Improving pumpset selection to support intensification of groundwater irrigation in the Eastern Indo-Gangetic Plains

Timothy Foster[1], Roshan Adhikari[2], Subash Adhikari[3], Scott Justice[3], Baburam Tiwari[3], Anton Urfels[3,4,5], Timothy J. Krupnik[6]

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[1]Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK
[2]Global Development Institute, University of Manchester, UK
[3]International Maize and Wheat Improvement Centre (CIMMYT), Sustainable Intensification Program, Nepal
[4]Water Resources Management Group, Wageningen University & Research, Netherlands
[5]Centre for Crop Systems Analysis, Wageningen University & Research, Netherlands
[6]International Maize and Wheat Improvement Centre, Sustainable Intensification Program, Bangladesh

Abstract

Intensification of groundwater irrigation is central to goals of improving food security and reducing chronic poverty faced by millions of rural households across the eastern Indo-Gangetic Plains (EIGP) of Nepal and parts of eastern India. At present, levels of groundwater use and access in the EIGP lag far behind other areas of South Asia despite abundant available groundwater resources. A key reason for prevailing access constraints is the dependence on diesel pumpsets for accessing groundwater, which are typically unsubsidised and therefore expensive to purchase and operate. To date, efforts to reduce access costs have focused almost exclusively on how to incentivise adoption of alternative electric or solar-powered pumping technologies, which are viewed as being cheaper to operate and less environmentally damaging due to their lower operational carbon emissions. In contrast, there has been little attention paid to identifying opportunities to make existing diesel pump systems more cost effective for farmers to operate in order to support adaptation to climate change and reduce poverty. In this study, we use evidence from 116 detailed in-situ pump tests along with interviews with pumpset dealers, mechanics and farmers in the Nepal Terai to assess how and why fuel efficiency and operational costs of diesel pump irrigation are affected by farmers' pumpset selection decisions. We show that costs diesel pumpset irrigation can be reduced significantly by supporting and incentivising farmers (e.g., through equipment advisories, improved supply chains for maintenance services and spare parts) to invest in newer low-cost, portable and smaller horsepower pumpset designs that are more effectively matched to local operating conditions in the EIGP than older Indian manufactured engines that have historically been preferred by farmers in the region. Such interventions can help to unlock potential for intensified irrigation water use in the EIGP, contributing to goals of improving agricultural productivity and resilience to climate extremes while also strengthening farmers capacity to invest in emerging low-carbon pumping technologies.

Keywords

Irrigation; Groundwater; Technological efficiency; Sustainable intensification, Water-food-energy nexus

1. Introduction

Agriculture is central to livelihoods, economies, and food security of rural households in countries across South Asia. Beginning with the onset of the Green Revolution, increased availability of pumping technologies and the expansion of groundwater irrigation has played an important role in intensifying agricultural production in many parts of the region (Shah, 2007). Groundwater can provide a reliable source of water supply, enabling year-round cultivation and helping farmers to more effectively buffer production against risks posed by monsoonal rainfall variability and climate change.

At present, it is estimated that over 90 million hectares of agricultural land in South Asia is currently irrigated, of which approximately 60% is supplied by groundwater (FAO, 2012). However, these figures mask important variability across the region in both the distribution of irrigated land areas and intensity of groundwater irrigation use. While concerns about over-exploitation of groundwater resources for irrigation in north-western India and Pakistan have been widely documented (Rodell et al., 2009; MacDonald et al., 2016; Fishman, 2018; Sayre and Taraz, 2019), in other parts of South Asia, agricultural systems are less intensive and rates of groundwater abstraction are much lower than estimates of available renewable resources (Amarasinghe et al., 2016; Bharati et al., 2016). For example, in the eastern Indo-Gangetic Plains (EIGP) – comprising Nepal and parts of eastern India (e.g., Bihar, West Bengal) – many farmers do not irrigate crops fully or cultivate a single crop under rainfed conditions during the monsoon, despite abundantly available groundwater resources. Low levels of irrigation have important ramifications for farm productivity and can be linked to low agricultural productivity, food insecurity and poverty in the EIGP. Evidence, for example, shows significant monsoon '*kharif*' season rice yield gaps that result from within-season dry spells, and dry-season land fallowing across the region (Jain et al., 2017; Krupnik et al., 2017; Balwinder-Singh et al., 2019; Urfels et al., 2020).

In response, the sustainable use of groundwater for irrigation has been proposed as part of the solution to improving agricultural productivity, rural livelihoods and improving farmers' resilience to climate change the EIGP (Balwinder-Singh et al., 2019; Nepal et al., 2019). Sustainable development of groundwater irrigation is however complex; it requires consideration of the social, economic and technical factors that currently limit farmers' use of available groundwater resources, as well as consideration of the longer-term social and environmental impacts of abstraction. In particular, while farmers elsewhere in South Asia benefited from development and subsidisation of electricity supply networks powering pumps, in the EIGP, the majority of farmers access groundwater using diesel- or petrol-powered pumpsets connected to shallow tubewells (Shah et al., 2006; Scott and Sharma, 2009). Diesel prices for agriculture are rarely or intermittently subsidised by governments, with fuel costs several times that of electricity-based connections (Mukherji, 2006; Shah, 2007; Urfels et al., 2020). This represents a significant economic and financial barrier to intensification, which is further exacerbated where farmers depend upon renting pumpsets, often at significant additional cost, from others in their communities (Bhandari and Pandey, 2006; Sudgen et al., 2014; Bastakoti et al., 2017; Foster et al., 2019).

Long-term solutions proposed to address economic barriers to sustainable use of groundwater irrigation in the EIGP include expansion of rural electricity supply networks, or the development of alternative renewable-based pumping technologies such as solar photovoltaic pumpsets (Shah et al., 2018; Nepal et al., 2019; Shirsath et al., 2020). There has however been comparatively little attention focused on understanding the opportunities to reduce the costs of the existing diesel and petrol pump irrigation systems readily available in markets and widely operated by irrigating farmers in the region. This represents a significant knowledge gap and, arguably, a potential missed opportunity for enabling near-term improvements in water security and rural livelihoods. Indeed, the expanded use of solar pumping systems in the region faces a number near-term socio-technical challenges including high levels of land fragmentation that favour more portable abstraction technologies (Gauchan & Shrestha, 2017; Urfels et al., 2020). This is in tandem with significant capital constraints faced by many households that may limit potential investment in technologies at current market prices (Agrawal and Jain, 2019). At the same time, expansion of rural electrification in the EIGP has historically been slow – in particular in Nepal and in parts of India – due to delays to major energy infrastructure projects (Lord et al., 2020; Saklani et al., 2020) along with sometimes restrictive government energy policies (Kishore, 2004; Oda and Tsujita, 2011; Mukherji et al., 2012). Given these factors, we argue that diesel and petrol pumps are likely to remain a key technology for irrigators across the EIGP for many years to come and that improving performance of these systems is likely to play an important role in supporting intensification of groundwater use among smallholder farmers.

In this paper, we address this critical development knowledge gap by combining data from *in-situ* pumping tests and surveys with farmers, pumpset dealers and mechanics in the Terai region (the lowland plains at the foot of the Himalayas) of Nepal, an area where agriculture dominates rural livelihoods and diesel pumpset represent the primary means of accessing groundwater for irrigation. We seek to understand how and why fuel efficiency and operational costs vary between farmers as a function of their choice of pumpset model and design, which vary significantly in Nepal and across the EIGP. This contrasts with the common focus that on achieving intensification of groundwater irrigation through replacement of expensive diesel pumping systems with alternative electric or renewable-based pumping technologies (Kishore et al., 2017; Shah et al., 2018; Nepal et al., 2019). Our analysis provides recommendations to farmers, governments and donors on how targeted support for existing low-cost and fuel-efficient engineering solutions can contribute to the immediate goals of intensifying groundwater irrigation, increasing agricultural productivity and improving rural livelihoods. More broadly, we discuss how such interventions could be positioned within longer-term national and regional irrigation development planning, including the goal of upscaling renewable-based pumping technologies across the EIGP.

In the following sections, we briefly contextualise the history and types of diesel pumpsets in operation in Nepal's Terai, noting key similarities and differences around the spread and characteristics of diesel pumpsets in comparison with the wider EIGP. We then provide an overview of the different modes of primary data collection conducted as part of our study, followed by a summary and discussion of our main findings and policy implications regarding differences in fuel efficiency and cost-effectiveness across key types of pumpsets currently in operation in the region.

2. Evolution and characteristics of pump irrigation systems in the Nepal Terai

In Nepal's Terai, and across the EIGP more widely, the primary means of accessing groundwater for irrigation is through motorised pumpsets (Shah et al., 2006). The majority of pumpsets in the Terai are low-lift suction designs connected to shallow tube wells (STWs), reflecting the fact that in the majority of areas water tables are shallow with typical variation between 3-5 m below ground level (ADB, 2012). An estimated 120,000 of such pumpsets were used in Nepal prior to 2010, primarily for rice and wheat cultivation in monsoon and dry winter season respectively (Justice and Biggs, 2013). Assuming continued historical growth of around 4,000 pumpsets per year, this would equate to 160,000 of such pumpsets used in 2020, although the actual number is likely to be significantly higher when accounting for the true extent of pumpset sales through private markets and dealers that may be poorly captured in census efforts. A smaller number of deep tube wells (DTWs) also exist in the Terai, but overall these are less prevalent due to high drilling costs and widespread presence of productive aquifer bodies at shallow depths (Center for Engineering and Development Research, 2007). DTWs were often installed as part of development projects that included support for rural electrification, and are typically connected to electric submersible pumps serving communities of farmers due to their large size and pumping lifts (Scott & Sharma, 2009; ADB, 2012).

