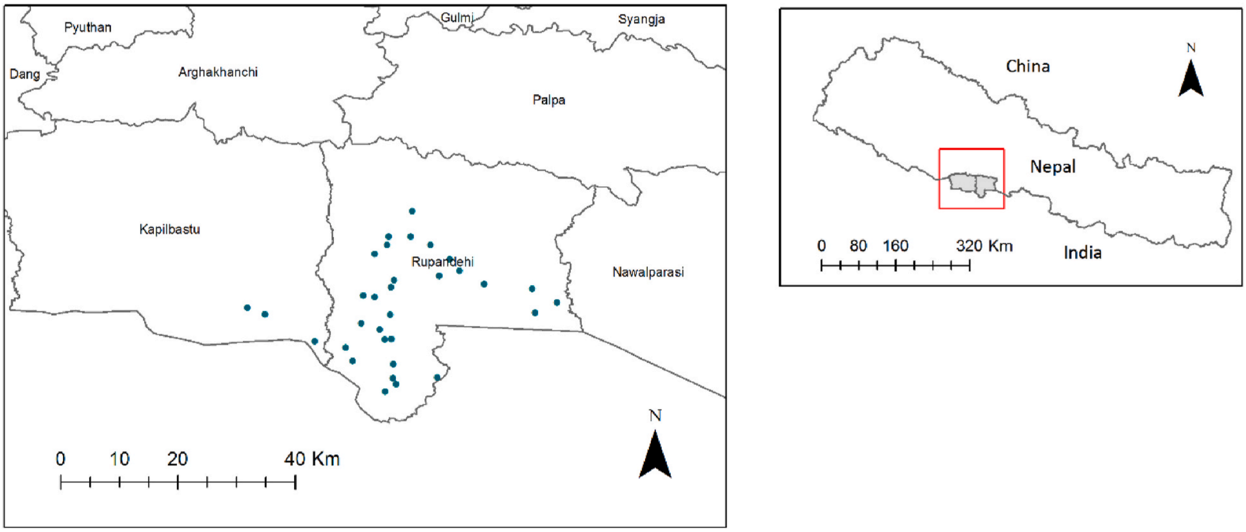

Fig. 1. Location of surveyed villages in Kapilvastu and Rupandehi districts (left) in Nepal (right).

Household surveys were conducted in 30 villages within Rupandehi and Kapilvastu districts. These villages were identified from national census lists and selected through a two-stage stratified and random sampling procedure (Fig. 1). Findings from interviews with national experts and semi-structured interviews revealed that Rupandehi district has extensive pump usage for irrigation, leading to the selection of 27 villages from Rupandehi and three from Kapilvastu. To ensure a representative sample of pump owners and renters, these 30 villages were selected proportionally based on the number of pumps in each district. Within each village, a random sub-sample of 12–16 farmer households, who reported using groundwater for irrigation in rice-wheat cropping systems, was selected. Our final sample comprises 434 households. From this, we used a subset of the sample—limited to rice growers in the kharif season of 2018 *(n=371)* and wheat growers in the dry winter season of 2018/19 *(n=354)*—to analyse differences in the number of irrigation events, time required for each event, and overall irrigation costs across farmers for the dominant cropping rotation in the EIGP. The focus on rice and wheat growers is due to the substantial irrigation and agricultural inputs dedicated to these two crops annually by farmers in the region. The sample was designed to be representative of the broader population of farmers in the Terai region. Villages were selected using a stratified random sampling method to ensure coverage across different socioeconomic and geographic areas.

Primary data collection through household surveys was necessary for this study because available secondary data sources in Nepal do not capture the detailed information required for analysing irrigation cost variability and its impacts on agricultural productivity. Existing national surveys, such as the Nepal Living Standards Survey and Agricultural Census, lack comprehensive coverage of: (1) detailed irrigation practices including frequency, duration, and costs of individual irrigation events; (2) technical characteristics of irrigation equipment and rental arrangements; (3) farm-level economic variables necessary for productivity analysis; and (4) household-level factors that influence technology adoption and irrigation decision-making.

We chose household surveys as our primary data collection method because they enable comprehensive gathering of household-specific information on demographics, assets, and agricultural production decisions that are crucial for understanding the complex relationships between pump ownership, irrigation costs, and productivity outcomes. This approach is well-established in the technology adoption literature, where detailed household-level data is essential for identifying causal relationships and controlling for potential confounding factors [30,31]. The survey method also allows for standardised data collection across a large sample, enabling robust statistical analysis while maintaining comparability across different farming contexts.

The selection of variables included in our analysis was based on extensive review of technology adoption and agricultural productivity literature, which identifies key determinants of agricultural technology adoption and productivity outcomes. Following established frameworks [30–32], our variable selection encompasses: (1) household demographic characteristics (age, education, gender of household head) that influence decision-making capacity and risk preferences; (2) asset ownership and wealth indicators that determine financial capacity for technology investment; (3) farm characteristics (size, land tenure arrangements) that affect technology suitability and returns to adoption; (4) labour availability and human capital that influence technology management capacity; and (5) agricultural inputs and practices that determine production outcomes.

Our survey instrument included a comprehensive questionnaire that collected gathered data on household demographics, assets, and decisions regarding agricultural production for both agricultural seasons in the previous year (2018 *kharif* season and 2018/19 dry winter season). We asked specific questions about irrigation practices, including features of borewells and pumps used for irrigation as well as the frequency, duration, and cost of irrigation events on the largest plot cultivated by the household. We chose the largest irrigated plot grown by respondents because it reflects farmers' highest irrigation expenditure and offers a standard comparison for assessing irrigation access costs and their effects on agricultural output across households. To investigate the relative contribution of irrigation costs to overall agricultural costs, we also gathered data on the total irrigation costs for all plots maintained by farmers. To differentiate irrigation characteristics of irrigation pump owners and renters and subsequent costs, we collected detailed information on pumps used for irrigation on farmers' main agricultural plot. This information includes technical characteristics of the pump and rental costs for pumps.

The survey design incorporated insights from preliminary semi-structured interviews with farmers, local experts, and government officials to ensure that all relevant factors affecting irrigation cost variability were captured. These interviews helped identify pump ownership as a key driver of cost variability, informed the selection of control variables, and provided qualitative context for interpreting quantitative findings. The combination of quantitative survey data and qualitative insights enables a comprehensive analysis of the mechanisms through which pump ownership affects irrigation costs and agricultural outcomes, addressing the complexity of technology adoption and its impacts in smallholder farming systems [30,31].

3. Empirical approach

We assume a profit-maximizing and economically rational farmer who assesses whether to purchase a pump based on available resources and management options. A farmer is assumed to purchase a pump if the net benefits from purchase outweigh the benefits without purchase (i.e., renting a pump). Modelling of selection decisions is comparable to approaches commonly used in technology adoption literature, where a farmer is assumed to choose to adopt a technology if it generates net benefits. However, in this study, non-adopting farmers still use pumps by renting them from other farmers, therefore the decision to not purchase (i.e., not adopt) a pump does not equate to non-use. Adopters in our sample therefore can be seen as farmers who own pumps for irrigation, whereas non-adopters are farmers who rent their pumps. We also note that all farmers in our sample use groundwater for irrigation, therefore all farmers irrigate their crops with either owned or rented pumps. Our approach is informed by technology adoption literature (e.g., Paudel et al. [31]; Di Falco et al. [30]) which highlights the importance of economic rationality and resource availability in farmers' decisions to adopt new technologies such as irrigation pumps.

A farmers' unobservable net benefits (Y^*) are represented as a function of observed factors in the following latent variable model as specified in Eq. (1), where a farmer purchases a pump if $Y^* > 0$:

$$Y^* = \beta X_i + \epsilon_i, \left\{ \begin{matrix} \tau = 1 & \mathit{if}\ Y^* > 0 \\ 0 & \mathit{otherwise} \end{matrix} \right\} \tag{1}$$

In Eq. (1), for each household *i, τ* is a binary variable that equals 1 if the household owns a pump and zero if the household rents a pump. β is a vector of parameters to be estimated, X_i is a vector of farm and household characteristics that determine pump ownership, and ϵ_i is an error term that is assumed to be normally distributed.

The simplest approach to estimate the impact of pump ownership on farm productivity and profitability would involve including a dummy variable equal to 1 for pump ownership in the outcome equation along with other control variables and subsequently applying ordinary least squares (OLS) regression. However, this approach presupposes that pump ownership is decided exogenously, whereas ownership may be endogenous [30]. For example, a farm household self-selects into owning a pump and this choice is influenced by both observable and unobservable elements[30]. As well as observable variables (such as farm size, inputs, and household size), pump owners and renters may also differ in their inherent farming abilities, efficiency, farm management skills, and their perceptions and farming objectives. Failure to account for unobservable heterogeneities may confound causal analysis and lead to over- or under-estimation of the outcome variables. For instance, if only the most skilled or motivated farmers decide to purchase pumps and we do not control for skills or motivation, then our findings will suffer from an upward bias (i.e., we would over-estimate the influence of pump ownership on rice and wheat productivity).

