Environment for Development

Discussion Paper Series May 2025 ■ EfD DP 25-05

Laser Land Leveling Technology for Paddy Production in Vietnam

Impact on Efficient Irrigation and Water Conservation

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Abstract

This research investigates the empirical effects of the laser land leveling (LLL) adoption on irrigation water and water efficiency in paddy production in the Mekong Delta region (MDR), using the randomized controlled trial (RCT) approach incorporated into input demand function models. The descriptive analysis highlights the potential for water reuse through farmers' drainage practices. However, the dependence on experiential methods for applying technology in paddy production poses challenges that could compromise long-term sustainability. The regression results indicate that the LLL treatment leads to savings of 1,975 m^3 ha^{-1} and 1,299.35 m^3 ha^{-1} in irrigation water and net water use in paddy production, respectively, compared to the control. These savings account for 20.52% of total irrigation water use and 28.64% of net water use. The projected savings on average of 375.51 and 247.05 million m^3 respectively for irrigation water and net water use with 5% implementation of the technology in the MDR. The research highlights the environmental benefits of the LLL technology and underscores the need for its promotion to achieve water conservation in paddy production, offering policymakers insights to enhance sustainable agriculture amid climate change and water scarcity. The study addresses significant gaps in existing literature by providing an in-depth analysis of LLL technology's impact on irrigation water and efficiency by extending the drainage performance within the paddy mono-cropping context and employing RCT methodology combined with input demand function models to comprehensively evaluate its impact on irrigation water usage.

Keywords: Precision Agriculture, Water Demand Modeling, Drainage Performance, Water Efficiency, Randomized Controlled Trials, Sustainability

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This research investigates the empirical effects of the laser land leveling (LLL) adoption on irrigation water and water efficiency in paddy production in the Mekong Delta region (MDR), using the randomized controlled trial (RCT) approach incorporated into input demand function models. The descriptive analysis highlights the potential for water reuse through farmers' drainage practices. However, the dependence on experiential methods for applying technology in paddy production poses challenges that could compromise long-term sustainability. The regression results indicate that the LLL treatment leads to savings of 1,975 m^3 ha^{-1} and 1,299.35 m^3 ha^{-1} in irrigation water and net water use in paddy production, respectively, compared to the control. These savings account for 20.52% of total irrigation water use and 28.64% of net water use. The projected savings on average of 375.51 and 247.05 million m^3 respectively for irrigation water and net water use with 5% implementation of the technology in the MDR. The research highlights the environmental benefits of the LLL technology and underscores the need for its promotion to achieve water conservation in paddy production, offering policymakers insights to enhance sustainable agriculture amid climate change and water scarcity. The study addresses significant gaps in existing literature by providing an in-depth analysis of LLL technology's impact on irrigation water and efficiency by extending the drainage performance within the paddy mono-cropping context and employing RCT methodology combined with input demand function models to comprehensively evaluate its impact on irrigation water usage.

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[1] This paper is published as Le, L. T., Tran, L. D., & Phung, T. N. (2025). Laser land leveling technology for paddy production in Vietnam: impact on efficient irrigation and water conservation. *Environmental Monitoring and Assessment*, *197*(1), 1-19.

Introduction

In the Mekong Delta, water scarcity intensified by climate change and seasonal saline intrusion threatens agricultural sustainability, mirroring a global challenge as water shortages increasingly undermine agricultural productivity and food security, especially for staple crops like paddy (United Nations, 2023; Barik et al., 2023; Takounjou et al., 2022). Scientific projections indicate a marked intensification in the frequency and severity of droughts as a consequence of climate change, with an anticipated global temperature increase of 1.5 to 2 degrees Celsius potentially elevating the proportion of the population exposed to water stress by as much as 50% (IPCC, 2018). The Mekong Delta region of Vietnam has represented 55% of Vietnam's total paddy cultivation area and 57% of its output (GSO, 2022; WB and ADB, 2021). This makes the region an important focus for irrigation efficiency studies. The region's agricultural sustainability is increasingly threatened by upstream water diversions, which reduce freshwater availability and alter sediment transport critical for soil fertility. These changes, combined with climate-driven salinity increases, have severely affected rice production in the area (Rahman et al., 2021; Cosslett et al., 2018). Recent increases in agricultural production, population growth, and urbanization have escalated groundwater withdrawal and intensified land subsidence in the Mekong Delta, compounded by upstream dam construction that reduces water and sediment flow, exacerbating saltwater intrusion and contributing to a rapid relative sea-level rise (Tran et al., 2024; Boretti, A., 2020). Addressing these concerns highlights the critical necessity for adopting innovative, climate-adaptive agricultural practices. Specifically, it is imperative to implement integrated water management strategies to bolster the resilience and sustainability of the delta's agricultural sectors amidst climate change challenges, with a particular emphasis on paddy cultivation (Minh et al., 2022; Othmane et al., 2021).

Precision agriculture technology is essential for addressing environmental challenges induced climate change in agriculture. It optimizes resource use through stages like land preparation, seeding, field management, and harvesting, thus conserving inputs and enhancing sustainability (Ren et al., 2023; Li, Caixia, 2023). The global adoption of Laser-Controlled Land Leveling (LLL) technology started in the United State in the 1970s and spread rapidly to other developed countries like the United Kingdom, Japan, and Russia. Its success led to subsequent adoption in developing regions, particularly in Southeast and East Asia, by the 1990s (Chen et al., 2024). The technology creates a soil environment ideal for global food production, enhancing efficiency in crops most particularly like rice, wheat, and maize. It also improves land utilization, irrigation and drainage efficiency, crop yield, and reduces fertilizer usage. For paddy production, LLL technology significantly boosts outcomes by enhancing adaptation to climate risks, increasing productivity, and optimizing resource efficiency, especially in managing and conserving irrigation water (Lybbert et al., 2018). Therefore, the LLL technology is identified as a prerequisite for sustainable paddy production in the Mekong Delta, Vietnam as it can adapt to emerging climatic variability, particularly in the context of water scarcity and shortages (Le, 2021).