Significant heterogeneity exists in the types of low-lift pumpsets used by farmers to access groundwater for irrigation (Foster et al., 2019). Early imports of pumpsets to the Terai began in the 1970s and 1980s, spreading largely through Nepal's long and porous border with India (Biggs and Justice, 2017). These pumpsets were commonly manufactured by well-known Indian brands such as *Kirloskar*, *Field*

Marshal, and *Usha*, and were imported by private traders that benefited from government subsidy programs to encourage the spread of STW irrigation (Biggs and Justice, 2017). Earlier Indian-manufactured diesel pumpsets models are characterised by vertical piston engine designs with larger horsepower (7-8 HP) and lower operating speeds (1,000-1,500 RPM) (Figure 1a). More recently, Indian manufacturers have been producing and exporting diesel pumpsets with smaller engine sizes (e.g., 4-5 HP) (Figure 1b), which are somewhat lighter in weight but maintain the same vertical engine design of larger Indian diesel pumpset counterparts (Biggs et al., 2011; Malik et al., 2014; Urfels et al., 2020).

From the early 2000's onwards, new models of pumpsets with smaller sized (e.g., 3-6 HP) horizontal engine designs (Figure 1c) began to be imported in larger numbers to the Terai. They arrived either directly from manufacturers in China or via Indian companies producing pumpsets using Chinese components and parts (Justice and Biggs, 2020). Most commonly, these pumpsets are powered using diesel. Alternative models that run on either petrol or kerosene can also be found (Figure 1d), but these are less prevalent in the Terai than in other parts of the EIGP (e.g., the states of West Bengal or Bihar in eastern India) where subsidies for domestic kerosene are sometimes exploited by farmers to offset the costs of non-subsidized irrigation pumping (Shah, 2007). Irrespective of fuel source, a key feature of horizontal engine pumpset designs is their lower capital cost, lightweight and compact design (Woodhouse et al., 2016; Urfels et al., 2020). The latter, in particular, enables these pumpsets to be easily transported by bicycle or motorcycle between highly fragmented landholdings that are a key characteristic of farming systems in the Terai and much of the EIGP.

Anecdotal and empirical evidence suggests that pumpsets differ in several ways that may influence both fuel efficiency and cost-effectiveness of irrigation for farmers. Lower powered, horizontal engine diesel pumpsets have been reported to have lower rates of fuel consumption than larger horsepower models traditionally preferred by farmers (Foster et al., 2019; Urfels et al., 2020). However, most comparisons are based on farmer-reported estimates of fuel consumption as opposed to data from *in-situ* testing. Moreover, there has been little assessment of how differences in engine sizing, design and operating setup (e.g., operating RPM) influence fuel efficiency in terms of consumption per unit of water delivered. For example, lower fuel consumption rates associated with smaller horsepower pumpsets could be partially counteracted by lower water discharge rates and hence greater required durations of irrigation associated with smaller engine sizes (Shah et al., 2000). However, these trade-offs and their implications for overall fuel efficiency of pumping technologies have yet to be rigorously quantified thus limiting ability to incentivise appropriate irrigation investments by farmers and support intensification of water use to improve agricultural productivity and rural livelihoods.

Similar knowledge gaps also exist when seeking to compare the cost-effectiveness of different pumpset designs currently available to farmers in the Terai and wider EIGP. As noted above, pumpsets with horizontal engine designs manufactured in China can typically be purchased at significantly lower costs than Indian manufactured and branded pumpsets. This holds true even when comparing pumpsets with similar horsepower specifications. However, the former pumpsets are also commonly associated with more frequent breakdowns and shorter lifespans (Adhikari et al., 2019; Foster et al., 2019). A trade-off thus exists between the capital, operational, maintenance and replacement costs of different pumpsets designs, for which improved empirical evidence is required to guide farmers' decision-making with respect to pump purchase and use, as well as for governments and donors seeking to select and incentivise energy- and cost-efficient pumpsets to support appropriate use of groundwater irrigation.

3. Materials and methods

3.1. Collection of in-situ pump test data

To assess the fuel efficiency and hydraulic performance of alternative diesel and petrol-powered pumpsets operational in Nepal, we conducted 116 *in-situ* pump tests in farmers' fields in Rupandehi district in the midwestern region of the Terai (Figure 2) between October 2019 and March 2020. Pumpsets selected for testing were identified by taking a representative stratified sample (in terms of key characteristics such as make/model, horsepower, RPM, and fuel type) from a large database of 446 pumpsets generated through household surveys of groundwater irrigators in Rupandehi and neighbouring Kapilvastu districts of the Terai conducted in 2018/19 by the authors (Foster et al., 2019). For a little over half of tests (*n* = 69), it was not possible to test the original pumpset selected through stratified sampling either due to the fact the owner was not contactable or because the pumpset had been recently sold or sent for repairs. In these cases, the pumpset was replaced by either selecting a comparable pumpset to sample from the larger database or within the wider village in which the owner of the originally sampled pumpset was located. For each tested pumpset, details were recorded about a range of key factors that may be important determinants of fuel consumption and hydraulic efficiency, including the pumpset make/model, engine design, horsepower, rated RPM, fuel type, outlet pipe diameter, age, number of repairs since purchasing, and design operating conditions (i.e. rated head, flow rate and efficiency) where these details were visible on pump engine plates.

Each of the 116 pump tests were conducted using a standardised procedure, which was designed to provide estimates of fuel consumption, discharge rates, and efficiency of pumpsets under normal operating conditions and setups used by farmers when irrigating. The pumpset was first transported to a nearby shallow tubewell that is normally used by the farmer for irrigation purposes, with key information recorded from the farmer (or borewell owner where this differed) about the characteristics of the borewell including the diameter, drilled depth, and year of construction. The borewell owner was also asked when the borewell had last been used. If the time of last use was less than 24 hours prior to the interview and planned test, the test was either delayed until the next day or an alternative borewell selected to avoid potential mis-estimation of fuel consumption and hydraulic efficiency if the underlying water table was still rebounding from a period of prior pumping. Any cap or hand pump connected to the tubewell was then removed. An initial measurement of the depth from the borewell outlet to the groundwater table prior to pumping was then taken using a Solinst 101B flat tape water level meter, and the outlet subsequently sealed (leaving handpump detached to enable of access at the end of the test) after taking. At this stage, participating farmers were also asked to provide an estimate of the typical rate of fuel consumption of their pumpset in litres per hour, which we subsequently compared with measured rates of fuel consumption acquired during the pump test itself.

Once these initial checks and measurements were completed, the pumpset was positioned on flat ground at the same elevation to the borewell outlet. The pumpset was then connected on one side to the outlet of the borewell and on the other to a Woltman LXLC-80 type flow meter (manufactured by Ningbo Aimei Meter Manufacture Co. Ltd in China, ISO 4064) using a flexible PVC plastic pipe. A short separate section of plastic pipe was connected to the outlet of the flow meter to enable water discharged during pumping to be channelled to the farmers' field or a neighbouring drainage ditch, the latter in the event fields were already sufficiently well-watered. In each case, hose clamps and heavy-duty tape were used to seal joins and ensure no water leakage at the points of connection between the pumpset, flow meter and plastic piping. To enable measurement of fuel consumption rates during the pump test, we disconnected the pipe connecting the pumpset fuel tank to its engine and instead injected fuel directly in to the pumpset engine via a short plastic siphon tube that drew fuel from a clear graduated cylinder installed on a stable, flat and raised platform. This ensured an unobstructed flow of fuel to the engine during the test. Figure 3 illustrates an example of the setup of testing rig and fuel injection mechanism from one of the 116 pump tests conducted in this study.

For each test, the pumpset was run for a total period of one hour. The graduated cylinder was initially filled with one litre of fuel, either diesel or petrol, depending on the type of pumpset being tested, which was refilled with an additional litre of fuel during the test if the fuel level dropped to 100 ml. During the test, regular measurements of water discharge were taken from flow meter readings at intervals spaced to align with different levels of cumulative fuel consumption (50, 100, 200, 300, 400, 500 ml, etc.) determined from observed changes in the fuel volume within the graduated cylinder. For each recording, the time since the start of pumping measured using a stopwatch. This enabled calculation of changes in fuel and water discharge rates at regular intervals over the duration of the test period. A measurement of the operating RPM – according to each participating farmer's typical setup – of the pumpset was made at the start of the test using a Lutron DT-2268 tachometer (Lutron Electronic Enterprise, Inc., Taipei, Taiwan). For 16 of the tested pumpsets, RPM measurements could not be obtained. In the majority of cases this was due to the monoblock style design of some pumpsets with horizontal engine configurations, for which the engine and drive shaft are directly coupled, limiting ability to take RPM measurements using a tachometer during operation. These tests were used to contextualise differences in fuel consumption and efficiency across different pumpset categories but were excluded from subsequent statistical analysis due to the lack of available measurements of actual operating RPM.

Following completion of one hour of pumping, final cumulative readings were taken for fuel consumption and water discharge. The pump was then switched off and disconnected, and a measurement made of the depth of groundwater level relative to the height of the borewell outlet (typically within 15-30 seconds following the end of pumping) using the Solinst 101B flat tape water level meter. Additional water level readings were then taken at regular intervals after the end of pumping at 1, 2, 3, 4, 5 and 10 minutes after pump shutoff to track the recovery of the water table following the end of pumping.

3.2. Analysis of drivers of fuel consumption and efficiency

To evaluate the potential drivers of pumpset fuel consumption, a multi-variate linear regression model was developed relating observed rates of fuel consumption to a set of explanatory variables capturing key pumpset characteristics and aquifer conditions. Explanatory variables relating to pumpset characteristics include horsepower, outlet diameter, pump age, fuel type, engine configuration (horizontal or vertical, which is also broadly consistent with Chinese vs Indian origin of manufacturing), and RPM. Pumpset RPM is specified in the model as the ratio of actual operated to rated RPM because, based on pump affinity laws, we expect that adjustments in the RPM relative to the manufacturer's rated value will be the primary mechanism through which RPM may influence fuel consumption after controlling for other characteristics such as horsepower. Effects of aquifer conditions on fuel consumption are captured in the model through a variable representing the depth to groundwater during each pumping test, calculated as the average of water table depths measured immediately before and after the one-hour pumping period.