Recent studies have used the endogenous switching regression (ESR) method to tackle this problem (see, for example, [30,31, 33–35]. The ESR method accounts for the full interaction of the treatment variable with both observable and unobservable variables that affect the outcome, thereby enabling us to isolate the true treatment effect of pump ownership on the outcome variables. Therefore, we apply the ESR method in this paper, using a probit model in the selection equation at the first stage, and outcome equation for farm productivity, cost of production, and profitability in the second stage as described below.

For the model type to be identified in the ESR first stage, an exclusion restriction or instrument must be specified that is correlated with pump ownership but not necessarily correlated to with outcome variables (yield, cost, and profits) and this instrument affects the outcome variables only through pump ownership. In this study, we use the number of years of pump ownership in the village – defined by the age of oldest pump available in a village – as our instrument. We argue that the time since the introduction of pumps in a village affects the availability of pumps and therefore the local pump rental markets and farmer decision to purchase pumps. However, the age of the oldest pump in the village is unlikely to have a direct relationship with the agricultural productivity, costs, and profits of individual farmers without pump ownership. To establish the admissibility of the instrument, we performed a falsification test following [30], the results of which are presented in the Appendix (Tables A1 and A2). The instrument falsification tests suggest that our instrument satisfies the exclusion restrictions for both crops' (rice and wheat) yields, irrigation costs, costs of production, and profitability, indicating satisfactory conditions for exclusion restrictions. Moreover, the test results of under- and weak identification presented in Table A1 and A2 shows that the selected instrument is valid. Using this framework and instrument, the ESR model addresses the problem of endogeneity by estimating the selection equation and the outcome equation simultaneously, using the full information maximum likelihood estimations [36].

The endogenous switching regression approach follows two steps. In the first step, we specify a binary choice function that represents pump ownership. A farm household assesses whether to own a pump based on available resources and management options. In the second step, based on the decision in the first stage, the outcome of interest (rice and wheat yields, irrigation costs, total costs, and profits) is regressed with farm and household level attributes.

$$\mathit{Outcome\ for\ pumpset\ owners} : Y_{1i} = f\ (PO, X, \beta_1) + \epsilon_{1i}, \mathit{if}\ \tau_i = 1 \mathit{Outcome\ for\ pumpset\ renters} : Y_{2i} = f\ (\ X, \beta_2) + \epsilon_{2i}, \mathit{if}\ \tau_i = 0 \tag{2}$$

Here, Y_{1i} and Y_{2i} represent the outcome indicators for pump owners and renters respectively and ϵ_i represents the error terms of the outcome variables. *PO* represents the ownership of a pump, *X* represents farm, household, operator, and other characteristics that determine pump ownership and β_1 and β_2 are the parameters to be estimated for pump owners and renters, respectively. The variable τ is equal to 1 if the farmer owns a pump; it is 0 otherwise. Additional details on the ESR method and assumptions can be found in Ref. [36,37].

Under the set of assumptions outlined above the ESR model estimates can be used to compare the expected outcome variables (rice and wheat yields, cost, and profit) for farmers that own pumps (Eq. (3)) with respect to farmers that rent pumps (Eq. (4)), and to estimate the counterfactual outcomes for hypothetical cases where the pump owners did not own pumps (Eq. (5)), and pump renters owned their own pumps (Eq. (6)). The conditional expectations for outcome variables for these four cases can be defined as follows:

$$E(Y_{1i}|\tau_i = 1) = f(PO, X, \beta_1) + \delta_{1i}\sigma_{1\mu} \tag{3}$$

$$E(Y_{2i}|\tau_i = 0) = f(PO, X, \beta_2) + \delta_{2i}\sigma_{2\mu} \tag{4}$$

$$E(Y_{2i}|\tau_i = 1) = f(PO, X, \beta_2) + \delta_{1i}\sigma_{2\mu} \tag{5}$$

$$E(Y_{1i}|\tau_i = 0) = f(PO, X, \beta_2) + \delta_{2i}\sigma_{1\mu} \tag{6}$$

Here, Eq. (3) represents the observed outcome variables for pump owners, while Eq. (5) represents the counterfactual, i.e., what the pump owners' outcomes would have been had they not owned pumps. Similarly, Eq. (4) represents the outcome variables for pump renters, whereas Eq. (6) represents the counterfactual outcome for pump renters, i.e., what their outcomes would have been had they owned pumps. The average treatment effect on the treated (ATT), i.e., the difference in productivity, irrigation and total costs, and profitability of pump owners had they rented pumps can be defined as the difference between Eqs. (3) and (5):

$$ATT = E(Y_{1i}|\tau_i = 1) - E(Y_{2i}|\tau_i = 1) \tag{7}$$

In contrast, the average treatment effect on the untreated (ATU), which is the difference between observed outcome variables of pump renters and their outcomes had they owned pumps, is the difference between Eqs. (4) and (6):

$$ATU = E(Y_{1i}|\tau_i = 0) - E(Y_{2i}|\tau_i = 0) \tag{8}$$

We use rice and wheat yields, irrigation and total variable costs, and gross margin (and indicator of profitability) as outcome variables to estimate the ESR model. Yields are self-reported harvest values converted to tons/hectare to permit meaningful comparison; total variable costs are the sum of costs for seed, rent (if plot is rented), tillage, hired labor, fertilizer, herbicide, and irrigation. Net agricultural profit is the difference between gross value of crop production and total variable costs. The explanatory variables in the model include demographic variables (age, education and gender of household head, caste of the household, and household size), farm variables (farm size, number of household members working on farm, proportion of cultivated land rented in, quantity of fertilizer used, variety of crop and irrigation frequency), and economic variables (number of household members who have migrated, proportion of household income from off-farm sources and household wealth index[1]). These variables were selected based on the review of literature related to impact evaluation[31,32]. The impacts of pump ownership on agricultural productivity and profitability are likely influenced by climatic variables (particularly precipitation levels) as well. However, rainfall is unlikely to vary within our region of study given the geographic coverage of the sample (Fig. 1). Nevertheless, we compare precipitation levels in 2019 to historic averages using gridded precipitation data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) [38] to show that precipitation levels in 2019 are representative of the general rainfall patterns in the region over time (Figure A1).

4. Results

4.1. Descriptive statistics

Our descriptive statistics show substantial differences in socio-economic and agricultural variables between pump owners and renters across both growing seasons (Table 1). Farmers who own their pumps cultivate more land than farmers who rent pumps (0.95 vs 0.86 ha among the farmers in the *kharif* season and 1.01 vs 0.46 ha among the farmers in the dry winter season). Moreover, total farmed land and size of the main plot are higher for pump owners; we find that on average, pump owners own 51 % more land and have 41 % larger main plots compared to pump renters. These differences contribute to pump renters cultivating 25 % fewer plots on average. Landholding is not only a good wealth indicator, but it also serves as a collateral for credit access in Nepal [39]. Therefore, these differences in landholding highlight disparities in asset levels across the pump ownership groups. Disparities in asset levels are further highlighted when exploring differences in household wealth index among the two groups of farmers, for which we find that, on average, pump owners have more asset [8,27].

Differences in socio-economic and agricultural production characteristics are also mirrored by differences in agricultural inputs and outputs of pump owners and renters for rice and wheat production in our study area (Fig. 2). Pump renters, on average, incur higher per-unit costs for all agricultural inputs and have lower yields and profits compared to pump owners. The higher costs for pump renters are not limited to irrigation alone; they extend to other agricultural inputs such as land preparation and fertilizer.

The most striking difference in costs between pump owners and renters arises from irrigation costs. Pump renters incur 62 % and 65 % higher costs compared to pump owners to grow rice and wheat respectively. As a result, the total variable input costs are 15 % higher for pump renters across both seasons, which leads to pump owners making 37 % higher profits with rice production and 87 % higher profits with wheat production. These results indicate that pump ownership substantially reduces the cost of rice and wheat production and hence increases farmer profits. As all these observed differences in socio-economic and production characteristics may affect a farmer's decision to own pumps, accounting for these differences using ESR is required to control the potential confounders and to derive the true treatment effects of pump ownership.