Most studies on LLL technology impacts concentrate on South Asia, specifically addressing the rice-wheat and sugarcane-wheat cropping systems, as evidenced by studies such as Ramya et al. (2022) in India, Tomar et al. (2020) for the mustard, sugarcance and rice – wheat rotation system in India, Aryal et al. (2020) and Lybbert et al. (2018) for the rice-wheat systems in India, Ali et al. (2018) for the rice-wheat system in Pakistan, and Das et al. (2018) for wheat system in India. While much of the existing research focuses on South Asia, little attention has been paid to Southeast Asia, particularly the paddy mono-cropping system in Vietnam. Despite Southeast Asia's critical role in global paddy production, particularly characterized by the paddy mono-cropping system, there is a noticeable lack of research investigating the effects of LLL technology in this region (Nguyen Van Hung et al., 2022). Considering its widespread adoption in Southeast Asian nations in paddy production, particularly Vietnam, the LLL impacts may diverge from the findings in the current scholarly discourse with small-scale and mono-cropping system. By investigating its widespread adoption in paddy production across Southeast Asia, particularly in Vietnam, the impacts of LLL may diverge from current scholarly findings, potentially revealing distinct water effects within small-scale, mono-cropping systems and specific input application.

The extant literature concerning the LLL impacts on paddy production has primarily concentrated on productivity outcomes, as evidenced by numerous studies of Pal et al. (2022); Kakraliya et al. (2019); and Li et al. (2018). The exploration of the LLL effects on water and associated variables, such as time and energy expended on irrigation, has been documented in various research efforts from Ramya et al. (2022); Nguyen Van Hung et al. (2022); Tomar et al. (2020); Ashrat et al. (2017). Moreover, water management within fields emerges as a crucial determinant in paddy production. The farmers' drainage practices influence the volume of water that is returned to rivers and subsequently captured downstream, thereby facilitating water conservation and greater savings of water irrigation and water use resulting from the technology adoption (Moursi et al., 2022; Lampayan et al., 2015). However, the existing body of literature has yet to integrate drainage performance into the analysis of the LLL impact on water utilization.

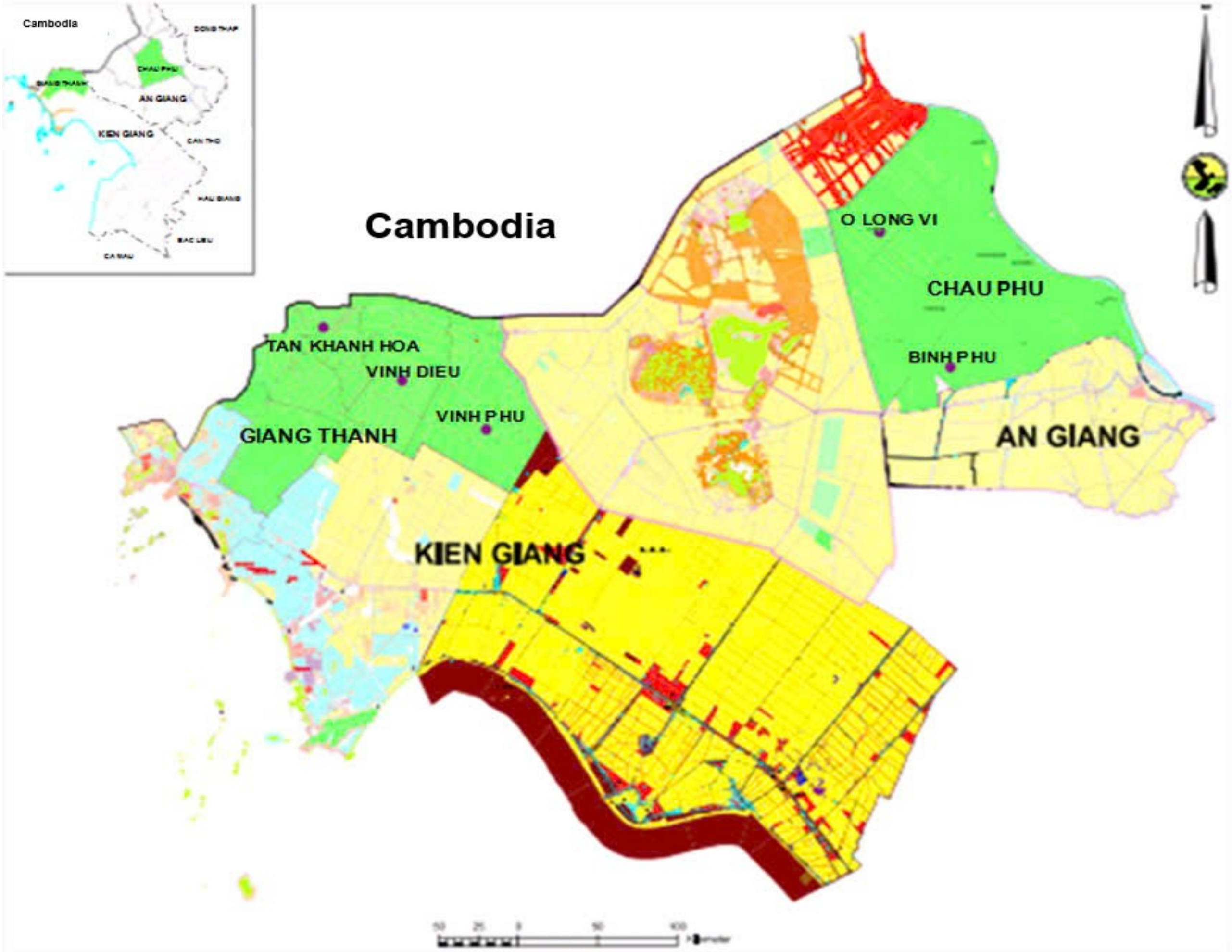
Scholarly investigations concerning the LLL effect on irrigation water, as well as and the associated time and energy expenditures, have predominantly utilized experimental field methodologies (Ramya et al., 2022; Tomar, 2020; Ashrat et al., 2017). This research theme is further enriched by descriptive comparative analyses (Aryal et al., 2015) and systematic reviews (Chen et al., 2024; Nguyen Van Hung et al., 2022). While the Randomized Control Trials (RCTs) are widely utilized for evaluating various interventions in agricultural research, their application to the LLL impacts remains limited, with Lybbert et al. (2018) for the rice – wheat system being a notable exception. Econometric analyses that incorporate the demand input function and RCT methodology to examine the LLL impact on irrigation water are notably absent in the existing literature.