Separate multivariate linear regression models were subsequently developed to assess drivers of both pumpset water discharge rates and water-fuel efficiencies as response variables. Pumpset water discharge was calculated by dividing the total water discharge by fuel consumption measured during each pumping test, providing an indicator of the number of cubic metres of water discharged per litre of fuel consumed. Both models used the same set of explanatory variables as specified the fuel consumption model above, along with a number of additional variables designed to capture key characteristics of the borewell used in each test that are expected to influence hydraulic performance but not fuel consumption. Additional explanatory variables include drilled depth of the borewell, borewell age (years since constructed), and the diameter of the borewell outlet.

3.3. Assessment of pumpset cost-effectiveness

We evaluated differences in the cost-effectiveness of alternative pumpsets used by farmers in our study sample, focusing on differences between four main types of pumpset observed in our sample and across the wider Terai and EIGP that are described in Section 2: (1) vertical engine 6-8HP diesel pumpsets (n = 24), (2) vertical engine 4-6HP diesel pumpsets (n = 44), (3) horizontal engine 4-6 HP diesel pumpsets (n = 33), and (4) horizontal engine 3-6HP petrol or kerosene pumpsets (n = 15).

Estimates of capital costs, repair and maintenance costs and pumpset lifespan were obtained through market surveys and interviews with a total of 10 pumpset dealerships in the towns of Bhairahawa and Butwal (the main supply centres for agricultural equipment and machinery in Rupandehi district) and 6 mechanics (locally referred to as ‘mistris’) serving villages where pump tests were conducted. Repair costs represent an average annual expenditure, including more minor regular expenditure on maintenance that typically occurs each year (e.g., replacement of the pumpset motor oil) and more expensive but infrequent maintenance costs (e.g., replacement of piston and associated parts). For the latter, average annual repair and maintenance costs account for reported differences in the frequency of major repairs and costs of spare parts across our four pumpset categories. For example, vertical engine pumpset models that are typically manufactured by Indian companies typically only require such repairs every 3 years, compared with every 2 years or 1 year for diesel or petrol pumps, respectively, with horizontal engine configuration that are manufactured in China.

For each of these four categories of pumpset, we calculated the equivalent annual cost (EAC) of the pumpset considering capital costs of purchasing the pumpset, fixed annual costs for pumpset repair and maintenance, and variable costs associated with fuel consumption for irrigation. The calculation of equivalent annual costs for a given type of pumpset is summarised in Equations 1 and 2 for EAC and net present value (NPV) respectively (Griffin, 2016). These account explicitly for potential differences in the expected lifespan between alternative pumpset owned and operated by farmers for irrigation.

$$EAC = NPV * \frac{d}{1-(1+d)^{-n}} \qquad (1)$$

$$NPV = Cc + \sum_{t=1}^{n} \frac{Rc_t + Vc_t}{(1+d)^t} \qquad (2)$$

Where: *EAC* is the equivalent annual cost (USD), *NPV* is the net present value (USD), *n* is the pumpset lifespan (years), *Cc* is the capital cost (USD) which occurs at the time of investment (i.e., in year 0), *Rc* is the annual costs for repair and maintenance (USD/year), *Vc* is the annual variable cost of irrigation (USD), *t* is the year of the pumpset's lifespan during the pump test, and *d* is the real discount rate expressed as a decimal value.

In calculations of EAC for each pumpset type, we assume a real discount rate of 4.76% based on nominal discount and inflation rates of 10% and 5%, respectively, consistent with previous economic assessments of irrigation and wider agricultural technologies in Nepal and the EIGP (Hossain et al., 2015; Bastakoti et al., 2020). Table 1 summarises differences in capital costs, fixed repair & maintenance costs, variable irrigation costs, and lifespan assumed in the calculation of EACs for each of the four pumpset types described above.

Variable costs of irrigation given in Table 1 were calculated as shown in Equation 3, accounting for differences in average fuel consumption and water discharge for each pumpset category obtained from *in-situ* pump tests.

$$Vc = Fp * \frac{I*A*D}{WFE} \qquad (3)$$

Where Fp is the fuel price (USD/litre), I is the number of irrigation events per year, A is the total landholding area (m^2) irrigated by each farmer (note: we do not consider other farmers landholding area irrigated using a pumpset, for example as part of a rental agreement), D is the typical depth of irrigation applied to fields per event given typical flood irrigation practices for rice and wheat production in the region (m), and WFE is the water-fuel efficiency measured during in-situ pump tests representing the volume of water delivered per volume of fuel consumed (m^3 water/litre fuel).

When calculating variable irrigation costs in Equation 3, we consider costs of pumpset operation by the owner ignoring any additional hours and land area of use associated with pumpset rental as rental rates in the Terai are typically set on a per hourly basis and were not observed to vary significantly according to the type of pumpset being rented (data not shown). Each pumpset is assumed to irrigate a landholding of 1 ha, a total of five times each year – three irrigation events for rice during the *kharif* (monsoon) season and 2 events for wheat during the *rabi* (dry) season – based on modal practices reported in a previous 2018/19 household survey (Foster et al., 2019) and supplemented by literature on irrigation water use in the Terai region (Paudel et al., 2017; Urfels et al., 2020). For each event, we assume that a total depth of 90 mm of water is applied for both rice and wheat production in the Terai, based on average farmer-reported estimates of hours required to irrigate a hectare of land in each season (Foster et al., 2019) and average well yields measured through pumping tests conducted as part of this paper. This assumed depth is consistent with reported estimates of farmer irrigation practices for rice and wheat found within in the IGP (Balwinder-Singh et al., 2016; Balwinder-Singh et al., 2019). Fuel prices are set equal to 1 USD and 0.75 USD for diesel and petrol, respectively, based on farmer-reported costs and estimates derived from wider market surveys during fieldwork, along with existing literature (Urfels et al., 2020).

4. Results and Discussion

4.1. Drivers of fuel consumption, discharge and efficiency

Average fuel consumption, water discharge rates and water-fuel efficiency were 0.84 litre/hour, 36.82 m^3/hour and 46.85 m^3/litre, respectively, across our 116 pump tests. However, values also varied significantly between tests reflecting significant heterogeneity in pumpset performance with standard deviations of 0.35 litre/hour, 11.46 m^3/hour and 17 m^3/litre in measured fuel consumption, discharge rates, and water-fuel efficiency, respectively. Table 2 summarises the results of regression analysis to understand drivers of heterogeneous fuel consumption, discharge, and water-fuel efficiency based on data for the 100 pump tests for which all predictor variables could be measured (Sections 3.1 and 3.2). Our analysis explains around 58% of the variance in pumpset consumption, compared with a lower proportion of the variance in discharge rates (29%) and water-fuel efficiency (33%) of pumpsets. The lower proportion of variance explained reflects the fact that discharge rates will be affected by factors beyond pumpset and borewell characteristics that are not readily observable when testing *in-situ* (e.g., vertical hydrogeological variability or deterioration of well construction).

Table 2 shows that a statistically significant relationship exists between pumpset horsepower and all three indicators of performance (fuel consumption: $p < 0.01$; water discharge: $p < 0.1$; pumping fuel efficiency: $p < 0.05$). Pumpset fuel consumption increases with horsepower, with an additional unit of horsepower associated with a 0.12 litre/hour increase in fuel use (standard error of 0.03 litre/hour). As would be expected, larger horsepower pumpsets are also associated with higher rates of discharge, with each additional unit of horsepower contributing to increased water output of 2.30 m^3/hour (standard error of 1.7 m^3/hour). However, overall, this effect is not sufficient to counteract increased fuel consumption, with larger horsepower pumps thus associated with a reduction in overall pumpset efficiency (3.21 fewer cubic metres of water discharged per litre of fuel consumed for a 1 HP increment in pump engine size; standard error of 1.27 m^3/litre).

We find no statistically significant impact of depth to water on either fuel consumption, discharge rates or water-fuel efficiency. We attribute the limited effects of pumping lifts on pumpset fuel efficiency and hydraulic performance to the shallow range of water table depths observed in our study area along with the small size of pumping lifts in comparison with pumpset operating head ranges. Average pumping lifts in our tests were equal to 3.5m (maximum of 7 m), which, even after accounting for potential friction head losses, would fall far below the rated operating heads of the majority of pumpsets tested in our sample (design operating heads ranged from 11m to 25 m, with mean of 15.4 m, for the 41 pumpsets for which information was still visible on manufacturer engine data plates as shown in Figure 1d).

In line with this hypothesis, we observed that reducing RPM below the rated value for the pumpset results in significant reductions to both pumpset fuel consumption and discharge rates ($p < 0.01$). This finding is consistent with affinity laws for pumps, which state that: (i) discharge rate will change proportionally with a change in RPM, and (ii) power output and therefore fuel consumption will change proportionally to a cubic change in RPM – e.g., a 2% reduction in RPM would decrease discharge by 2% and power output by 4.7% all else held constant (Yu et al., 2018). Reducing RPM below the pump rated value is a common practice of farmers in our study area, in particular for horizontal engine pumpset designs that typically have a high rated speed (3000-4000 RPM). Farmers reported during testing that they made such adjustments to RPM to enhance pumpset longevity and reduce fuel consumption. The latter appears to be an effective correction for apparent oversizing of engines relative to operating conditions but does not have a positive effect on overall pumpset water-fuel efficiency when considering the subsequent reductions in discharge rates. This suggests that true fuel consumption savings from adjusting pump operating speed may be minimal when comparing in terms of a specific volumetric level of irrigation.