4.2. Irrigation system characteristics

Among all farmers in our survey, 76 % used their own pumps to irrigate their plots. The remaining 24 % of surveyed individuals

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[1] The wealth index is a composite measure of a household's cumulative living standard (for an example on construction and use of wealth index indicators, please see [65]. The wealth index is calculated in two steps using available data on assets owned by a household. (1) We create dummy variables for household/agricultural asset ownership using assets owned by <95 % and >5 % of all households. (2) We use Principal Component Analysis (PCA) to divide households into five quantiles of relative wealth levels, where 5 = most assets. Variables used to construct the wealth index include tractor, rotavator, sprayer, motorcycle/scooter, refrigerator, fans, television, computer, pump and concrete/cement roof.

Table 1
Socio-economic attributes of pump owners and renters in the rice-wheat cropping systems of Nepal.

Variables	Rice growers			Wheat growers		
	Pump owners	Pump renters	Difference (%)	Pump owners	Pump renters	Difference (%)
	Mean (St. error)	Mean (St. error)		Mean (St. error)	Mean (St. error)	
Age of household head (years)	51.41 (0.73)	47.43 (1.35)	8.37**	51.62 (0.76)	47.13 (1.37)	9.53**
Gender household head (1 = Male, 0 = Female)	0.95 (0.01)	0.86 (0.04)	10.64**	0.94 (0.01)	0.87 (0.04)	7.60*
Caste of household (1 = non-marginalized, 0 = marginalized)	0.70 (0.03)	0.68 (0.05)	3.96	0.71 (0.03)	0.72 (0.05)	−1.58
Farm size (ha)	1.05 (0.05)	0.52 (0.04)	101.29***	1.09 (0.06)	0.53 (0.04)	105.46***
Education of household head (years)	4.32 (0.24)	3.51 (0.40)	23.05	4.29 (0.25)	3.61 (0.42)	18.78
Household size (no)	8.94 (0.33)	6.92 (0.34)	29.09**	9.12 (0.34)	7.01 (0.36)	29.99**
Number of household members working on farm (no)	4.91 (0.16)	3.57 (0.17)	37.59***	4.97 (0.17)	3.59 (0.19)	38.41***
Number of migrated household members (no)	0.47 (0.05)	0.30 (0.06)	56.58	0.47 (0.05)	0.28 (0.06)	65.89
Proportion of land rented-in (%)	0.13 (0.02)	0.09 (0.02)	51.79	0.12 (0.02)	0.09 (0.02)	35.98
Household income from off farm sources (%)	45.02 (1.91)	58.30 (3.76)	−22.78***	43.75 (1.97)	57.74 (4.01)	−24.22***
Wealth index	3.07 (0.08)	1.72 (0.10)	78.32***	3.13 (0.08)	1.72 (0.11)	82.44***
Amount of fertilizers applied on plot (tons/ha)	365.83 (7.83)	401.46 (18.15)	−8.87**	353.99 (13.42)	385.19 (25.00)	−8.10
Variety types (1 = improved, 0 = others) †	0.77 (0.03)	0.78 (0.04)	−1.62	0.86 (0.02)	0.91 (0.03)	−4.79
Irrigation frequency (no)	2.77 (0.07)	2.21 (0.10)	25.38***	1.80 (0.03)	1.62 (0.05)	10.82**
Number of years of irrigation pumps available in the village (years)	6.64 (0.35)	15.11 (0.53)	−56.06***	6.64 (0.35)	15.11 (0.53)	−55.87***
Number of observations	281	90		269	85	

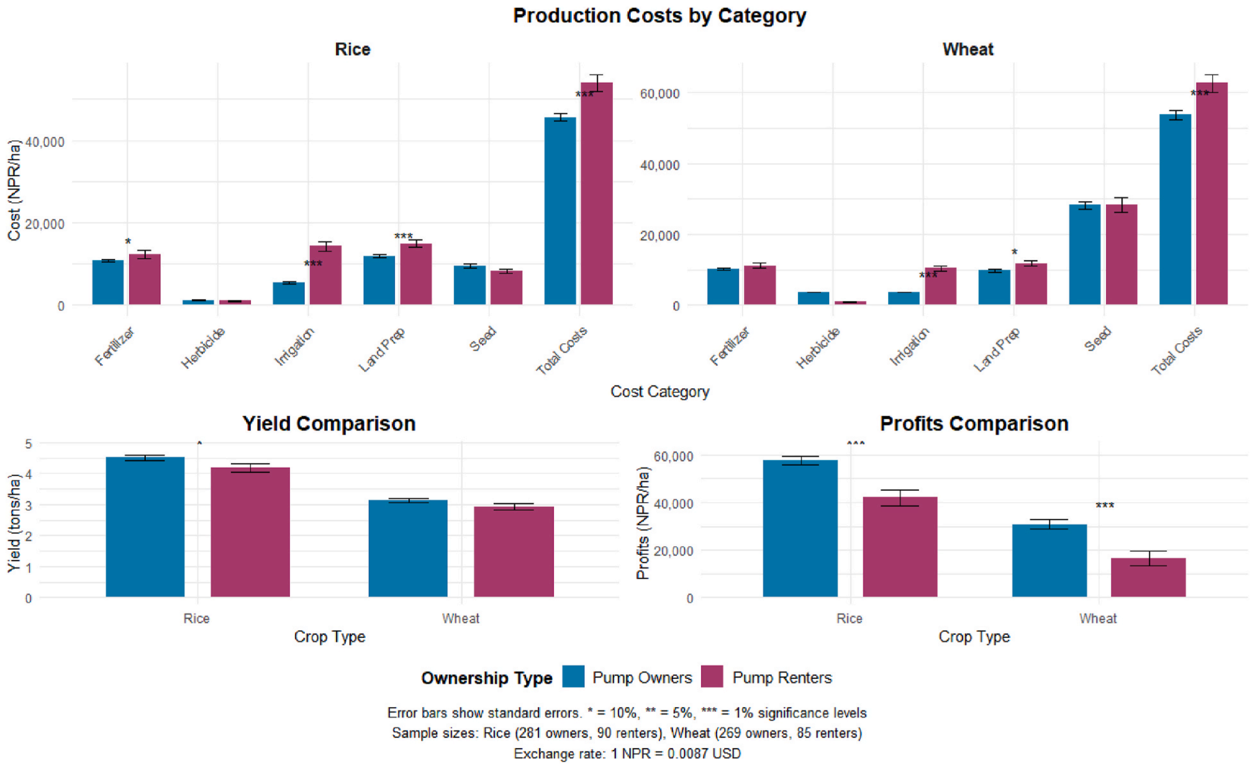
Note: a) *, **, and ***, indicate significance at 10 %, 5 %, and 1 % level of significance respectively. b) Nepalese Rupees (NPR) exchange rate was 1 NPR = 0.0087 USD at the time of the survey. c) †improved varieties in case of rice indicate the hybrid varieties. d) Percentage differences refer to the differences in values of pump owners relative to pump renters.

relied upon rented pumps for irrigation. Rental agreements for pumps typically involve a fixed price per hour, covering transportation and operation costs for irrigation. Renters may or may not be required to provide their own fuel, with lower rates typically charged when fuel is not included. Substantial variability exists in the costs of irrigation among farmers. Among rice growers in the *kharif* season, the cost to completely irrigate a hectare of land was on average NPR 3227 (USD 28), with a range from NPR 450 to 19,990 (USD 4 to 170) across households. Similar irrigation costs were observed among wheat growers in the dry winter season, with an average of NPR 3135 (USD 27) per hectare and a range from NPR 450 to 23,988 (USD 4 to 208) among households. Two key factors found to explain this variability in the costs of irrigation.

First, pump ownership was a major determinant of the costs of irrigation experienced by different farmers.Renters of pumps pay on average NPR 198/hour (USD 1.7/hour) to access a pump excluding embedded costs of fuel, which add on average NPR 100/hour (USD 0.87/hour) to irrigation costs given reported fuel prices and consumption rates. Rental prices vary across the region, with some villages observing high market prices of up to NPR 402 per hour (USD 3.4 per hour) without considering fuel costs, while in other areas, pumps are shared free of charge if the renting farmer provides their own fuel. This substantial variability and high costs are critical in understanding the overall irrigation expenses.

Second, differences in the duration of pumping per irrigation event constitute a further, important source of variation in irrigation costs for farmers. The time for a single irrigation of rice on 1 ha in the *kharif* season ranged between 6 and 89 h per hectare and between 5 and 82 h per hectare in the dry winter season. The average time required to irrigate a plot is about 25 h per hectare for both seasons. These variations in the duration of time taken to irrigate reflect the diverse factors that influence irrigation management and scheduling by farmers, including borewell yields, rainfall patterns, crop growth stages, soil characteristics, plot size, distance to the water source, individual irrigation practices, and crop water demand. While a detailed analysis of the underlying drivers of differences in irrigation duration was beyond the scope of this study, it is evident that any inefficiencies in irrigation duration and scheduling may in turn amplify the existing disparities in irrigation costs between pump renters and owners, particularly when multiple irrigation events are required to maximise yields of crops like rice and wheat.