The study aims to investigate the empirical impact of LLL adoption on irrigation water and water efficiency in paddy production in the Mekong Delta region. This study addresses two critical gaps in the literature. First, it offers an in-depth analysis of the impacts of LLL technology on irrigation water use and efficiency, incorporating drainage performance within the context of paddy mono-cropping. Secondly, the study employs the RCT methodology combined with input demand function models to rigorously evaluate the impacts of the LLL technology on irrigation water usage. The structure of paper is as follows. Section 2 presents the methodology with the experimental design, water estimation, econometric model, study sites. Section 3 describes the results and discussion. Section 4 contains the conclusion of this study.

Materials and Methods

Study sites and data collection

For the selection of primary data sample, the cluster sampling technique was employed in this study. Particularly, An Giang and Kien Giang provinces were selected as the sites for this empirical study due to their prominence in paddy cultivation, encompassing the largest cultivation areas among the 13 provinces of the Mekong Delta (Fig. 1). In addition, An Giang's long-established rice farming tradition has led to a landscape characterized by smaller, carefully leveled fields, while Kien Giang, where paddy farming has been adopted more recently, is marked by larger fields shaped through ongoing land reforms. This contrast highlights the variation in soil types and intensive cropping systems, differences in freshwater availability, the utilization of technology, and irrigation management—whether managed individually or cooperatively (GSO, 2023). These provinces also demonstrate variations in topographical flatness, which acts as an indicator of the suitability for technology implementation, as well as in agricultural extension programs (Lampayan et al., 2015). These are important factors in the analysis of water efficiency resulting from the LLL technology adoption.



Source: An Giang DNRE (2023); Kien Giang DNRE (2023)

Fig. 1 Study sites in An Giang and Kien Giang provinces

Two communes were selected in each province in compliance with two distinct criteria. Firstly, at the time of the study in 2020, the LLL technology had not been broadly adopted as a common practice in paddy field. Secondly, a significant proportion of farmers own plots larger than 1000 square meters, the minimum size necessary for the LLL service implementation. For each commune, 75 farmers were randomly chosen in accordance with two previously defined criteria. We conducted seminars to introduce LLL technology. From an attendee list of approximately 100 farmers per commune, we selected participants on a rotating basis, choosing three for every one omitted. A total of 303 households, encompassing 764 paddy fields, were interviewed to conduct a BDM auction to select 201 winning plots based on a predetermined price. Finally, 97 plots were randomly allocated to either the treatment or control group via a lottery system. These 97 plots were investigated for their irrigation management, including irrigation water volumes, net water use, drainage practices, input applications, and other relevant data during the three Winter-Spring crops in 2020, 2021, and 2022 (see Tables 2 and 3 for detailed information).

Analytical framework and experimental design

This research utilizes the theoretical frameworks developed by Ellis (1993) and Rasmussen (2012) to establish a microeconomic basis for analyzing the decision-making behaviors of farmers concerning the usage of irrigation water. Ellis (1993) presents a holistic approach that emphasizes the importance of maximizing efficiency and productivity through optimally utilizing inputs and adapting to economic and environmental changes. Rasmussen (2012) articulates that input demand functions have been derived from production theory, cost minimization, and profit maximization, elucidating the interconnections among input prices, output prices, technological advancements, and input usages. Accordingly, the demand for inputs is defined by a function that includes the prices of key inputs, output prices, and additional factors that clarify the production function (Kehinde et al., 2024; Weerasooriya and Hemachandra, 2020; Rasmussen, 2012).