After controlling for pumpset characteristics, borewell properties and aquifer conditions, we find that the configuration (horizontal or vertical) of pumpset engine design had no significant impact on water discharge. However, we observed statistically significant increases in fuel consumption ($p < 0.05$) and resultant reductions in pumping fuel efficiency ($p < 0.01$) for vertical engine designs associated with Indian manufactured pumpsets relative to horizontal engine designs more common for Chinese manufactured models. All else being equal, we find that the sampled vertical engine diesel pumpsets on average deliver approximately 12.4 fewer cubic metres of water discharge per litre of fuel consumed (standard error of 3.65 m^3/litre), suggesting that horizontal engine designs for diesel pumps may provide an inherent fuel efficiency advantage even after accounting for differences in engine sizing and discharge rates under real-world operating conditions. Efficiency benefits of Chinese-style horizontal engine pumpsets are only found for diesel-powered models. Pumpsets operated using petrol/kerosene fuel (all reported as manufactured in China in our sample) were associated with significant increases in fuel consumption and reductions in water-fuel efficiency ($p < 0.01$). This suggests that cost-effectiveness of such pumpsets is likely to be heavily dependent on subsidisation of fuel prices, a factor which we explore further in Section 4.2.

4.2. Efficiency and cost effectiveness of alternative pumpset types

Analysis of variability in pumpset fuel consumption, efficiency and cost-effectiveness can play an important role in supporting farmers, government and donors to select pumpsets that minimise costs of groundwater access, supporting intensification of irrigation water use and improvements in agricultural productivity. Building on the analysis presented in Section 4.1, we compared the performance and cost-effectiveness of the main types of pumpsets found within our sample and observed across the wider Terai and EIGP. We distinguish between four main types of pumpset (see Section 3.2), grouped according to differences in engine design, horsepower, fuel type and origin of manufacturing.

Figures 4 and 5 show boxplots of measured fuel consumption and pumping fuel efficiencies, respectively, across for each of these four pumpset types. Results shown are consistent with prior regression analysis: horizontal engine diesel pumpsets consume the lowest amount of fuel and have highest pumping fuel efficiencies, significantly outperforming ($p < 0.005$ based on pairwise Wilcoxon rank sum tests) vertical engine diesel pumpsets with either comparable (4-6 HP) or larger (7-8 HP) engine sizes. We find little benefit in terms of pumping fuel efficiency from the reduction in engine size when comparing vertical engine pumpset models with smaller (4-6 HP) or larger (7-8 HP) engine sizes. This is because the lower fuel consumption rates for smaller 4-6 HP engines are counteracted by lower groundwater discharge rates relative to larger 7-8 HP models from brands such as Kirloskar. Petrol or kerosene monoblock pumpsets manufactured in China have similar fuel consumption rates to larger vertical engine Indian manufactured diesel pumpsets. However, due to their smaller engine sizes (3-6 HP vs 7-8 HP) petrol or kerosene pumpsets in our sample also generate lower discharge rates, resulting in the lowest overall water-fuel efficiency ratio (mean of 33 m^3 water discharge per litre of fuel consumed) of all four pumpset categories.

Comparing the cost-effectiveness of each pumpset type in terms of their equivalent annualized costs (Figure 6), which reflects differences in the expected lifespans across pumpset categories, we found that horizontal engine diesel pumps (Figure 1c) have the lowest equivalent annualized costs (127.6 USD/year). This was 9.2% (12.9 USD/year) and 23.3% (38.7 USD/year) lower than for smaller 4-6 HP pumpsets (Figure 1b) and larger 7-8 HP (Figure 1a) diesel pumpsets with vertical engine designs. The main drivers of lower costs for horizontal engine diesel pumpsets are their lower purchase price, greater fuel efficiency, and cheaper repair and maintenance costs. In combination, these factors more than counteract the significantly lower estimated lifespan (10 years) relative to vertical engine diesel pumpsets that are reported as being more durable and long-lasting (lifespan of 30-40 years). Cost differences between pumpsets compare with a typical average per capita income in the study area of 695 USD/year (UNDP, 2014), suggesting that potential cost savings may amount for as much as 5% of average incomes.

Horizontal engine petrol/kerosene pumpset designs also outperform vertical engine diesel pumpsets with large horsepower (3.5% lower annualized cost), with their low upfront costs sufficient to compensate for their very short lifespan (5 years) and relatively poor water-fuel efficiency. However, our analysis suggests that these pumpsets are not overall an efficient investment for farmers given prevailing petrol and kerosene prices in the Terai, with these pumpsets recording much higher annualized costs than both horizontal and vertical engine diesel pumpsets due to their low fuel efficiency and limited lifespan (~5 years). Indeed, holding all other parameters constant, an approximately one third reduction in petrol prices (i.e., from USD 0.75 to USD 0.5) would be required to make petrol or kerosene pumps currently in operation in our study area equally cost-effective investments to their diesel counterparts.

One of the mains concerns raised by farmers about horizontal engine pumpsets during field surveys and wider interviews was their shorter overall lifespan, commonly attributed to poor control of manufacturing and import quality from main manufacturing locations in China along with difficulty in obtaining some spare parts due to less well-developed supply chains compared with Indian manufactured pumpset models. To explore the potential benefits of improving the longevity of Chinese-style horizontal engine diesel pumps, we repeated our cost-effectiveness analysis for alternative hypothetical lifespans 15 and 20 years assuming all annual capital, operation and maintenance costs remained constant. We found that increasing the lifespan of existing horizontal engine diesel pumpsets would further extend their economic advantage over traditional vertical engine diesel pumpsets commonly imported from India. If the lifespan of low-cost horizontal engine diesel pumpsets were increased to either 15 or 20 years, these pumpsets would economically outperform vertical engine counterparts with equivalent horsepower by 13.4% and 15.5%, respectively. This is despite the lifespans analysed (15-20 years) being still significantly lower than lifespans of existing 4-6 HP vertical engine diesel pumpset designs available from Indian manufacturers (30 years) that are commonly preferred by farmers in the Terai. Cost savings increase to 17.5% when considering equivalent 30-year lifespans. Moreover, Chinese-style horizontal engine diesel pumpset designs still retain an economic advantage of 13.3% relative to vertical engine Indian-style diesel counterparts if capital costs are assumed to be identical (e.g., if costs of horizontal engine pumps had to increase to reflect need for enhanced product quality and longevity in manufacturing locations such as China), reflecting the significantly greater pumping fuel efficiency of smaller horsepower horizontal engine diesel pumpset designs for typical operating conditions for irrigation in the Nepal Terai and wider EIGP. Nonetheless, it is important to acknowledge that such improvements to manufacturing quality and reliability – even if accompanied by increases to purchase prices – may take multiple years to achieve, and so the benefits are less likely to contribute to short-term improvements in cost-effectiveness of groundwater irrigation than simply altering choices of existing available pumpset models and designs to better match real-world operating conditions

4.3. Farmer awareness of fuel consumption and savings potential

Contrary to what would be expected from the results presented above, available evidence suggests that the majority of pumpsets currently used by farmers are vertical engine diesel models that have historically been manufactured and imported from major agricultural equipment providers in India. For example, of the 446 pumpsets recorded in the database that was used to sample pumpsets for *in-situ* testing in this study, 59% were vertical engine designs manufactured by Indian firms (Foster et al., 2019). Higher market penetration of alternative horizontal engine designs produced primarily by Chinese manufacturers has been reported in other in other agrarian districts in the Terai and parts of the EIGP where pump irrigation systems are the main source of water for smallholder agriculture (Shah, 2007; Urfels et al., 2020). However, this has typically been associated with either capital constraints limiting farmers ability to invest in more expensive Indian branded pumpsets or the presence of large subsidies on petrol or kerosene that incentivise adoption of Chinese-style pumpset models to exploit these cost savings (Shah, 2007).

One potential reason for low adoption of more efficient horizontal engine pumpset designs is that farmers are unaware of the magnitude of potential fuel savings and their benefits for overall cost-effectiveness of irrigation. To test this hypothesis, we compared farmers' estimates of pumpset fuel consumption (recorded before the start of each test) with that measured during *in-situ* testing conducted under typical irrigation operating conditions. Mean fuel consumption rates estimated by farmers (0.87 litres/hour) were comparable to those measured during testing (0.84 litres/hour). However, farmers' estimates of fuel consumption exhibited lower levels of variability than those measured during testing (standard deviation of 0.26 vs 0.35 litres/hour, respectively). Figure 7 illustrates this difference, showing that errors in farmers' self-reported estimates of pumpset fuel consumption rates appear to underestimate the true variability in fuel consumption that is introduced by pumpset selection and operating conditions. In particular, farmers have a tendency to underestimate fuel consumption rates for pumpsets that, in reality, had larger than average actual consumption rates, while also overestimating fuel consumption for pumpsets with lower than average actual consumption rates. Given the relationships between fuel consumption and pumpset characteristics shown in Section 4.1, this suggests that farmers typically are more likely to understate fuel efficiency of horizontal engine, lower horsepower diesel pumpsets that have become more available in recent years in the Terai and EIGP with the growth in imports from Chinese manufacturing centres. We explore the implications of this for encouraging appropriate pumpset selection and irrigation intensification policy further in Section 5 below.

5. Discussion

Diesel pump irrigation systems are the dominant means of accessing groundwater for millions of farmers across the EIGP (Shah et al., 2006), and are likely to remain a key component of the irrigation technology mix in the region for many years to come. In contrast to the common perception of all diesel pumpsets as inefficient, expensive and 'dirty' technologies (Verma et al., 2019), our findings show that opportunities exist to enhance the efficiency and economic performance of these systems in order to support irrigation intensification and improve agricultural productivity and livelihoods alongside longer-term efforts to scale-out renewable energy pumping systems.

We find that considerable variability exists in both fuel efficiency and costs of purchasing, operating and maintaining pumpsets depending on technical characteristics, manufacturing design and quality, and how the pumpset is operated by farmers. Specifically, we show that a farmer operating a horizontal engine low horsepower diesel pumpset model (Figure 1c) can benefit from average improvements in pumping fuel efficiency of 44% and reductions in annual costs 23% (Section 4.2) when compared with larger horsepower vertical engine diesel pumpsets (such as shown in Figure 1a). This appears to be because many vertical engine diesel pumpsets imported from Indian manufacturers are significantly oversized for the conditions under which they are operated, with longer lifespans insufficient to compensate for significantly greater capital and operational costs of large 6+ horsepower pumpsets relative to horizontal engine designs with lower horsepower specifications imported from manufacturers in China.