Differences in irrigation costs between farmers have significant impacts on the intensity of irrigation. Our results show that farmers with higher irrigation costs irrigate their crops less frequently than those with lower costs (Figure A2). Statistically significant



Error bars show standard errors. * = 10%, ** = 5%, *** = 1% significance levels
Sample sizes: Rice (281 owners, 90 renters), Wheat (269 owners, 85 renters)
Exchange rate: 1 NPR = 0.0087 USD

Fig. 2. Inputs and outputs for rice and wheat production for pump owners and renters in Nepal.

differences in average irrigation costs for different frequencies of irrigation (at a 5 % level) highlight that higher water access costs can force farmers to reduce irrigation inputs, increasing their exposure to drought risks. However, irrigation costs also vary greatly among farmers irrigating at the same frequency, indicating the role of individual behavior and production conditions in irrigation decisions. Groundwater access costs significantly impact irrigation intensity, with pump renters irrigating less frequently than pump owners (Table A3). Renters pay up to three times more for irrigation than owners, leading to higher costs across all irrigation intensity levels (Figure A2). During the *kharif* season, pump renters irrigate their plots 2.2 times compared to 2.8 times for owners, and in the dry winter season, renters irrigate 1.6 times compared to 1.8 times for owners. Renters also spend less time per irrigation event per hectare than owners in both seasons.

4.3. Drivers of pump ownership, agricultural productivity, and profitability

Given the central role of pump ownership in driving difference in irrigation access costs, it is important to identify the factors that contribute to higher or lower levels of pump ownership. The estimates from our selection equation for rice and wheat growers suggest that household assets and irrigation practices are the major drivers of pump ownership in our study (Tables 2 and 3).[2] Households with larger farm sizes and wealth indexes are more likely to own pumps. Moreover, the number of household members working on farm also drives pump ownership across both seasons. Finally, frequency of irrigation events significantly influences pump ownership in our study. Overall, descriptive statistics and marginal effects from the ESR model show that wealth, landholding, and irrigation practices are the major drivers of pump ownership in the region.

While there are common factors influencing profitability for both pump owners and renters, such as the number of household members working on the farm and the amount of fertilizer applied, our analysis highlights key distinctions. For pump owners, the ability to irrigate more frequently and efficiently directly and positively impacts yields and profits. In contrast, renters face higher variable costs due to rental fees and less frequent irrigation, which in turn has the knock-on effect of reducing their overall agricultural productivity and profitability. These differences underscore the importance of asset ownership in enhancing agricultural profitability.

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[2] The estimates of the selection equation can be interpreted as normal probit coefficients; the estimates on ρ_1 and ρ_2 in Tables 3 and 4 represent the correlation between the error terms in the selection equation and the outcome equation. The coefficient of ρ_2 is negative and statistically significant whereas the coefficient on ρ_1 is statistically non-significant. The significant coefficient on ρ_2 indicates the presence of selection bias and therefore justifies the use of an ESR framework as opposed to OLS for estimation in this study.

Table 2

Endogenous switching regression model for pump ownership and its impacts on rice yield, costs, and profits in Nepal.

Variables	Selection equation#	Outcome models							
		On rice yield		On irrigation cost		On total variable cost		On profit	
		Owners	Renters	Owners	Renters	Owners	Renters	Owners	Renters
Age of household head (years)	−0.009 (0.011)	-4E-04 (0.001)	−0.006* (0.003)	0.001 (0.002)	0.004 (0.006)	-6E-04 (0.001)	-7E-04 (0.002)	-6E-05 (0.001)	−0.001 (0.002)
Gender of household head (1 = Male)	0.052 (0.412)	−0.153** (0.071)	0.201* (0.107)	−0.158 (0.133)	0.117 (0.187)	−0.199** (0.079)	−0.004 (0.083)	−0.049 (0.050)	0.098 (0.075)
Caste of household (1 = non-marginalized)	0.013 (0.244)	0.018 (0.035)	0.009 (0.088)	0.014 (0.067)	−0.143 (0.155)	0.013 (0.039)	−0.108 (0.069)	0.013 (0.026)	0.034 (0.062)
Farm size in log (ha)	0.992*** (0.236)	0.007 (0.032)	−0.050 (0.070)	−0.013 (0.060)	−0.129 (0.126)	0.015 (0.036)	−0.112** (0.057)	-7E-04 (0.023)	0.038 (0.049)
Education of household head (years)	−0.022 (0.031)	−0.001 (0.004)	0.005 (0.010)	0.006 (0.008)	−0.018 (0.017)	0.002 (0.004)	0.008 (0.008)	−0.001 (0.003)	0.002 (0.007)
Household size (no)	−0.062 (0.045)	−0.007 (0.006)	−0.007 (0.014)	0.014 (0.010)	−0.008 (0.024)	0.009 (0.006)	−0.007 (0.010)	−0.006 (0.017)	−0.007 (0.009)
Number of household members working on farm (no)	0.211** (0.094)	0.018* (0.011)	0.022 (0.028)	−0.015 (0.020)	0.053 (0.049)	−0.004 (0.011)	−0.006 (0.022)	0.011 (0.008)	0.004 (0.020)
Number of migrated household members (no)	−0.092 (0.201)	−0.037 (0.023)	0.057 (0.067)	−0.112** (0.044)	−0.038 (0.118)	−0.074*** (0.027)	0.039 (0.052)	6E-04 (0.017)	0.015 (0.048)
Proportion of land rented-in (%)	−0.331 (0.394)	−0.035 (0.064)	0.040 (0.129)	−0.333*** (0.120)	0.083 (0.228)	0.153** (0.071)	−0.039 (0.100)	−0.123*** (0.046)	0.012 (0.092)
Household income from off farm sources (%)	−0.005 (0.004)	3E-05 (0.001)	-4E-05 (0.001)	0.004*** (0.001)	6E-04 (0.002)	-7E-04 (6E-04)	−0.001 (9E-04)	-4E-06 (4E-04)	7E-04 (8E-04)
Wealth index	0.519*** (0.104)	0.008 (0.014)	−0.030 (0.047)	0.010 (0.026)	0.132 (0.086)	0.040** (0.016)	0.003 (0.041)	−0.011 (0.010)	−0.022 (0.035)
Amount of fertilizers applied on plot (tons/ha)	0.468 (0.305)	0.171*** (0.048)	0.064** (0.029)	0.143 (0.091)	0.047 (0.049)	0.339*** (0.054)	0.034 (0.022)	0.008 (0.034)	0.019 (0.020)
Variety types (1 = hybrids)	0.008 (0.255)	0.064* (0.038)	0.205** (0.088)	−0.127* (0.071)	0.167 (0.156)	0.002 (0.042)	0.061 (0.069)	0.039 (0.027)	0.108 (0.063)
Irrigation frequency (no)	0.415*** (0.115)	−0.022 (0.014)	−0.064 (0.046)	0.267*** (0.027)	0.270*** (0.083)	0.075*** (0.016)	0.091** (0.038)	−0.039*** (0.010)	−0.084** (0.033)
Number of years of irrigation pumps available in the village (years)	−0.149*** (0.018)								
Constant	−1.799 (1.900)	0.625** (0.310)	0.964** (0.304)	6.829*** (0.580)	7.723*** (0.536)	8.542*** (0.348)	10.449*** (0.239)	12.099*** (0.223)	11.808*** (0.216)
$ln\ \sigma_1$		−1.372*** (0.044)		−0.736*** (0.042)		−1.258*** (0.044)		−1.684*** (0.046)	
$\rho_{1\mu}$		−0.379 (0.258)		−0.022 (0.227)		0.373 (0.308)		−0.664** (0.285)	
$ln\ \sigma_0$			−1.078*** (0.091)		−0.553*** (0.076)		−1.350*** (0.089)		−1.449*** (0.083)
$\rho_{0\mu}$			−0.643** (0.306)		0.116 (0.283)		−0.424 (0.382)		−0.355 (0.306)
No of observations	371	281	90	281	90	281	90	281	90
Wald χ^2	40.300								
Log likelihood	−123.723								

Note: a) *, **, and ***, indicate significance at 10 %, 5 %, and 1 % level of significance respectively. b) #This selection model was taken from rice productivity and the results for other outcome variables are slightly different. b) Numbers inside the parenthesis indicates the standard errors of the coefficients.

Table 3

Endogenous switching regression model results for pump ownership and its impacts on wheat yield, costs, and profits Nepal.