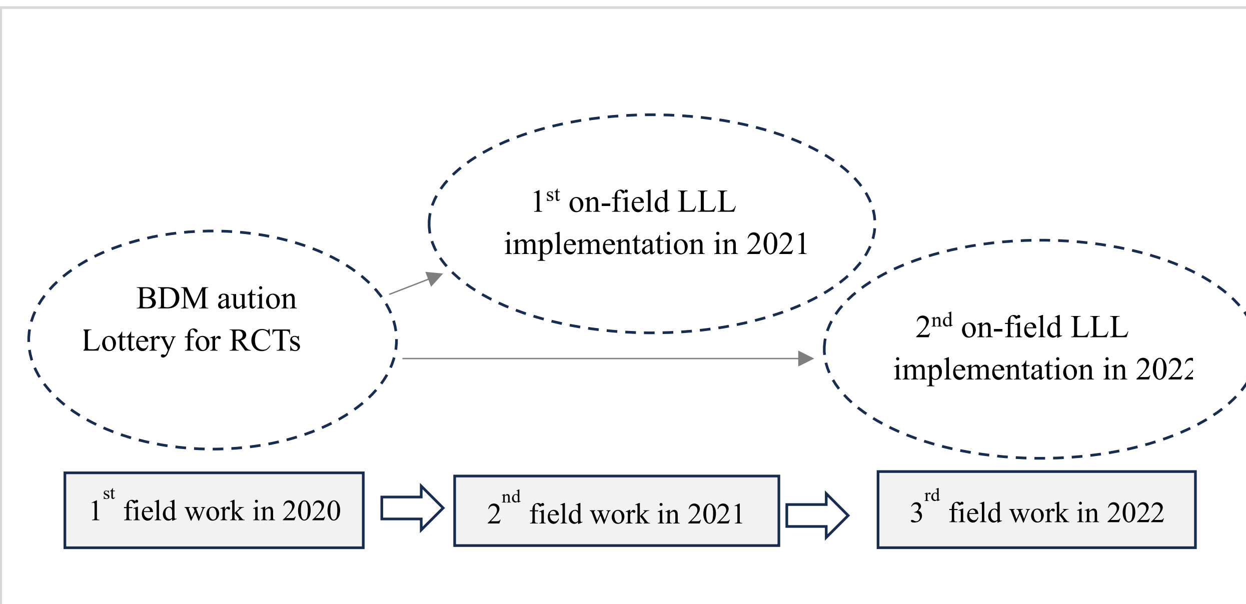


Fig. 2 Analytical framework and experimental design

In the initial fieldwork, a Becker, DeGroote, Marschak (BDM)-style auction was utilized to elicit the WTP for the LLL adoption, allowing farmers to individually bid against a confidential predetermined price without direct competition (Lybbert et al., 2018; Berry et al., 2015; Demont and Ndour, 2015) (Fig. 2). The sealed bid auction was set at 400,000 Vietnamese Dong per hour, aligned with the standard rental rate for LLL in the region. This auction was conducted on 764 plots from 303 households, identifying 201 plots with a WTP above the set price, which were then selected for the subsequent lottery step. The RCT was then conducted to assign plots either to a treatment or a control group, facilitating an unbiased evaluation of the technology adoption's effect on irrigation water by comparing outcomes between the groups. Given constraints on the number of available LLL service providers and short intervals between cropping seasons, a lottery was employed to allocate 56 plots to the treatment group and 41 to the control group, maintaining compliance with RCT methodology (Fig. 3).

The on-field LLL was implemented immediately after the Winter-Spring crop in February 2021 under the cooperation of project experts, local agricultural agencies, service providers, and farmers to ensure the proper delivery of LLL services, from land preparation to laser leveling. The flatness of paddy plots in both control and treatment groups was measured before and right after LLL implementation for the irrigation water estimation. In 2021, LLL services were executed on 40 of the 56 plots in the treatment group, constrained by the limited availability of service providers and early-season rainfall affecting some plots. The remaining 16 plots in the assigned treatment group and one in the control group received LLL services, while the others continued as the controls in the next Winter-Spring crop in 2022. The LLL service was paid by farmers under their budget constraints, which determined the leveling hours performed. This directly affected the flatness achieved, measured immediately after LLL adoption for the leveled plots.