Given identified differences in fuel efficiency and cost-effectiveness, it is surprising that Indian manufactured vertical engine diesel pumpsets – in particular larger 6-8 horsepower engines – continue to be the preferred technology for many farmers in the Terai, despite the diversity of pumpset models and designs now widely available within local markets in the Terai. Below we discuss some of the key factors that underpin inefficiencies in pumpset selection and operation in Nepal's Terai, with implications for the wider EIGP, highlighting a number of potential pathways for addressing these challenges within national and regional irrigation development planning and policy.

5.1. Supporting efficient pumpset selection and operation

Our findings suggest one factor driving inefficiencies in pumpset selection is that many farmers appear to be unaware of differences in fuel consumption of different pumpset designs (Figure 7). Areas with higher rates of adoption of smaller horsepower Chinese pumpsets commonly tend to be found in areas with lower household wealth and higher poverty rates, with farmers in these areas purchasing these cheaper pumpsets due to a lack of credit to invest in more expensive and larger horsepower Indian manufactured models (Urfels et al., 2020). Indeed, one farmer interviewed during testing noted that only "farmers in the village who can't afford Indian pumpsets or don't have labourers to transport the larger Indian pumps tend to buy Chinese pumpsets". In contrast, farmers tended to associate bigger Indian engines with greater reliability, durability, prestige, and status (Shah et al., 2000; Foster et al., 2019; Urfels et al., 2020). For example, a farmer who participated in our study noted that he "bought a Kirloskar pump (7 HP) because my neighbours own Indian pumpsets and they last forever. I usually only have to pay maintenance costs after around 150 hours of use and costs for repairs every 3-4 years whereas Chinese pumpsets require annual repairs" while another stated that "I can run an Indian pump continuously for 10 -12 hours in the winter and 8-9 hours in the summer heat. My neighbour's Chinese pump lasts 6-7 hours before heating up and needs to be turned off and cooled down."

Perceptions about greater durability and robustness of larger horsepower Indian manufactured pumpsets are further reinforced by marketing slogans and messages used by leading Indian brands (Figure 8a), while we also found evidence of attempts by Chinese manufacturers to imitate Indian companies by copying brand names and logos while still retaining the modified horizontal engine configuration (Figure 8b). Similar dynamics have also been observed in groundwater irrigation systems elsewhere in the EIGP and wider South Asia. For example, in Pakistan and India, the oversizing of pumpset engines and slow market uptake of newer and more fuel-efficient engine designs has been linked to a tendency for farmers to gravitate towards existing and well-established technologies (Shah et al., 2000). Together, these factors lead to a market consolidation of well-established larger Indian pumpsets, while reducing demand for newer pumping designs or models even where these may represent significantly more efficient and cost-effective choices.

A key implication of these findings is that there is a need for greater focus within government and irrigation development initiatives in the Nepal Terai and other parts of the EIGP to provide effective advisory services to farmers about efficient pumpset operation and selection. Historically, there has been rather limited emphasis on provision of such support to encourage adoption of efficient small-scale agricultural machinery in Nepal. Irrigation development initiatives as part of national agricultural and rural development policies (e.g., Agriculture Prospective Plan and National Agricultural Policy) have focused on donor-driven infrastructure investments priorities, such as development of large-scale canal systems (Biggs and Justice, 2015) or expanding networks of shallow and deep tubewells (Government of Nepal, 2005; ADB, 2012). More recently, focus have shifted to introduction of new renewable-based pumping technologies such as solar or microhydro (Mukherji et al., 2017; Bastakoti et al., 2020), reinforced by Nepal's most recent national Rural Energy Policy in 2006 that introduced significant subsidies (50-75+%) on agricultural machinery powered by renewable energy (Gauchan and Shrestha, 2017). In contrast, there has been comparatively little emphasis with agricultural and rural development policies on pumpset selection and helping farmers to make more efficient use of technologies already readily available in local markets. As a result, most farmers rely almost exclusively on local knowledge (e.g., experience of pumpsets from owned by others within their community) or the advice of local '*mistris*' (mechanics) and pumpset dealers for advice when deciding to purchase a pumpset. These groups tend to reinforce demand for existing and well-established pumpset types due their greater familiarity with these technologies and, in the case of dealers, an incentive to preferentially market larger Indian pumpsets due to higher upfront costs and stronger links with suppliers across the border in India.

Through development of datasets such as presented in this paper, opportunities exist for researchers and donor agencies to work with local and national government extension agencies (e.g., Agricultural

Machinery Testing and Research Centre – AMTRC – in Nepal) and private sector actors (e.g., pumpset dealers and *mistris*) to generate and disseminate evidence-based guidance to support farmers about how to make informed decisions about cost-effective pumpset selection. Similar initiatives have also been developed in other parts of the South Asia, for example using pump head-capacity curves to inform selection and sizing of axial flow pumpsets for surface water irrigation in Bangladesh (Krupnik et al., 2015; Yu et al., 2018). Such approaches have an important role to play in goals of Nepal's government to expand agricultural mechanisation as part of goals improving agricultural productivity and rural livelihoods (e.g., national Agriculture Mechanisation Promotion Policy and Agriculture Development Strategy), and will need to be supported by efforts to develop and strengthen institutional and human resources with both the public and private sector around mechanisation advisory and extension that are currently limited within Nepal (Gauchan and Shrestha, 2017).

Generation of advisories should also extend beyond pump selection to include increased awareness about efficient pumpset operation and maintenance. For example, our findings suggest that reducing pumpset speed appears to be an effective solution to increase operational efficiency of lower cost Chinese style pumpsets, consistent with previous work on diesel pumpset rectification in South Asia (Bom et al., 2001). At the same time, evidence from our wider household surveys (Foster et al., 2019) also suggests that there remain large gaps in farmers' knowledge about best irrigation scheduling practices. Where irrigation events are mistimed or of inappropriate volume, for example when irrigation is delayed resulting in initiation of plant water stress, or where excess water is applied resulting in rapid percolation or over-bund flow, the profitability of irrigation can in turn be reduced (Sudhir-Yadav et al., 2011; Balwinder-Singh et al., 2019). In this context, efforts will also be needed to develop guidelines for farmers about profitable irrigation scheduling practices. Where guidelines do exist, they typically consider only agronomic criteria and/or weather conditions, though our analysis suggests that enhanced guidelines developed in awareness of heterogeneity in cost structures and pump type and access arrangements could be beneficial to improve water resource use decision-making across the EIGP.

5.2. Enhancing supply chains for efficient pumping technologies

To enhance uptake and use of fuel-efficient pumping technologies, policies must also look beyond just affordability and cost effectiveness, as these have been shown to only partially determine farmers' decisions to invest in agricultural technologies (Burney & Naylor, 2012; Dessalegn & Merrey, 2015). In the Terai, for example, additional factors that currently constrains uptake of more fuel efficient pumpset designs imported from Chinese markets are the deficiencies in supply chains for these technologies. Timely access to quality spare parts and specialist maintenance services for Chinese manufactured pumpsets is a common problem in the Terai, and has also been reported as a limitation for adoption of small horizontal engine petrol or diesel pumps in other regions including sub-Saharan Africa (Colenbrander & van Koppen, 2013; Giordano & de Fraiture, 2014). Together with more variable quality control in pumpset manufacturing and limited warranties offered by dealerships, these issues reduce demand and lower the expected overall lifespan of horizontal engine Chinese pumpsets with farmers often forced to scrap them after 5-10 years.

In contrast, few farmers reported difficulties or delays in accessing maintenance services and parts for vertical engine diesel pumpsets supplied from Indian manufacturing centres across the border from the Terai, with the majority of dealerships also offering warranties (typically 1-2 years) with purchases as part of business tie-ups with machinery manufacturers. These issues around reliability, longevity and access to repair services were frequently highlighted by farmers who participated in our study who noted, for example, that "Chinese pumpsets require annual repairs" and "although Chinese pumps are cheaper, they come without any warranty and parts for repairs are not always available. I can find Indian pump parts just across the border". Similar challenges were highlighted by dealers interviewed as part of our study, one of whom noted "when the Chinese pumps were first introduced, there was a lot of demand for these pumpsets as they were smaller and easier to transport. However, as the average lifespan tends to be 4-5 years, many farmers did not buy them again. We sell mostly Indian pumpsets now. I import Indian pumpsets from India and I have worked with the same dealer there for many years. These pumpsets come with at least one-year warranty and I have all the repair parts in my shop sent by the manufacturer. We are not able to provide warranty on Chinese pumps as the importers in Kathmandu guarantee a warranty."

Several entry points exist through which provision of spare parts and improvements to quality control of newer low cost, fuel efficient pumpsets could be realised. The greater availability of spare parts and maintenance services for Indian manufactured vertical engine pumpsets widely found across the Terai reflects not only the Terai's close geographic proximity and long open border with India, but also longstanding trading agreements between India and Nepal (e.g., Nepal-India Transit Treaty) and connections between Nepali pumpset dealership and manufacturers in India which enable uninhibited flow of equipment and skilled labour (e.g., mechanics). While Nepal's current trade policy is also favourable to the importation of agricultural machinery from other countries such as China, imports of replacement parts and raw materials incur significantly higher rates of import duty that limit their availability in local markets and disincentivise growth of local manufacturing industries needed to enable growth of maintenance services for low-cost fuel-efficient pumpsets (Gauchan and Shrestha, 2017). Reduction of import tariffs on spare parts as part of ongoing liberalisation of trade relationships between Nepal and China may therefore provide a pathway for improving market access and adoption by farmers of inexpensive fuel-efficient pumpsets in Nepal (Duwadi et al., 2020. Indeed, removal of tariff and non-tariff barriers on the import of agricultural machinery, including diesel pumps, by the Bangladeshi government in the 1980's has been highlighted as a key factor in spurring the rapid spread of small Chinese pumpsets and associated local maintenance and manufacturing services (Huang et al., 2007; Biggs and Justice, 2017; Mottaleb et al. 2019). Alternatively, the re-exportation of Chinese spare parts or equipment for fuel efficient horizontal engine designs by Indian manufacturers may also offer a means of enhancing provision and uptake of these technologies. For example, we found evidence of Indian companies re-exporting Chinese-style pumpsets originally manufactured wholly or partially in China to dealerships in the Terai. Use of Indian brand names could have a positive effect of increasing farmers' willingness to invest in technologies otherwise viewed as unreliable or sub-par by farmers who associate traditional Indian brands and pumpset designs with prestige and durability. However, at present, prices of these re-exported pumpsets remain higher than equivalent models imported directly from manufacturing locations China thereby negating some of the potential irrigation cost savings.