Variables	Selection equation$^{\#}$	Outcome models							
		On wheat yield		On irrigation cost		On total variable cost		On profit	
		Owners	Renters	Owners	Renters	Owners	Renters	Owners	Renters
Age of household head (years)	−0.007 (0.010)	7E-04 (0.002)	−0.006 (0.003)	−0.003 (0.002)	0.010 (0.007)	-2E-04 (6E-04)	4E-04 (0.001)	0.001 (0.001)	−0.003 (0.003)
Gender of household head (1 = Male)	0.044 (0.383)	0.063 (0.088)	0.225** (0.106)	0.008 (0.117)	−0.067 (0.216)	0.040 (0.029)	0.034 (0.046)	−0.008 (0.067)	0.085 (0.081)
Caste of household (1 = non-marginalized)	0.001 (0.239)	0.052 (0.047)	−0.003 (0.081)	−0.078 (0.063)	−0.133 (0.160)	0.022 (0.015)	0.004 (0.033)	0.008 (0.036)	−0.004 (0.061)
Farm size in log (ha)	0.617** (0.216)	0.038 (0.043)	−0.122 (0.075)	−0.026 (0.058)	−0.110 (0.168)	−0.009 (0.014)	0.055** (0.028)	0.034 (0.033)	−0.163** (0.052)
Education of household head (years)	−0.029 (0.030)	−0.001 (0.006)	0.010 (0.009)	−0.008 (0.008)	−0.002 (0.019)	-5E-04 (0.001)	0.003 (0.004)	0.000 (0.004)	0.007 (0.007)
Household size (no.)	−0.016 (0.046)	0.001 (0.008)	−0.009 (0.013)	0.003 (0.010)	−0.030 (0.028)	0.004* (0.002)	−0.002 (0.005)	−0.008 (0.006)	−0.004 (0.010)
Number of household members working on farm (no.)	0.159* (0.093)	−0.009 (0.013)	0.058** (0.027)	0.016 (0.018)	0.096* (0.056)	0.001 (0.004)	0.003 (0.011)	−0.009 (0.011)	0.043** (0.020)
Number of migrated household members (no.)	−0.139 (0.204)	0.019 (0.032)	0.069 (0.063)	−0.080* (0.042)	0.035 (0.125)	−0.011 (0.010)	0.018 (0.027)	0.036 (0.024)	0.034 (0.048)
Proportion of land rented-in (%)	−0.204 (0.406)	0.083 (0.092)	−0.013 (0.129)	−0.156 (0.123)	0.134 (0.256)	0.051* (0.030)	−0.007 (0.053)	−0.046 (0.070)	−0.050 (0.099)
Household income from off farm sources (%)	−0.005 (0.003)	-5E-04 (7E-04)	−0.002** (0.001)	0.003 (0.001)	0.000 (0.003)	9E-05 (2E-04)	−0.001*** (4E-04)	0.000 (0.001)	0.000 (0.001)
Wealth index	0.555*** (0.106)	−0.003 (0.019)	−0.015 (0.062)	-4E-04*** (0.025)	0.106 (0.155)	−0.006 (0.006)	0.029 (0.018)	0.001 (0.014)	−0.018 (0.035)
Amount of fertilizers applied on plot (tons/ha)	0.162 (0.279)	0.190*** (0.053)	0.085 (0.097)	0.152 (0.071)	0.165 (0.200)	0.087*** (0.017)	0.140*** (0.038)	0.007 (0.040)	−0.151** (0.072)
Variety types (1 = improved)	−0.352 (0.332)	0.138 (0.063)	0.184 (0.129)	−0.014 (0.084)	0.151 (0.267)	0.132*** (0.020)	−0.072 (0.049)	−0.094** (0.048)	0.177* (0.094)
Irrigation frequency (no.)	0.690** (0.221)	0.014 (0.046)	−0.063 (0.093)	0.464*** (0.060)	0.485** (0.218)	0.009 (0.014)	0.118*** (0.034)	0.004 (0.034)	−0.166** (0.064)
Number of years of irrigation pumps available in the village (years)	−0.131*** (0.017)								
Constant	−0.455 (1.752)	−0.209 (0.336)	0.356 (0.641)	6.440*** (0.444)	6.533*** (1.320)	11.227*** (0.108)	11.129*** (0.248)	11.860*** (0.253)	12.359*** (0.474)
$ln\ \sigma_1$		−1.094*** (0.043)		−0.812*** (0.043)		−2.220*** (0.043)		−1.376*** (0.043)	
$\rho_{1\mu}$		−0.226 (0.223)		−0.022 (0.196)		−0.097 (0.203)		−0.210 (0.216)	
$ln\ \sigma_0$			−1.169*** (0.101)		−0.491*** (0.116)		−1.909*** (0.117)		−1.408*** (0.099)
$\rho_{0\mu}$			−0.413 (0.487)		0.361 (0.693)		1.634*** (0.558)		−0.694** (0.302)
No of observations	354	269	85	269	85	269	85	269	85
Wald χ^2	26.140								
Log likelihood	−195.531								

Notes: a) *, **, and ***, indicate significance at 10 %, 5 %, and 1 % level of significance respectively. b) $^{\#}$This selection model was taken from rice productivity and the results for other outcome variables are slightly different. b) Numbers inside the parenthesis indicates the standard errors of the coefficients.

4.4. Impacts of pump ownership on agricultural productivity and profitability

To further investigate the links between pump ownership and agricultural outcomes, we make use of treatment effects estimates from our ESR model. The treatment effects of pump ownership for irrigation show that pump ownership has a positive and significant impact on rice yields (ATT = 1.19 tons/hectare) (Table 4). If pump owners had not purchased pumps for irrigation, their rice yields could decrease by 37 %, whereas if renters had conversely purchased pumps, their rice yields could increase by 18 % (ATU = 0.72 tons/hectare). The treatment effects for agricultural costs of production and profits also show significant advantages of pump ownership. Pump ownership for rice irrigation leads to significant reductions in irrigation costs of NPR 12,307 (USD 107); equivalent to a 72 % decrease in irrigation costs due to pump ownership. As a result, the ATT on total variable costs of rice production and net agricultural profits also indicate economic advantages of owning pumps. The treatment effect on total variable costs of rice production suggests a decrease in 7 % of costs due to pump ownership for irrigation that, together with associated yield gains, amount to a 94 % increase in net profits.

Pump ownership for irrigation also has a similar positive and significant impact on wheat yields (Table 5). If pump owners had rented pumps, their wheat yields could decrease around 20 % (ATT = 0.5 tons/hectare) whereas if the renters had owned pumps for irrigation, their wheat yields could increase by 11 % (ATU = 0.31 tons/hectare). For pump owners, owning a pump for irrigation has a positive and significant impact on irrigation cost reduction that amounts to NPR 10,247/hectare (USD 89/hectare); equivalent to a 62 % decrease in irrigation costs. The treatment effects on total variable costs of production and net agricultural profits for wheat growers also highlight the significant advantages conferred by owning a pump. The treatment effect on variable costs for pump renters suggests an increase in 10 % of costs (ATU = NPR 6039/hectare (USD 53/hectare)) if they had owned a pump. The average treatment effect results on profits for the pump owners suggest that the owners could have faced losses, had they not owned pumps for irrigation, while the pump renters could have increased their profits by 119 % (ATU = NPR 16,314/ha (USD 142/hectare)), had they owned pumps for irrigation.

5. Discussion

Our results demonstrate that pump ownership significantly reduces irrigation costs by eliminating rental fees and reducing cost variability. Pump owners benefit from lower per-hour irrigation costs and more efficient water use, which together contribute to lower overall expenses. This consistency in costs allows for more predictable budgeting, enhancing the financial stability and profitability of pump-owning farmers. The connection between pump ownership and reduced costs for non-irrigation agricultural inputs operates through several interconnected mechanisms. First, asset ownership enhances farmers' economic position and bargaining power in input markets. Pump owners, who generally have higher levels of assets and landholdings, can negotiate better prices for bulk purchases of inputs such as fertiliser and pesticides. This purchasing power advantage extends beyond irrigation to all farm inputs, as suppliers often offer volume discounts and preferential terms to customers with demonstrated financial capacity.

Second, pump ownership serves as collateral for credit access, enabling owners to secure loans for purchasing other agricultural inputs at favourable terms. In Nepal's rural credit markets, physical assets like pumps provide security that allows farmers to access formal credit systems rather than relying on expensive informal lending [39]. This improved credit access reduces the effective cost of all agricultural inputs by enabling bulk purchases and timely acquisition of quality inputs. Third, the reliability and efficiency of owned pumps enable better overall farm management, leading to optimised input use and reduced waste. When farmers can irrigate according to optimal schedules without depending on pump availability from others, they can time other operations—such as fertiliser application and pest management—more precisely. This coordination reduces input costs through improved efficiency rather than simply reducing input quantities.