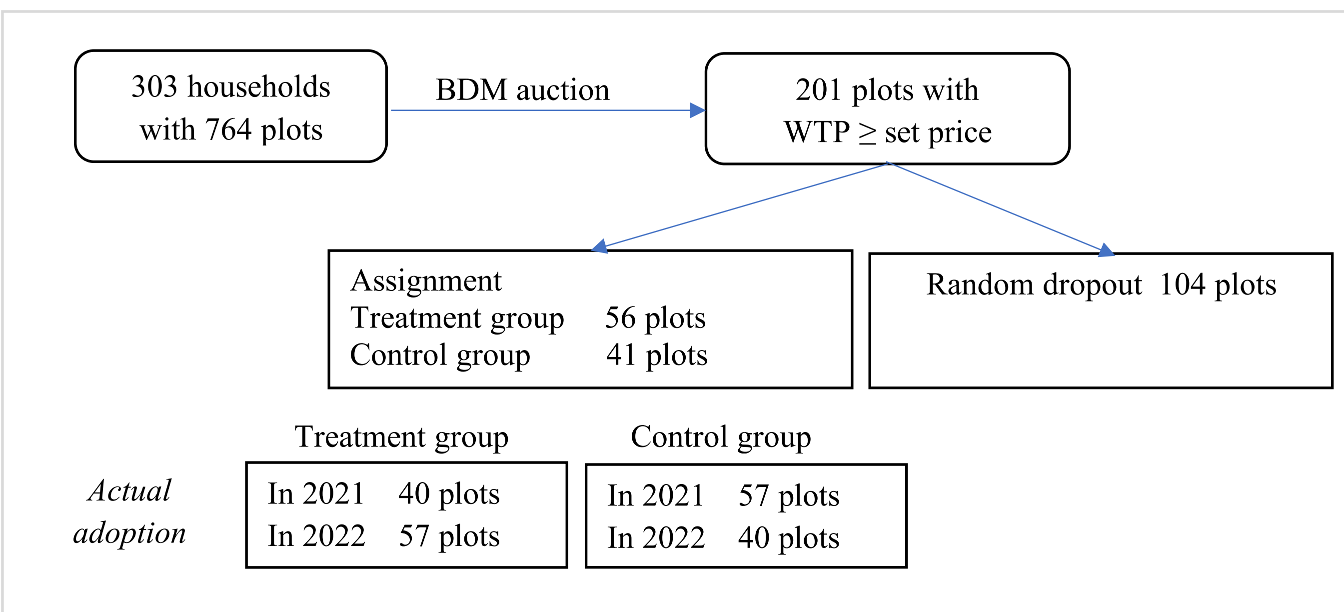


Fig. 3 Experimental design and sample allocation

Irrigation water estimation for paddy cultivation

The primary sources of irrigation are canal water or collectively pumped water within the dike system of the Mekong Delta region. Farmers partially dismantle the dike enclosing the field to allow water to enter during irrigation, and subsequently close it once the irrigation is complete. For this reason, unlike other studies that estimate water usage based on farmers' pump types and the frequency and duration of pumping (Lybbert et al., 2018; Tomar et al., 2020; Ashrat et al., 2017) or on water meter readings before and after irrigation (Kakraliya et al., 2018), this study estimated the volume of irrigation water for paddy production by measuring plot flatness and the irrigation management practices of farmers in both control and treatment groups. Field flatness is essential for irrigation efficiency, as it facilitates uniform water distribution, prevents runoff and excessive accumulation in low-lying areas, thereby reducing water usage and supporting consistent crop growth. Field flatness is essential for irrigation efficiency, as it facilitates uniform water distribution, prevents runoff and excessive accumulation in low-lying areas, thereby reducing water usage and supporting consistent crop growth. For the control plots, flatness measurements were taken once in 2020, and these values were used for analysis across three Winter Spring seasons, under the assumption of negligible changes over the periods without LLL implementation. For the treatment plots, measurements were conducted twice, before and after the implementation of the LLL technology. For each plot, the number of measured locations varies, ranging between 10 and 45, contingent upon the respective plot areas. The concept of flatness is elucidated through the h_i values, which represent the distances from the cross-section baseline to the field surface at location i and is quantitatively expressed as the standard deviation of these distances.

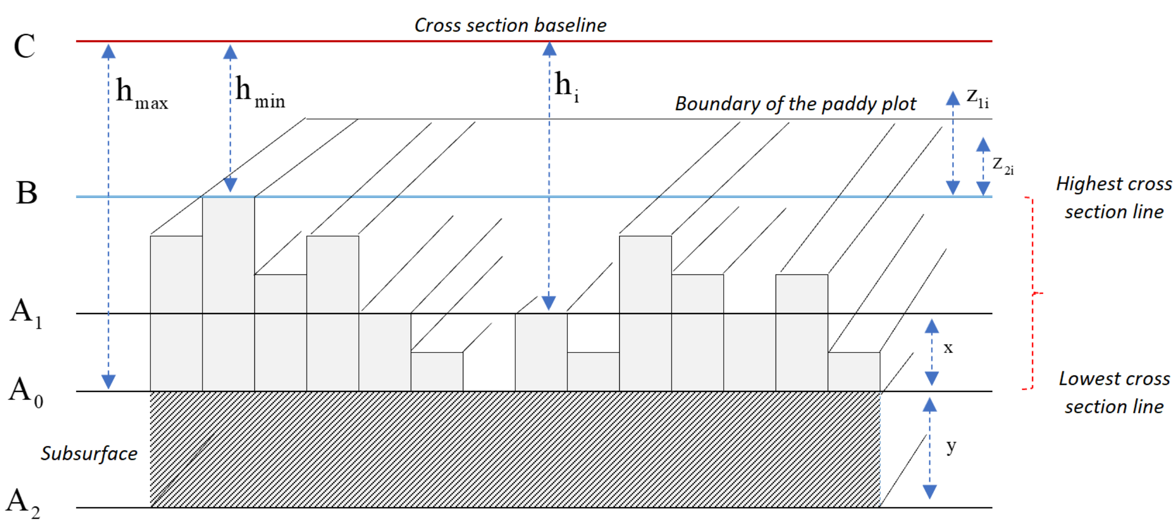


Fig. 4 Flatness measurement and irrigation water estimation

The estimation of irrigation water is depicted in Fig. 4. The cross-section lines A_0, B, and C represent the lowest, highest, and baseline cross-section lines of the field surface, respectively. To estimate the amount of irrigation water utilized for a crop, three interrelated volumes of water are examined: water volume irrigated into the field (V_{in}) , the volume that drains from the field (V_{out}) and the volume of water used (V_{use}), which is calculated as the difference between the first two metrics. These volumes are estimated depending on individual farmers' irrigation management practices and the surface flatness.

$$V_{use} = V_{in} - V_{out}$$

To estimate the water volume, at each location i, where i ranges from 1 to k, with the h_i value, the areas are equivalent and calculated as $S_i = \frac{S}{k}$ with S being the plot area and k being the total number of measured locations. The h_{max} and h_{min} represent the distances from the baseline cross-section C to the cross-section lines A_0 and B, respectively.

The water volume irrigated into the field is estimated depending on individual farmers' irrigation management practices and the surface flatness. In line with farmers' irrigation practices, they first determine the field conditions under which to initiate irrigation of their paddy fields—whether in a state of wetness or saturation, with standing water at a height of x centimeters, or in dry conditions characterized by hairline cracking of the surface at a depth of y centimeters. Secondly, they decide on the inlet water level of a height of z_{1i} centimeters from the highest cross section line, B. Thirdly, if applicable, they determine that once the standing water reaches a height of z_{2i} centimeters, they will begin to drain water from the fields. The volume drained from the field is estimated as the sum of volume from the cross section line A_0 to the highest cross section line, B (V_4) and volume from B to the height of z_{2i} centimeters standing water (V_5), assuming farmers drain the paddy fields until they reach the state of wetness or saturation. A detailed explanation is provided in Supplementary Information 1.

Empirical models for the effects of LLL adoption on irrigation water usage

Over the past two decades, the adoption of randomized controlled trials (RCTs) has significantly increased (Glewwe and Petra, 2022; de Souza Leão and Eyal, 2019). Following this approach, individuals from the target population are randomly assigned to either a treatment group, which receives the treatment, or a control group, which does not. The trials have been widely employed in agricultural research to assess the impacts of various interventions of the drip irrigation in India (Fishman et al., 2023), of the improved wheat varieties in Ethiopia (Yitayew et al., 2021), of the microcredit in Tanzani (Nakano and Magezi, 2020), and the LLL technology in India (Lybbert et al., 2018).