Supply chain policies and interventions should not focus simply on making it easier to import fuel-efficient pumpsets models and their spare parts. Chinese manufactured pumpsets available in Nepal and other major export markets in South Asia and Africa are often of low or variable quality (Albric et al., 2011; Giordano & de Fraiture, 2014; Foster et al., 2019; Urfels et al., 2020), with limited lifespans and frequent maintenance needs deterring investment and adoption by local farmers and dealerships even where these pumpset designs still offer potential fuel and cost savings. Development of robust independent certification standard and registries for different pumpset models could help farmers to obtain objective information about alternative technology choices, while also incentivising manufacturers to improve reliability and quality of products. Certification standards could be enabled by development of testing partnerships with relevant governmental ministries, comparable with stricter standards applied to imports of consumer products, and disseminated via existing extension initiatives targeted to farmers (e.g., radio or phone campaigns). At the same time, efforts to support fledgling manufacturing industries for appropriate and efficient pumps in Nepal could also be considered.

Alongside provision of improved information to aid decision-making around pumpset selection and operation, research and extension efforts must also be targeted towards understanding and addressing the key underlying causes of breakdown of lower cost pumpsets that currently remain a barrier to widespread adoption despite their apparent fuel efficiency benefits. This knowledge would provide valuable guidance to help to target training and educational programs for local mechanics, and, in turn, enable provision of improved pumpset maintenance services to farmers. Together these measures could help to ensure both that fuel efficiency benefits are maintained in the years after purchase, while helping to eliminate cost and resource inefficiencies resulting from the current tendency to replace smaller horsepower Chinese-style horizontal engine pumpsets after only a few years of operational use.

5.3. Future directions and information needs

Our analysis focused specifically on opportunities to deliver near-term improvements in the efficiency and cost-effectiveness of diesel irrigation systems through more effective pumpset selection. However, further improvements in performance of diesel pump irrigation could also be achieved through alterations to the way pumpsets are operated by farmers. In particular, our study did not assess how fuel efficiency of irrigation is affected by delivery systems used to move water from borewells to fields. In much of the Terai and EIGP, there has been a transition over recent years to use of flexible plastic pipe (locally referred to as lay-flat pipes) to convey pumped water to fields (de Bont, 2014; Justice and Biggs, 2020). Fragmentation of landholdings in the EIGP means that lengths of lay-flat pipes can often be substantial, on average in the tens of metres and sometimes extending over much larger distances (Shrestha, 2010; Urfels et al., 2020). Although more efficient than field-to-field transfer by small canals, use of long sections of lay-flat piping has the potential to induce significant head losses (e.g., due to friction effects or pipe leakage), which could in turn increase fuel consumption and operating costs of pumpsets connected to lay flat pipe (Humphreys & Lauritzen, 1964; Provenzano et al., 2016). Further research is needed to understand how alternative lay-flat specifications (e.g., length, diameter, materials) influences the magnitude of head losses, and to what extent use of lay-flat pipes influences trade-offs between alternative pumpset designs. Such information would be valuable to support awareness raising amongst farmers about how to reduce fuel inefficiencies associated with water distribution, for example through regular replacement of piping to reduce leakage or sharing of borewells to minimise conveyance distances.

Attempts to reduce costs of diesel pump irrigation systems in the Nepal Terai and EIGP must also be framed in the context of the fact that many of the poorest and most marginalised farmers often still depend on renting pumpsets from wealthier households (Sudgen et al., 2014). The specific structure of rental markets for pumpsets varies across the EIGP (Foster et al., 2019; Mottaleb et al., 2019; Urfels et al., 2020). However, a common regional practice is for farmers to pay a fixed hourly or seasonal rental rate with pricing rarely conditioned on volumetric discharge or the type of pumpset being rented. These pricing structures mean that any improvements in pumpset fuel efficiency and operational costs may not be passed on to farmers who continue to lack capital to purchase their own equipment. Indeed, similar trends have been observed in the responsiveness of rental market rates to changes in diesel prices in parts of eastern India, with evidence suggesting that reduced fuel costs have not been passed on equally to those renting pumping services (Shah et al., 2009).

Given these dynamics, additional interventions may be needed to realise cost savings for pumpset service renters. For example, availability of finance and credit for small-scale farmers currently remains very low in both Nepal and other parts of the EIGP such as Eastern India (Gauchan and Shrestha, 2017; D'Souza, 2020), limiting ability of rural households – especially those that are poor and marginal – to purchase agricultural machinery such as pumpsets. The Government of Nepal has recently introduced subsidies to encourage banks and lenders to expand credit provision to rural households. While implementation has to date been slow, opportunities exist to link future expansion in access to credit and financial services with incentives to encourage adoption of fuel efficient pumpset technologies (e.g., by combining rural lending with pumpset selection advisories, or by making credit conditional on purchase of fuel efficient pumpset models or designs). Alternatively, it may be possible to reduce lower pumpset rental rates by supporting or incentivising new modalities of irrigation service provision. Prevailing high rental rates for diesel pumpsets in the Terai and other parts of the EIGP are in part a function of underlying cost of diesel fuel (Mukherji, 2007). However, they also reflect the transactions and opportunity costs faced by pumpset owners when supplying pumpset irrigation services, for example to transport pumpsets to renters' fields and collect fees. Opportunities may therefore exist to enable lower cost rental services through support to rural entrepreneurs to develop new dedicated pumpset rental businesses, leveraging enhancements to supply chains for low-cost pumping equipment in combination with technical support for efficient irrigation management to maximise value added for renters. Further research is needed to understand the extent of cost savings that could be achieved through this approach, along with the scale of unmet rental demand that could be unlocked in absence of accompanying reductions in diesel fuel costs.

In the longer-term, larger reductions in costs of groundwater access may be achievable through support for scaling of alternative pumping technologies such as electric or solar pumpsets. In the Nepal Terai, for example, the unit cost of accessing groundwater using electric pumpsets is significantly lower than that for diesel pumpsets (Urfels et al., 2020), while solar-based pumping systems in theory reduce fuel costs of irrigation pumping to zero. We suggest that enabling uptake of these technologies and attempts to improve cost-effectiveness of existing diesel pump systems should not, however, be seen as mutually exclusive policy interventions. One of the main constraints to adoption of electric and solar pumpsets is the significant capital costs associated with purchasing these alternative technologies, in addition to lack of knowledge among farmers and mechanics on how to use, maintain, and repair solar equipment (Agrawal and Jain, 2018; Hartung & Pluschke, 2018). Farmer adoption currently therefore is often dependent on high levels of subsidisation of capital costs by government or development initiatives (Bastakoti et al., 2020). For example, recent estimates suggest that a total of 1,700 solar irrigation pumps are currently installed across Nepal – less than 1% of the number of diesel pumpsets estimated to be operational in the Terai – the majority (1,400 out of 1,700) of which were supplied through government subsidy programmes (Pandey and Gyawali, 2020). Reliance on subsidies could potentially be reduced if improvements to performance of existing diesel pumpsets were used as an intermediate step in the technology transition. Further research is needed to understand the magnitude of livelihood and welfare improvements that can be generated by improving the efficiency of diesel pumps in the EIGP, along with the role of wider policies (e.g., support for crop procurement – Mukherji et al., 2020) in enabling transitions to more appropriate systems of groundwater management in the region. However, such efforts must also be conscious of potential risks of over-abstraction associated with any interventions that lead to large reductions in variable irrigation costs. While groundwater resources are underexploited in the EIGP, they could plausibly become depleted if reductions in access costs are not accompanied by wider measures to monitor and incentivise conservation (Closas & Rap, 2017) such as systems to allow farmers to sell excess solar energy back to the grid as has been proposed in India (Shah et al., 2018).

6. Conclusions

Diesel pump irrigation systems remain the primary means of accessing groundwater for irrigation across much of the EIGP, including Nepal's Terai, eastern India and in Bangladesh. Current government and donor policies to support intensification of irrigation in the region but disproportionately focus on expansion of irrigation and/or support for electric or solar-based pumping technologies, with limited attention to improving performance of existing diesel pump irrigation systems.

Drawing on primary data collected from 116 in-situ pump tests and surveys with actors across technology supply chains (farmers, mechanics, dealers), our analysis shows that opportunities exist to significantly enhance both fuel efficiency and the overall cost-effectiveness of diesel pump irrigation through changes to both the selection and operation of diesel pumpsets by farmers. Our analysis highlights the need for researcher and planners to engage with institutional actors with both public and private sectors to develop and implement effective development pathways for intensifying irrigation water use in the EIGP. In particular, our findings suggest that there will be a need to work with key institutional actors and stakeholders to enhance availability and provision of evidence-led advisories to enable farmers to make informed decisions about pumpset selection, including adoption of lower cost, portable, smaller horsepower diesel pumpsets that our analysis suggests may be better suited to land use and hydrogeological conditions in the Terai and wider EIGP. In addition, efforts are also needed to enhance supply chains and maintenance services for low-cost fuel efficient pumpset designs from manufacturers in China and elsewhere, which at present limit potential cost savings and act as a deterrent to investment for some farmers. This will require interventions at a range of policy levels, including reforms to national level policies around import taxes along with local level support and training for development of rural engineering industries needed to provide maintenance services to encourage adoption of low-cost diesel pumpsets and, in the future, alternative pumping technologies powered by renewable energy.