These results are consistent with findings from other studies in the EIGP that suggest large disparities in groundwater access and use in the region. Particularly, marginal farmers with scattered land holdings lack the resources and command areas to buy pumps, therefore they rely on renting pumps from their neighbours for irrigation [8,27]. Our research aligns with existing literature, underscoring the crucial role of landholding and household and agricultural assets in determining the adoption of pumps and other agricultural machinery. This relationship has been consistently observed in studies examining pump adoption among small-scale

Table 4

Impacts of pump ownership on rice yield, costs, and farm profits for rice growers.

Outcome variables	Farm sub-samples	Decision to		Treatment effects	Change (%)
		Adopt	Not-to adopt		
Rice yield (tons/ha)	Pump owners (ATT)	4.38 (0.02)	3.19 (0.28)	1.19*** (0.03)	37 %
	Pump renters (ATU)	4.74 (0.07)	4.02 (0.07)	0.72*** (0.07)	18 %
Irrigation cost (NPR/ha)	Pump owners (ATT)	4897.99 (114.03)	17,205.96 (390.24)	−12,307.97*** (324.27)	−72 %
	Pump renters (ATU)	4460.59 (165.20)	12,068.43 (419.00)	−7607.83*** (339.94)	−63 %
Total variable cost (NPR/ha)	Pump owners (ATT)	43,810.95 (484.42)	47,111.04 (460.24)	−3300.09*** (524.68)	−7 %
	Pump renters (ATU)	37,523.09 (794.98)	52,054.57 (885.84)	−14,531.48*** (834.62)	−28 %
Profits (NPR/ha)	Pump owners (ATT)	55,384.36 (557.71)	22,620.74 (780.83)	32,763.61*** (610.37)	145 %
	Pump renters (ATU)	75,275.59 (1284.67)	38,755.20 (1469.03)	36,520.39*** (1470.38)	94 %

Notes: a) *, **, and ***, indicate significance at 10 %, 5 %, and 1 % level of significance respectively. b) ATT refers to the Average Treatment effect on the Treated; ATU refers to the Average Treatment Effect on the Untreated.

Table 5

Impacts of pump ownership on wheat yield, costs, and farm profits for wheat growers.

Outcome variables	Farm household types	Decision to		Treatment effects	Change (%)
		Adopt	Not-to adopt		
Wheat yield (tons/ha)	Pump owners (ATT)	2.97 (0.01)	2.47 (0.02)	0.50*** (0.02)	20 %
	Pump renters (ATU)	3.12 (0.03)	2.80 (0.06)	0.31*** (0.04)	11 %
Irrigation cost (NPR/ha)	Pump owners (ATT)	3304.07 (55.87)	13,551.98 (287.58)	−10,247.92*** (255.20)	−76 %
	Pump renters (ATU)	3323.26 (108.46)	8805.88 (291.23)	−5482.61*** (230.10)	−62 %
Total variable cost (NPR/ha)	Pump owners (ATT)	53,719.72 (667.59)	97,633.57 (1127.37)	−43,913.85*** (1201.99)	−45 %
	Pump renters (ATU)	57,192.34 (1036.92)	63,231.90 (1625.27)	−6039.57*** (1467.98)	−10 %
Profits (NPR/ha)	Pump owners (ATT)	27,060.26 (538.12)	−8973.54 (886.28)	36,033.80*** (1258.95)	+++ NA[†]
	Pump renters (ATU)	30,024.08 (1021.14)	13,709.27 (1581.46)	16,314.81*** (1939.67)	119 %

Notes: a) *, **, and ***, indicate significance at 10 %, 5 %, and 1 % level of significance respectively. b) ATT refers to the Average Treatment effect on the Treated; ATU refers to the Average Treatment Effect on the Untreated. b) [†] NA: Not applicable. The percentage change will be substantially higher and sometimes erroneous while comparing the negative and positive values. However, this result indicates that farmers who own pumps for irrigation and cultivate wheat could have faced losses had they rented pumps, indicating ownership as major driver for profits.

farming households in Nepal [40], Pakistan [41], and Ethiopia [42], as well as the adoption of farm machinery in Nepal [43] and South Asia [44]. Findings from these studies collectively emphasise the significant influence of assets on farmers' decisions to adopt and invest in agricultural equipment. By reaffirming this relationship, our research contributes to the expanding body of evidence highlighting the pivotal role of assets as a key determinant in technology adoption and effective utilisation of machinery in agricultural contexts.

The decision by farmers not to purchase their own pumps, even when it might be economically beneficial, is a complex issue influenced by multiple factors documented in the literature. First, the high upfront cost and liquidity constraints represent the major issue among smallholders. Evidence from our semi-structured interviews reveals that pumps typically cost USD 200 to 1,000, depending on the horsepower. Although loans can theoretically ease financial constraints, many smallholders face liquidity constraints that limit their ability to make the initial down payment or to manage repayment schedules. Binswanger and Khandker [45] and Carter and Barrett [46] emphasise that lack of immediate cash flow and savings inhibits investment in durable goods like pumps.

Second, farming is inherently risky due to weather variability, price fluctuations, and input uncertainties. Even with loans, farmers may avoid purchasing pumps due to fear of defaulting if the expected returns do not materialise [47,48]. This risk aversion is compounded in areas with unpredictable water availability or fluctuating crop markets.

Third, while credit may be available in principle, the terms and conditions such as high interest rates, short repayment periods, and stringent collateral requirements can discourage uptake [49]. Rural credit markets in the Terai region require substantial collateral for agricultural loans, often demanding land titles or other fixed assets that many smallholder farmers cannot provide. Moreover, informal money lenders may charge prohibitively high interest rates. The asset disparities evident in our wealth index results reflect these underlying credit constraints—farmers who already possess assets can more easily access credit to purchase additional equipment, while asset-poor farmers remain trapped in rental markets despite recognising the long-term benefits of ownership. These asset-based advantages in accessing agricultural resources during periods of stress are not unique to Nepal's irrigation systems. Recent evidence from Chile demonstrates how drought mitigation policies tend to disproportionately benefit larger, asset-rich producers, leading to increased income concentration among agricultural producers during water scarcity periods [50]. This pattern reinforces our findings that asset ownership creates compounding advantages in agricultural resource access, particularly during challenging conditions when reliable irrigation becomes most critical.

Fourth, pump ownership requires technical know-how to operate and maintain pumps. Farmers lacking this expertise or access to repair services might avoid purchasing to circumvent potential downtime or costs. Fifth, social norms and community practices sometimes favour communal use or shared resources rather than individual ownership. Investment decisions might also be shaped by household gender dynamics or household decision-making processes regarding who can make major investment decisions [51]. These findings align with broader literature on agricultural technology adoption constraints in South Asia, where credit market failures and institutional weaknesses perpetuate asset inequality among smallholder farmers [31,44].

The greater benefits of pump ownership for rice compared to wheat production reflect fundamental differences in crop water requirements, growing season conditions, and market dynamics. First, rice requires continuous or frequent flooding, particularly during transplanting and early vegetation stages. Timely irrigation is therefore critical for transplanting operations, and delays can significantly affect rice yields [8]. Pump ownership enables rice farmers to irrigate on-demand, avoiding delays caused by unreliable canals or rental pumps. Our data show that rice farmers irrigate an average of 2.8 times per season compared to 1.8 times for wheat, making the efficiency gains from pump ownership more pronounced for rice production.

Second, while rice is grown during the monsoon season, rainfall is often erratic, particularly in the Eastern IGP. Canal systems are often unreliable or poorly maintained during the early kharif season. With more farmers needing irrigation at the same time, rental pumps become more expensive or unavailable during the most critical periods. Mukherji and Facon [52] show that water rental markets during the kharif season are often monopolised or marked by elite capture, leading to inefficiencies and inequitable access. Hence, pump ownership may have different effects for rice and wheat cultivation.

Third, pump ownership for rice farmers removes coordination problems, eliminates waiting time, and ensures timely transplanting and puddling. In contrast, wheat is less water-intensive and more forgiving of delays in irrigation, as it is grown in the winter season with more predictable water needs. The economic value per unit of water applied also differs between crops, with rice typically generating higher gross returns per hectare than wheat in the study region, making yield gains from improved irrigation more economically significant. Seasonal labour dynamics also contribute to differential impacts, as monsoon season labour constraints make time savings from owned pumps more valuable for rice than wheat cultivation during the dry season. All these factors—crop-specific water demand, seasonal differences, availability of alternative irrigation sources, and climate variability—contribute to differences in irrigation costs, input use, yields, and profits between rice and wheat cultivation, both for pump owners and renters.