For the causal effect of LLL adoption on irrigation water usage, parameters, under perfect compliance, will be derived by incorporating a binary variable of LLL adoption to isolate its impact on the water outcome while controlling for plot-specific attributes and other influential variables. Since the assignment to treatment and control groups is randomized, selection bias at the randomization stage is not a concern. However, the randomness of treatment assignment may be compromised by potential endogeneity in program placement and by unobservable individual heterogeneity arising from beneficiaries' self-selection (Glewwe and Petra, 2022; Khandker, 2009).

In this study, where 16 plots in the treatment group did not adopt LLL, it is crucial to address endogeneity concerns to accurately estimate the parameters of causal inference and account for noncompliance in experimental settings. For this purpose, a model employing an instrumental variable to estimate the Local Average Treatment Effect (LATE) is utilized in this analysis, as suggested by previous researchers, e.g., Abadie and Cattaneo (2018); Lybbert et al. (2018). The bias from the endogeneity in the actual adoption decision can be resolved by employing an instrumental variable (IV) that affects the actual LLL adoption but remains uncorrelated with the outcome variable, within the framework of the two-stage least squares estimation (Glewwe and Petra, 2022; Khandker, 2009). Accordingly, in the first stage, the probit regression model is used to estimate the probability of actual LLL adoption using the instrumental variable along with the other exogenous variable, as specified in Equation (1).

$$P(\mathrm{LLL}_i = 1 | ASS_i, \mathrm{ELE}_i) = \Phi(\mu_0 + \mu_1 ASS_i + \mu_2 \mathrm{ELE}_i) \qquad (1)$$

Where $P(LLL_i = 1 | ASS_i, \mathrm{ELE}_i)$ is the conditional probability that plot i adopts LLL in actuality conditioned on its assignment to the treatment group (ASS_i); its elevation characteristics (ELE_i) and Φ denotes the cumulative distribution function of the standard normal distribution valuing 0 and 1; μ_0 is the intercept term; μ_1 is the coefficient for the assignment variable (ASS_i) which is an IV indicating whether the plot i was randomly assigned to adopt LLL (1 if assigned, 0 otherwise); μ_2 is the coefficient for the elevation characteristics.

In the second stage, the predicted values of LLL ($\widehat{LLL_i}$) are utilized to estimate the LLL impact on the volumes of the irrigation water and the net water use for paddy production (Table 1). The LATE parameter quantifies the average effect of the LLL adoption on the outcomes of water volumes in this analysis among those who follow the LLL program, as selected by the lottery. The estimation of the LATE on the water volumes are delineated in Equation (2) and (3).

$$\mathrm{IRR_i} = \beta_0 + \beta_1(\widehat{\mathrm{LLL_i}}) + \textstyle\sum_{k=2}^{9}(\beta_k \mathrm{P\_input_{ki}}) + \beta_{10}\mathrm{PPAD_i} + \beta_{11}\mathrm{STD_i} + \beta_{12}\mathrm{CRO_i} + \beta_{13}\mathrm{VAR_i} + \mathrm{e_i} \qquad (2)$$

$$\mathrm{WAT_i} = \beta_0 + \beta_1(\widehat{\mathrm{LLL_i}}) + \textstyle\sum_{k=2}^{9}(\beta_k \mathrm{P\_input_{ki}}) + \beta_{10}\mathrm{PPAD_i} + \beta_{11}\mathrm{STD_i} + \beta_{12}\mathrm{CRO_i} + \beta_{13}\mathrm{VAR_i} + \mathrm{e_i} \qquad (3)$$

Where IRR_i and WAT_i are the volume of irrigation water and net water use applied per hectare for plot i, note that these dependent variables are expressed in logarithmic form; P_input_{ki} denotes the price of input k for plot i, k=2-9 specifically seed, pesticide, labor, machine hours; fertilizers of nitrogen, phosphorus, and potassium, $PPAD_i$ is the price of fresh paddy associated with plot i; STD_i standard deviation of land surface in logarithm; VAR_i is dummy variable indicating the variety of the crop, assigned a value of 1 if the crop's growing period is 95 days or longer, and 0 if shorter; CRO_i is another dummy variable representing the crop time, with a value of 1 for the interval from November 2020 to March 2021, and 0 for the interval from November 2021 to March 2022; β_o is intercept; other β are coefficients; e_i is residuals. The parameter β_1 is the primary parameter of interest, capturing the local average treatment effect on the outcome dependent variable of the actual LLL adoption, assuming that other variables remain constant (Glewwe and Petra, 2022).

Table 1 Variables in the model for treatment effects of LLL adoption on water usage

Variables	Notation	Unit
Dependent variables		
Irrigation	IRR	1000 m^3 ha^{-1}
Net water use	WAT	1000 m^3 ha^{-1}
Independent variables		
Actual adoption	LLL	= 1 if LLL actual adoption, = 0 if non adoption
Price of seed	PSEE	1000 VND kg^{-1}
Price of fertilizer		
- Price of P_2O	PP2O	1000 VND kg^{-1}
- Price of K_2O	PK2O	1000 VND kg^{-1}
- Price of NIT	PNIT	1000 VND kg^{-1}
Price of pesticide	PPES	1000 VND g AI^{-1}
Price of labor	PLAB	1000 VND $hour^{-1}$
Price of machine	PMAC	1000 VND $hour^{-1}$
Price of water	PWAT	1000 VND m^{-3}
Price of paddy	PPAD	1000 VND kg^{-1}
Paddy variety	VAR	= 1 if crop growing period is 95 days or longer =0 if crop growing period is shorter than 95 days
Land surface	STD	centimeter
Crop time	CRO	=1 if Winter-Spring crop from November 2020 to March 2021 =0 if Winter-Spring crop from November 2021 to March 2022