Combining such initiatives with broader awareness raising of efficient irrigation management practices offers an opportunity to enhance appropriate irrigation water use in the EIGP, contributing to the goals of improving agricultural productivity and rural livelihoods. Higher yields and incomes that result from appropriate use of cost-effective irrigation could also strengthen future pathways towards out-scaling access to and appreciation for alternative low-carbon pumping technologies, while also helping to loosen capital constraint barriers to adoption of electric and solar pumping technologies. We suggest that significantly underexploited opportunities exist to enhance integration of such short- and long-term technology and policy interventions, which together could provide a more effective pathway to enable the appropriate intensification of groundwater use for irrigation in Nepal and the EIGP.

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Table 1. Summary of capital costs, fixed annual repair and maintenance costs, variable annual irrigation fuel costs, and lifespan of each pumpset type. Cost values are based on a conversion rate of 1 NPR = 0.0086 USD, and taken as an average of estimates reported by surveyed dealerships and equipment providers.

Pumpset type	Capital cost (USD)	Maintenance and repair costs (USD/year)	Variable cost of irrigation fuel (USD/year)	Lifespan (years)
Diesel, 6-8HP, vertical engine	450	35	105.9	40
Diesel 4-6HP, vertical engine	320	28	92.2	30
Diesel 4-6HP, horizontal engine	180	31	73.5	10
Petrol/kerosene 3-6HP, horizontal engine	110	33	102.3	5

Table 2. Regression results showing the contribution of aquifer conditions, pumpset and borewell characteristics to observed fuel consumption, water discharge, and water-fuel efficiency of pumpsets during in-situ testing.

	Fuel consumption (litre/hour)	Water discharge (m^3/hour)	Water-fuel efficiency (m^3/litre)
Aquifer conditions			
Depth to water (metres)	0.01	-0.96	-0.78
	(0.02)	(0.87)	(1.20)
Pumpset characteristics			
Horsepower	0.12^{***}	2.30^{*}	-3.21^{**}
	(0.03)	(1.17)	(1.27)
RPM (Actual:Rated)	-0.64^{***}	-25.51^{***}	7.33
	(0.18)	(8.16)	(11.32)
Age (years)	0.01^{*}	0.02	-0.02
	(0.003)	(0.16)	(0.21)
Fuel type (1 = petrol/kerosene, 0 = diesel)	0.58^{***}	0.07	-34.71^{***}
	(0.12)	(5.34)	(7.40)
Engine configuration (1 = vertical, 0 = horizontal)	0.14^{**}	1.19	-12.42^{***}
	(0.06)	(2.62)	(3.65)
Outlet diameter (1 = 4-inch, 0 = 3-inch)	-0.02	5.11	2.18
	(0.08)	(3.83)	(3.95)
Borewell characteristics			
Drilled depth (metres)		-0.11	0.02
		(0.09)	(0.13)
Age (years)		-0.01	-0.03
		(0.17)	(0.23)
Outlet diameter (1 = 4-inch, 0 = 3-inch)		6.46^{**}	2.18
		(2.86)	(3.95)
n	100	100	100
Adjusted R^2	0.58	0.29	0.33
RMSE	0.21	9.31	13.01

*Standard errors are displayed in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*

Figures

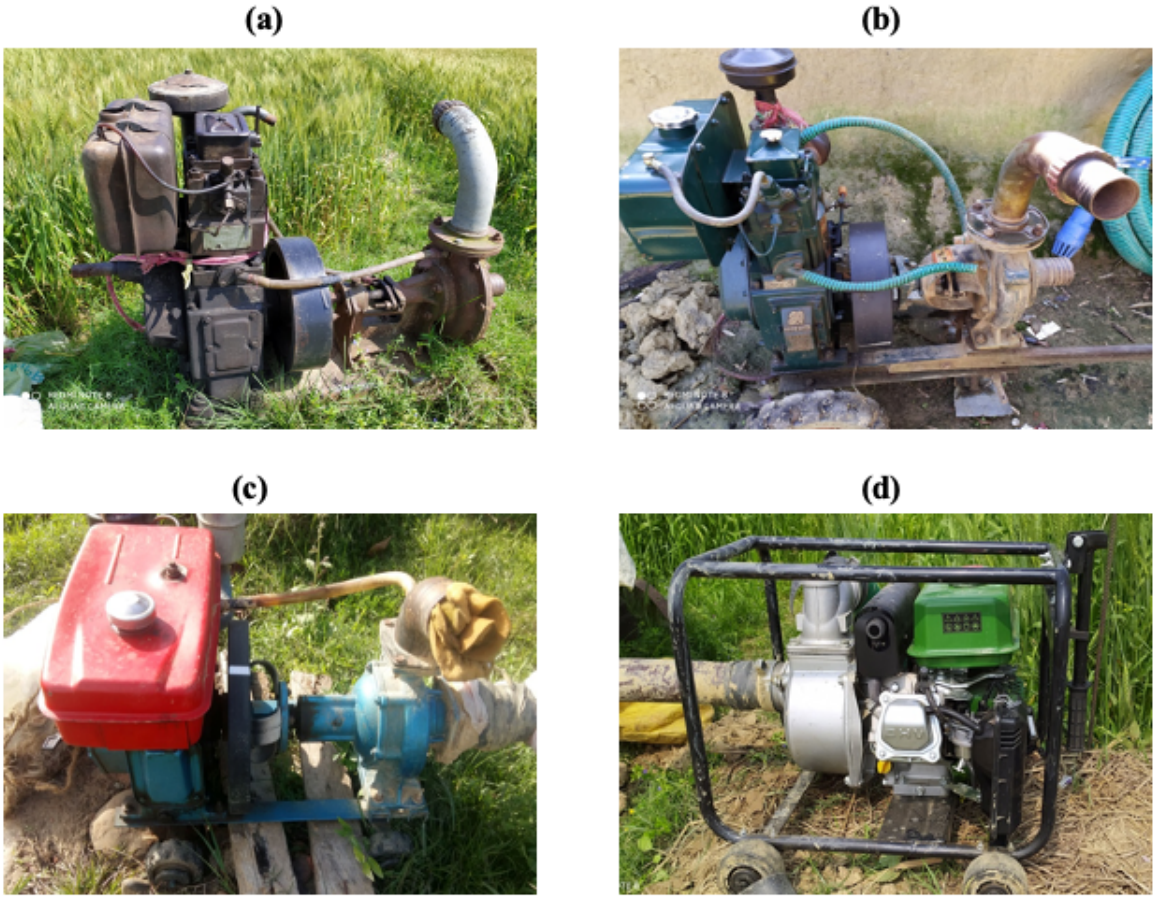

Figure 1. Examples of typical irrigation pumpsets used by farmers in Terai: (a) diesel pumpset with large 6-8 HP vertical engine, (b) diesel pumpset with smaller 4-6 HP vertical engine, (c) diesel pumpset with 4-6 HP horizontal engine, and (d) petrol/kerosene pumpset with 3-6 HP engine.

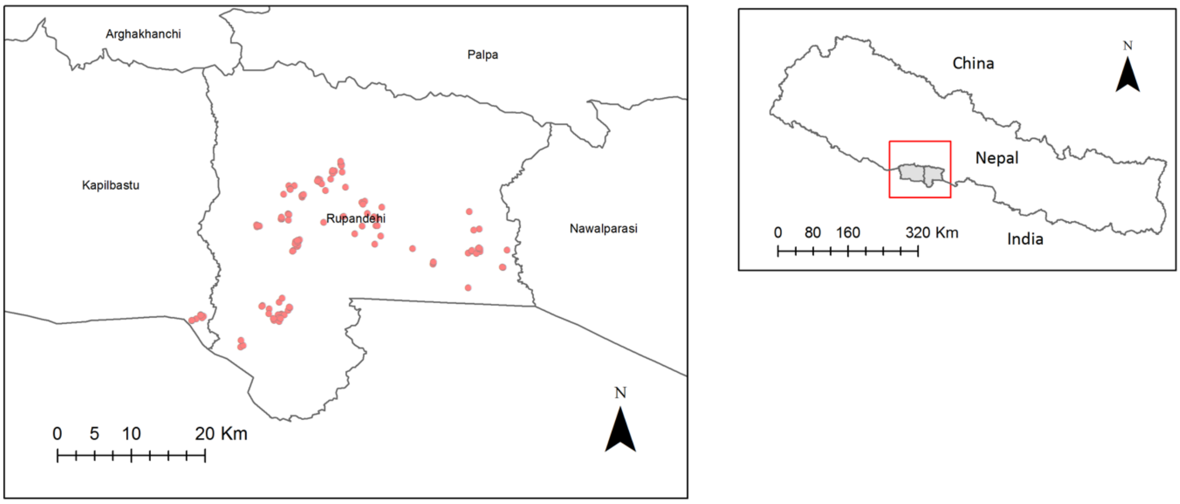

Figure 2. Map showing the locations of 116 in-situ pumpset tests conducted in Rupandehi and Kapilbastu districts in the Midwestern Terai region of Nepal

Figure 3. Setup of pump testing rig during one of the 116 in-situ tests conducted as part of this study. Inset image shows a close-up view of the fuel injection from the graduated measuring cylinder into the pump engine.