It's crucial to acknowledge the multifaceted factors influencing irrigation access and use, which lead to improved yields, reduced costs, and higher profits. Our findings clearly show that pump ownership plays a vital role in improving livelihoods by lowering irrigation expenses and fostering increased irrigation intensity. The high costs of irrigation access due to pump rental rates, along with a substantial variability in these costs across different households and regions, are consistent with findings from previous studies [28]. These results align with previous studies that highlight the connection between affordable irrigation and long-term positive welfare outcomes for smallholder farmers [4]. Sustained access to affordable irrigation has been shown to improve crop yields, household incomes, and food security over multiple growing seasons[4]. Additionally, other studies emphasise the benefits of pump ownership—despite higher initial investment costs—on crop yields and household welfare [53,54], further supporting our findings on the importance of pump ownership in reducing costs and their variability, improving productivity, and increasing farm profits.

We find that the effects of pump ownership on irrigation management and agricultural production outcomes exhibit important differences between crops and growing seasons. For instance, we find that farmers benefit more significantly from pump ownership for rice production than wheat, suggesting that tailored support for rice irrigation could yield substantial productivity gains. Future research should focus on the long-term sustainability of these interventions, particularly the potential for integrating renewable energy sources into irrigation systems. Our findings also highlight barriers that prevent many farmers from purchasing their own pumps, which can help guide and inform interventions to reduce current variability in groundwater irrigation access costs among farmers in the Terai.

Given the variability in groundwater access costs between pump owners and renters identified in our study, along with their impacts on productivity and profitability, a key recommendation from our study is that irrigation development policies should prioritise improving the purchase and maintenance of pumping equipment. In Nepal, current government programs focus primarily on expanding irrigated area and subsidizing the cost of borewell drilling [22]. Of the 19 % of the overall budget allocated to irrigation in the national Agricultural Development Strategy roadmap for 2035, almost all the budget is apportioned to irrigation expansion and borewell drilling [55]. Subsidies for pumps remain small and often support solar irrigation pumps through the Alternative Energy Promotion Centre in Nepal[56]. While tubewell expansion is vital for agricultural productivity in the Terai, our analysis suggests that borewells are not the primary drivers of high groundwater access costs. Instead, support should target marginalized farmers who rely on pump rentals.

Beyond this, we suggest that there is also a need for policymakers to explore mechanisms for developing more competitive markets for irrigation services for farmers lacking capital to purchase equipment, even with partial subsidies or reduced capital costs. Insights from our analyses suggest that the current oligopolistic local rental markets in the Terai and some other parts of the EIGP means that poor and marginal farmers may not benefit greatly from enhancements in the performance of existing pumps (e.g., in terms of improved fuel efficiency). Findings from our semi-structured interviews suggest that social capital and the economic perception of pump owners and renters are the main drivers of irrigation water pricing methods in the Terai. We also find substantial variability in pump rental costs within the two districts in our sample. Alternative models of irrigation provision, such as private sector equipment rentals and pay-as-you-go irrigation services used in other countries [57,58] could reduce high access costs in oligopolistic rental markets and address concerns about government and donor costs when relying on subsidies alone for sustainable intensification.

Looking further into the future, we argue that policymakers should seek to exploit synergies between improving the cost effectiveness diesel-pump irrigation systems and transitioning to renewable-based pumping technologies. Our analysis shows that diesel pump ownership is associated with greater irrigation use, higher productivity, and increased household wealth. Maximizing returns from existing diesel pumping systems could therefore enable more farmers to invest in new technologies such as solar irrigation pumps, which are typically highly capital intensive [11]. For instance, a cheap solar pump with 1 HP (1200 kW peak) presently costs around USD 3800 per system (NPR 4,37,000 per system)[11]. Although subsidies and other financial incentives reduce these initial costs, uptake of solar irrigation pumps remains largely limited to wealthier farmers or those able to benefit from and access government subsidies [11].

While we identify opportunities for interventions to diesel pump systems to work synergistically with SIPs, it is important to note that the socio-organisational and economic traits of agricultural systems in the Terai and wider EIGP may continue to impact the scalability of renewable technologies like solar irrigation. For example, land fragmentation is high and increasing across the Terai[59], meaning that farmers willingness to adopt SIPs as a substitute for existing diesel systems often depends on being able to access and afford portable high-capacity solar pump designs that mimic lightweight diesel pumps. Current solar pumps are typically much heavier, more expensive, and deliver lower water output than low-cost Chinese diesel or petrol pumps [60] Therefore, diesel and petrol pumping systems are likely to remain dominant in EIGP irrigated agriculture for decades, even as demand for renewable technologies increases and drives costs down. Indeed, recent evidence from Ref. [12] shows that farmers in the Terai with access to SIPs continue to maintain and utilise their existing diesel pumps, "stacking" technologies to enhance overall irrigation capacity. The study also emphasises the need for regulatory frameworks that support the adoption of renewable energy solutions while addressing groundwater management and equity challenges in access to emerging pumping technology.

Finally, future efforts to intensify irrigation water use, whether by reducing operating costs of diesel systems and/or by introducing new pumping technologies such as solar irrigation systems, must consider groundwater sustainability hazards posed by reduced irrigation pumping costs [4,16]. Although overall groundwater resources are presently underexploited in the EIGP, aggregate regional statistics mask spatial heterogeneity in aquifer conditions that could locally limit sustainable extraction potential [61]. For instance, farmers in some villages we surveyed reported difficulties finding reliable groundwater sources at shallow depths, particularly during the dry season when borewell returns were sometimes insufficient to fully irrigate landholdings. These findings align with broader data showing significant local variation in shallow sustainable groundwater yields across the IGP [61].

Our research adds to the existing body of knowledge by providing empirical evidence of the positive impact of pump ownership on agricultural productivity and profitability. These insights are not only relevant to the Terai region but also to other regions where groundwater is a critical resource for irrigation. High or highly variable costs of water access for irrigation have been documented in parts of Africa and Latin America, where groundwater is also an important source of water supply for irrigation. The principles of cost reduction and efficient water use demonstrated in this study can be applied to improve irrigation practices globally. Additionally, while this study focuses on rice and wheat, strategies for enhancing irrigation efficiency and reducing costs are applicable to a wide range of crops, potentially benefiting diverse agricultural systems.

In addition to reducing irrigation access costs, there are other strategies that can enhance agricultural productivity and profitability in the Terai region. Timely irrigation and tailored farmer advisories are crucial, as highlighted in Ref. [62], emphasising the importance of scheduling and precision in irrigation practices to maximise crop yields and water use efficiency. Moreover, structural transformation in farm sizes could play a significant role in improving outcomes. Larger farm sizes can benefit more from irrigation technologies due to economies of scale [62]. Furthermore, changing cropping patterns to less water-intensive crops can alleviate water stress and improve sustainability [63]. These broader opportunities and interventions are essential for creating resilient and sustainable agricultural systems. Thus, a multifaceted approach that includes improving irrigation access, optimising farm sizes, and adapting cropping patterns is necessary to enhance the overall agricultural landscape in the Terai region and the wider EIGP.

Given the recent significant investments in irrigation development in Sub-Saharan Africa, it is crucial to draw lessons from experiences in South Asia. For instance, the integration of renewable energy and the development of competitive markets for irrigation services are vital strategies that can be adapted. Major investments, such as those in the Shire Valley Transformation Program in Malawi and various projects in Kenya and Nigeria, should consider the adaptive investment pathways suggested in our and other research. These involve small, step-wise investments rather than large lump-sum investments to build resilience and sustainability in irrigation practices. These strategies should be considered to ensure that irrigation investments in Sub-Saharan Africa and other regions are both sustainable and adaptable to future climate and socio-economic changes.

6. Conclusion

Smallholder farmers in the EIGP, including those in the Terai region of Nepal, are currently constrained in their ability to intensify agricultural production and consistently protect crops against production risks like drought and monsoon rainfall variability due to the high costs of accessing technology for groundwater irrigation. **This study demonstrates that improving the ownership of diesel-pump irrigation systems can significantly reduce irrigation costs and increase agricultural productivity for millions of farmers across the Terai region and wider EIGP**. Our results show that pump ownership reduces irrigation costs for rice and wheat cultivation by 72 % and 76 % respectively, while increasing rice and wheat productivity by 37 % and 20 % respectively.

Our endogenous switching regression analysis provides robust empirical evidence that pump ownership causally improves agricultural outcomes by addressing selection bias concerns. The findings reveal that household assets, farm size, and irrigation practices are the primary drivers of pump ownership, highlighting the role of wealth and credit constraints in determining access to cost-effective irrigation. The policy implications are clear: irrigation development strategies should prioritise improving farmers' ability to purchase and maintain pumping equipment rather than focusing solely on expanding irrigated area.

Future interventions should exploit synergies between improving existing diesel pump systems and transitioning to renewable-based technologies, while considering groundwater sustainability and local aquifer conditions to avoid overexploitation. The principles demonstrated in this study—reducing irrigation access costs through improved technology ownership—are applicable beyond South Asia to other regions where smallholder farmers face high or variable water access costs. This research contributes to the growing evidence base supporting technology ownership as a pathway to agricultural intensification and poverty reduction in resource-constrained environments.