Results and discussion

Characteristics of paddy farmers, plots, and paddy production

The sample comprises 49 paddy farmers, from whom 97 plots were selected out of 201 auction-winning plots based on a predetermined price and lottery assignment method. The dataset covers two Winter-Spring cropping seasons in 2021 and 2022, encompassing 194 plots divided equally between 97 treated and 97 control observations. The demographic analysis of the 49 households surveyed reveals a predominantly older and male-dominated group of paddy farmers with considerable experience in paddy cultivation (Table SI.1). Farmer age is closely linked to farming experience, which aids in issue identification, yield forecasting, and improved agronomic practices (Ho et al., 2022; Kyire et al., 2023). However, Wu et al. (2022) note that older farmers are less likely to adopt new technologies, as they are more inclined toward traditional practices, potentially hindering technology adoption in agriculture. Educational levels among these farmers are generally limited to primary and secondary school, encompassing 80.95% of the sample, which reflects the challenges they may face in adopting advanced agricultural technologies. While a significant 71.43% of farmers have participated in local trainings on paddy cultivation, an appreciable 28.57% have not engaged, highlighting a key opportunity for improvements in agricultural extension services.

Regarding land fragmentation, most farmers conduct their paddy production across two to three plots, with more than 85% of the total plots being small to medium-sized, each less than 4 hectares (Table SI.2). The distribution of plot sizes indicates that the majority of plots in both groups are concentrated within the range from 2 to 4 hectares, comprising approximately 46.9 % of the total plots. The mean plot size is almost equivalent between the two groups, averaging about 24.5 thousand square meters. Regarding land surface roughness, measured on a 1-10 Likert scale, the farmers' assessment reveal that 77.32% of plots scored between 4 and 10 points, demonstrating relatively high levels of roughness. This analysis provide a comprehensive overview of the sample's demographics, characteristics of paddy field and plot in the Mekong delta region.

Table 2 Characteristics of paddy production in the Mekong Delta region

Unit: in percentage

Indicators	Unit	LLL=0 (N=97)	LLL=1 (N=97)	Full sample (N=194)
Technology in paddy cultivation[1]	=1 if 3R3G	22.68	15.67	19.07
	if VietGAP	15.46	13.40	14.43
	if IPM practice	0.00	3.09	1.53
	= 0 if farmer's experience	61.86	68.04	64.95
Soil types	= 1 without acid and salt	18.75	25.00	21.79
	= 0 otherwise	81.25	75.00	78.21
Paddy variety	Certified	79.38	82.47	80.93
	Self-produced	20.62	17.53	19.07
	= 1 if ≥ 95 days	61.86	76.29	69.07
	= 0 if otherwise	38.14	23.71	30.93
Intensive	= 1 if 3 crop year^{-1}	16.49	9.28	12.89
	= 0 if 2 crop year^{-1}	83.51	90.72	87.11
Total		100.00	100.00	100.00

Note: [1]: 3R3G is "three reductions, three Gains" with the reductions of seeds, fertilizer and pesticides and the increase of productivity, quality and efficiency, VietGAP is the Vietnamese Good Agricultural Practices; IPM stands for Integrated Pest Management.

For paddy cultivation practices, the majority of both groups heavily rely on farmers' experience, with a significant portion of 64.95% (Table 2). The remaining plots utilize either the 'three reductions, three gains' technology, VietGAP, or integrated pest management. More than 80% of farmers prefer certified varieties, and a substantial majority utilize varieties with growth periods of 95 days or longer. Rice varieties are closely associated with irrigation water requirements and net water use, as different varieties exhibit variations in cropping duration and irrigation needs (Poddar et al., 2022). Crop intensity data shows a dominance of two cropping cycles per year in the sample. In the Mekong Delta, alluvial soil is a prevalent type for rice cultivation. Of these soil plots, 21.79% are free from acidity and salinity, while 26.07% and 52.14% consist of saline alluvial soil and acidic alluvial soil, respectively. This comprehensive overview highlights the characteristics of soil type, intensive farming, roughness, and paddy production practices at the study site.

Table 3 Irrigation water management practice in paddy production

Unit: in percentage[1]

Indicators	Unit	LLL=0 (N=97)	LLL=1 (N=97)	Full sample (N=194)
Irrigation pumping type				
– Individual pumping	%	91.75	90.72	91.24
– Collective pumping	%	8.25	9.28	9.76
Energy used for irrigation				
– Diesel	%	76.54	66.96	70.92
– Electricity	%	16.05	33.04	26.02
Number of irrigation times	times $crop^{-1}$	7.38	7.44	7.42
– When paddy field was standing water condition	times $crop^{-1}$	2.31	1.48	1.82
– When paddy field was wet or saturated	times $crop^{-1}$	4.42	5.4	4.99
– When paddy field was dry	times $crop^{-1}$	0.65	0.57	0.6
Number of drainage times	times $crop^{-1}$	5.32	5.37	5.35
Water				
– Irrigation	$m^3\ ha^{-1}$	9,579	6,515	7,781
– Drainage	$m^3\ ha^{-1}$	5,192	3,525	4,214
– Net water use	$m^3\ ha^{-1}$	4,388	2,990	3,567

Note: The cooperative irrigation system in the communes, if available, facilitates collective pumping.

In view of irrigation water management practices in paddy production, the majority of paddy plots rely on individual pumping systems for irrigation, with 91.75% of total plots, suggesting an availability constraint of cooperative irrigation system leading to individual solutions and challenges that farmers may encounter with water scarcity in the context of climate change in the Mekong Delta region. Energy usage for irrigation demonstrates a predominance of diesel, with diesel-powered pumping machines employed in 70.92% of the plots.