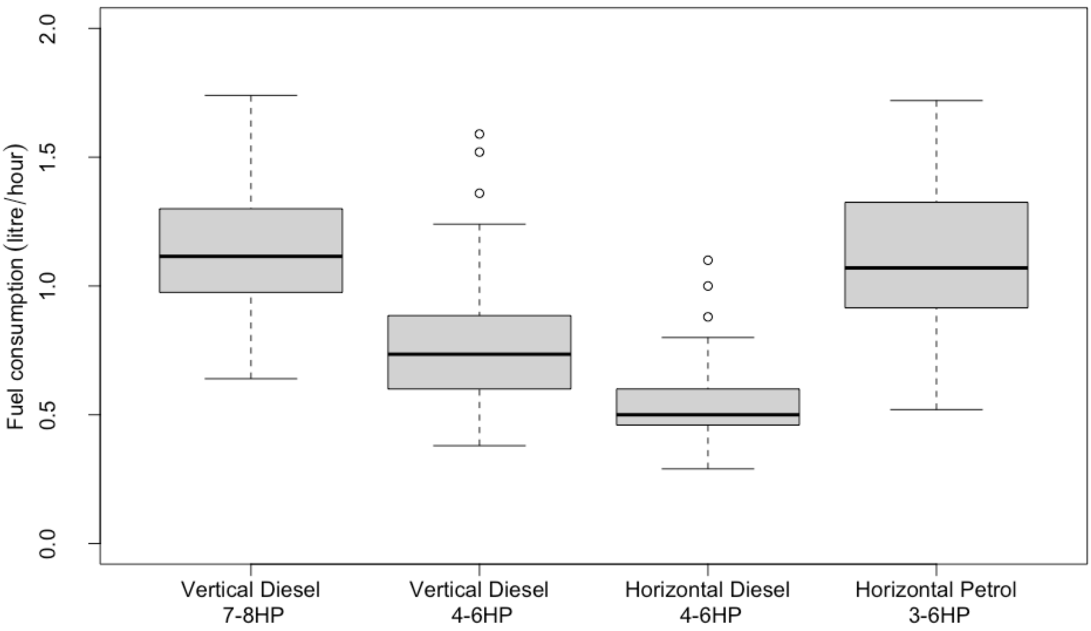

Figure 4. Distribution of measured fuel consumption rates (litre/hour) for each of the four main categories of pumpset tested as part of our study

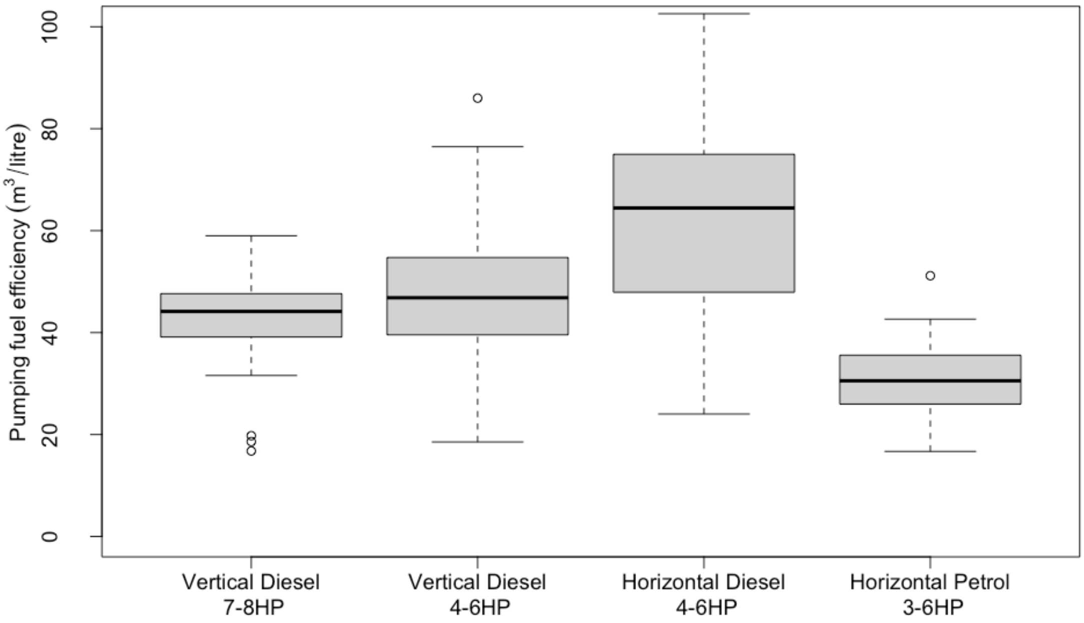

Figure 5. Distribution of measured water-fuel efficiencies (m^3 water discharged per litre of fuel consumed) for each of the four main categories of pumpset tested as part of our study

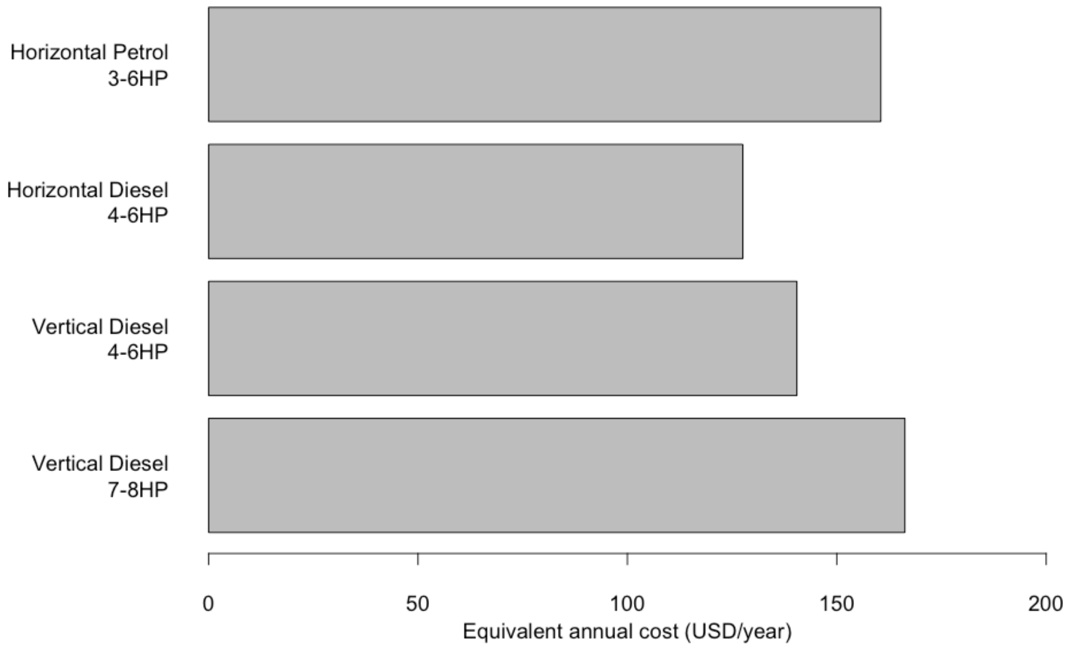

Figure 6. Estimated equivalent annual costs of owning and operating (USD/year) for each of the four main categories of pumpset considered in our analysis

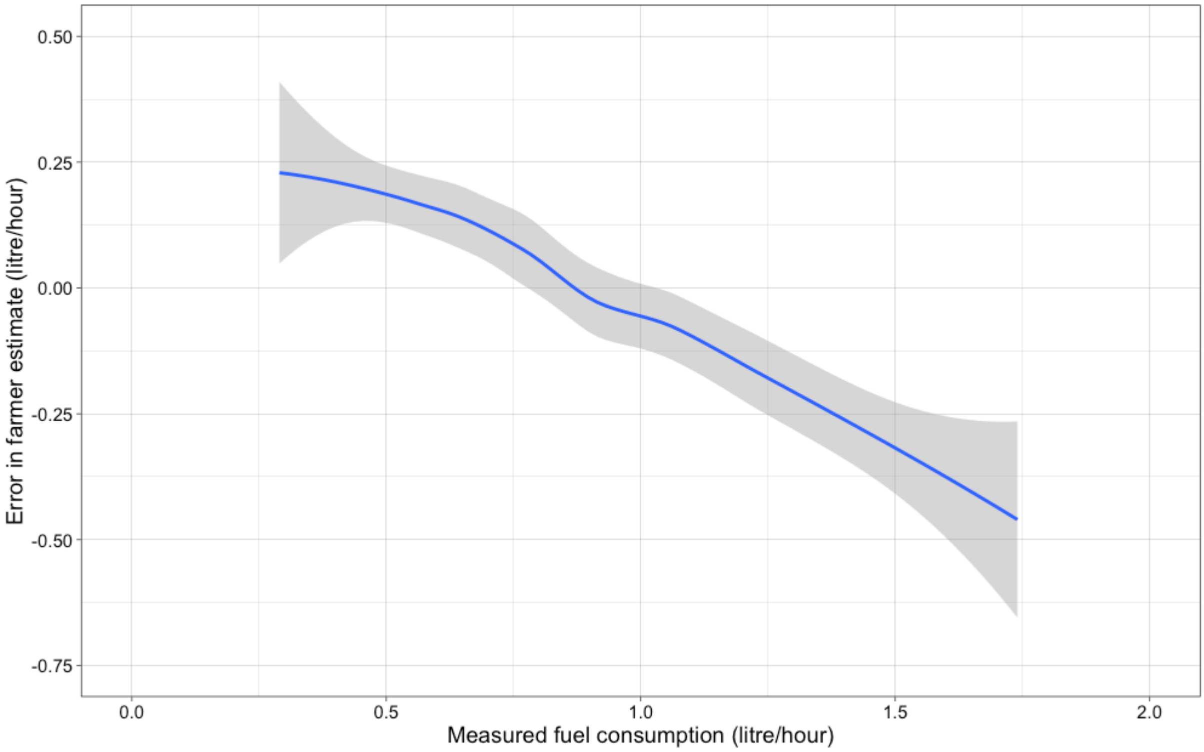

Figure 7. Error in farmer-reported estimates of pumpset fuel consumption as a function of the actual measured rate of fuel consumption during in-situ testing. Solid blue line shows the loess fit and shaded area illustrates the 95% confidence interval based on data from 116 pump tests.

Figure 8. (a) typical branding of Indian brand pumpsets – such as Kirloskar – emphasising reliability and durability, and (b) Chinese manufactured pumpset imitating Indian brand names through false labelling.