CRediT authorship contribution statement

Roshan Adhikari: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Timothy Foster:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Gokul P. Paudel:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Anton Urfels:** Writing – review & editing, Data curation, Conceptualization. **Subash Adhikari:** Writing – review & editing, Data curation, Conceptualization. **Timothy J. Krupnik:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Validity test for selection instrument for rice growers.

Parameter estimates	Dependent variable (1 = pump owners)	Irrigation cost for pump renters (NPR/ha)	Rice yield for pump renters (tons/ha)	Profit for pump renters (NPR/ha)	Total variable cost for pump renters (NPR/ha)
	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)
Constant	−1.601 (2.351)	−10159.660 (22052.560)	4.033 (3.18)	54342.370 (54849.410)	38025.410 (53404.840)
No of years of irrigation pumps available in villages (years)	−0.151*** (0.024)	−117.984 (256.181)	−0.057 (0.036)	−770.027 (916.587)	−543.7562 (466.0573)
Wald test on instrumental variable	$\chi^2 = 231.8$	*F* stat = 1.85	*F* stat = 1.49	*F* stat = 1.03	*F* stat = 1.44
Other controls	Yes	Yes	Yes	Yes	Yes
Number of observations	371	90	90	90	90
Underidentification (Andreson canon. corr. LM statistics)	*P=0.000*	*P=0.000*	*P=0.000*	*P=0.000*	*P=0.000*
Weak identification (Cragg-Donald Wald F statistics)	134.663	134.663	134.663	134.663	134.663

Note: a) *, ** and *** indicate significance at 10 %, 5 % and 1 % respectively. b) Nepalese Rupees (NPR) exchange rate was 1 NPR = 0.0087 USD at the time of the survey. Standard errors were bootstrapped 500 times. The under identification test is an LM test based on [64], rk LM statistics with the null hypothesis that the model is under identified whereas the weak identification represents the Cragg-Donald Wald F statistics.

Table A2
Validity test for selection instrument for wheat growers.

Parameter estimates	Dependent variable (1 = pump owners)	Irrigation cost for pump renters (NPR/ha)	Wheat yield for pump renters (tons/ha)	Profit for pump renters (NPR/ha)	Total variable cost for pump renters (NPR/ha)
	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)	Coefficient (Standard error)
Constant	−0.680 (1.941)	−28235.090 (22132.640)	0.793 (2.220)	84955.100 (66109.890)	−63526.940 (57431.750)
No of years of irrigation pumps available in villages (years)	−0.133*** (0.022)	−49.116 (129.679)	−0.024 (0.024)	−913.241 (808.073)	238.26 (571.434)
Wald test on instrumental variable	$\chi^2 = 207.56$	*F* stat = 1.64	*F* stat = 1.86	*F* stat = 1.30	*F* stat = 1.48
Other controls	Yes	Yes	Yes	Yes	Yes
Number of observations	354	85	85	85	85
Underidentification (Andreson canon. corr. LM statistics)	*P=0.000*	*P=0.000*	*P=0.000*	*P=0.000*	*P=0.000*
Weak identification (Cragg-Donald Wald F statistics)	113.660	113.660	113.660	113.660	113.660

Note: a) *, ** and *** indicate significance at 10 %, 5 % and 1 % respectively. b) Nepalese Rupees (NPR) exchange rate was 1 NPR = 0.0087 USD at the time of the survey. Standard errors were bootstrapped 500 times. The under identification test is an LM test based on Kleibergen and Paap (2006), rk LM statistics with the null hypothesis that the model is under identified whereas the weak identification represents the Cragg-Donald Wald F statistics.

Table A3
Difference in irrigation frequency and time: pump owners and pump renters

Rice grown in the summer monsoon season	Pump owners	Pump renters	Difference (%)
Irrigation frequency	2.8 (1.1)	2.2 (1.0)	20***
Irrigation time (hours/ha)	25 (11)	23 (10)	9**
Number of plots	90	281	
Wheat grown in the dry winter season	Pump owners	Pump renters	Difference (%)

(*continued on next page*)

Table A3 (*continued*)

Rice grown in the summer monsoon season	Pump owners	Pump renters	Difference (%)
Irrigation frequency	1.8 (0.5)	1.6 (0.5)	10**
Irrigation time (hours/ha)	25 (10)	22 (10)	12*
Number of plots	85	269	

Note: a) Means are followed by standard deviation in parentheses for all variables in the first two columns. b) Significance on *t*-test of differences: *p < 0.1, **p < 0.05, ***p < 0.01.

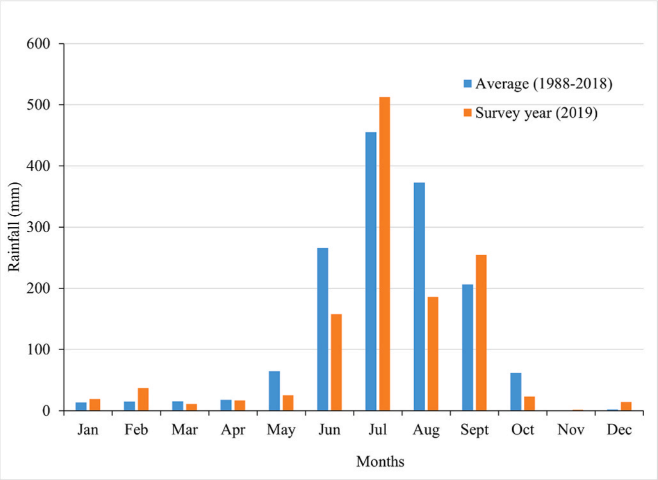

Fig. A1. Long-term rainfall (years 1988–2018) compared to rainfall in the survey year (2019) in the study area.
Note: We use gridded rainfall data from the CHIRPS dataset (Funk et al., 2014) for this graph.

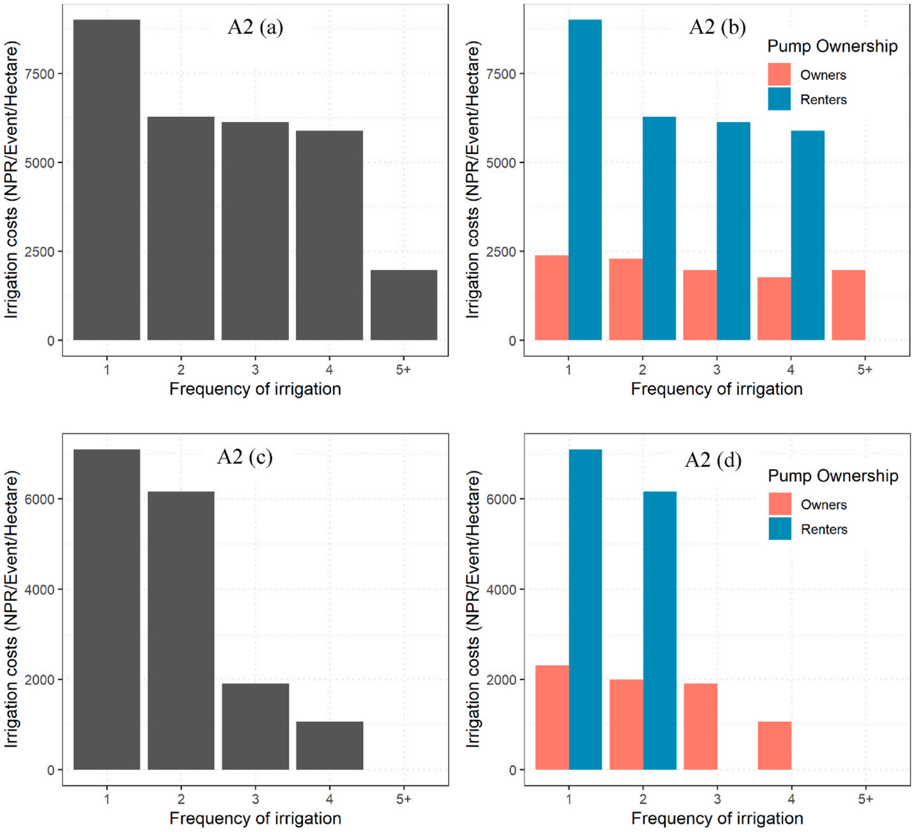

Fig. A2. Average cost (NPR) to irrigate 1 ha of plot for pump owners and pump renters subdivided by the number of irrigation events in the *kharif* season in 2018 (Figures A2(a) and A2(b)) and wheat growers in the dry winter season in 2018/19 (Figures A2(c) and A2(d))
Note: Nepalese Rupees (NPR) exchange rate was 1 NPR = 0.0087 USD at the time of the survey.

Data availability

Data will be made available on request.

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