Irrigation of paddy fields necessitates precise water management tailored to various developmental stages of the crop. According to the alternative wetting and drying technique, fields are initially flooded post-transplantation, and farmers subsequently allow water levels to decrease until slight cracking of the soil occurs or the water completely recedes. This practice is designed to enhance root development, reduce water consumption, and decrease greenhouse gas emissions (Le, 2021; Cheng et al., 2022). Effective water management is essential not only for optimizing crop yields but also for conserving resources and promoting environmental sustainability.

In this study, water management practices are analyzed through the frequency of irrigation, the specific field conditions under which irrigation is applied, and the efficiency of drainage, as detailed in Table 3. Though the irrigation frequency is nearly uniform across the sample, the conditions under which farmers irrigate their paddy field reflect more adaptive water management strategies towards the treatment group. Treated plots have fewer irrigation instances under standing water conditions but more when the field is wet or saturated. The frequency of drainage is quite similar across both groups, with an overall average of 5.35 times per crop. Treated plots are notably more efficient in water usage, using significantly less water for both irrigation and drainage than untreated plots, which translates into a considerable reduction in net water use. Due to increased field flatness, the treated plots achieved uniform water distribution, preventing unnecessary water accumulation in low-lying areas and reducing the need for excessive irrigation in standing water conditions, ultimately enhancing irrigation efficiency.

Variable description and balance test

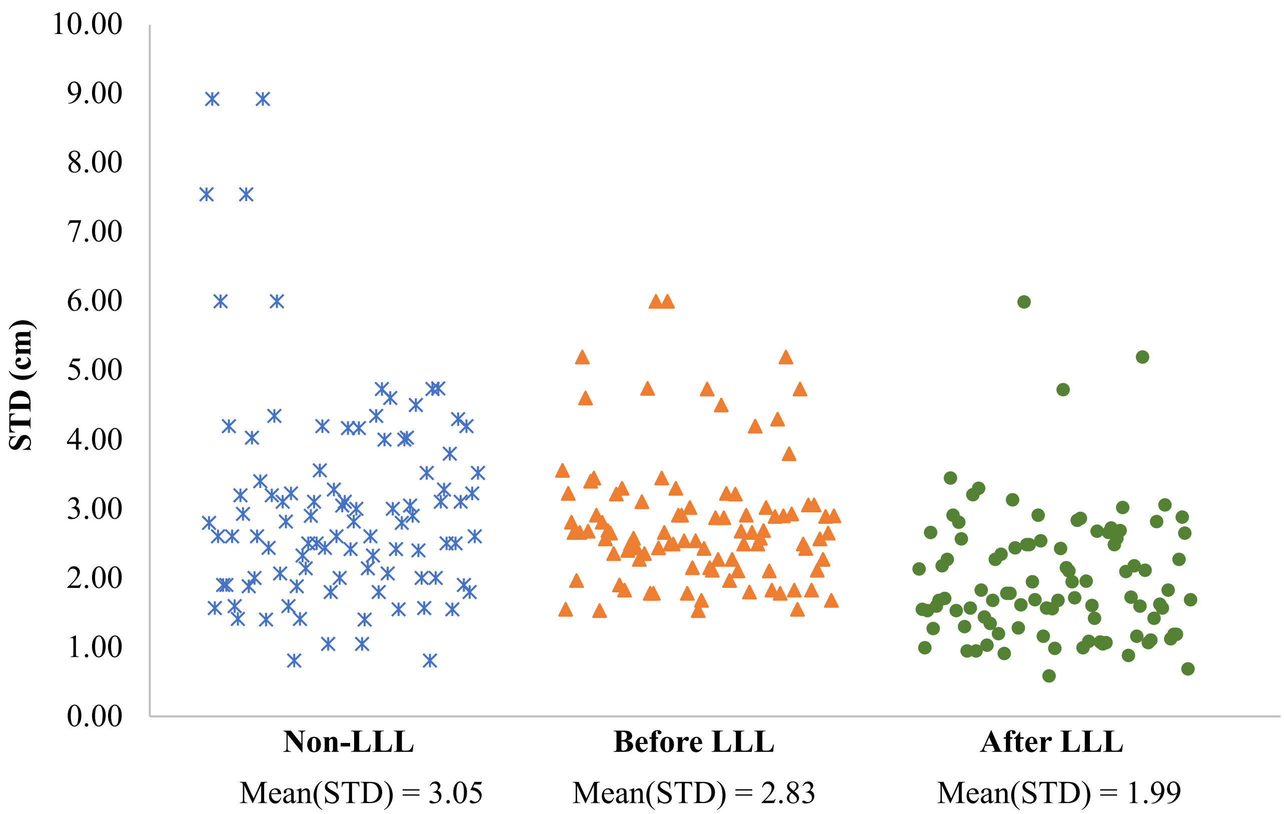


Fig. 5 Standard deviation of paddy land surface

Table 4 Variable description in the model for the LLL adoption impact on input usage

Variables	Unit	LLL = 0 (N=97)				LLL =1 (N=97)				Total (N=194)			
		Mean	Std.Dev	Min	Max	Mean	Std.Dev	Min	Max	Mean	Std.Dev	Min	Max
IRR	$m^3\ ha^{-1}$	9,623.90	2,736.45	5,274.00	22,333.00	5,999.03	1,266.92	3,551.00	9,981.00	7,811.46	2,797.32	3,551.00	22,333.00
WAT	$m^3\ ha^{-1}$	4,536.12	2,141.77	1,910.00	14,017.00	2,684.23	956.86	1,246.00	5,460.00	3,610.18	1,897.09	1,246.00	14,017.00
PSEE	1000 VND kg^{-1}	13.38	3.15	4.80	17.00	14.46	1.76	4.80	17.00	13.92	2.60	4.80	17.00
PP2O	1000 VND kg^{-1}	26.65	6.57	15.27	41.68	28.40	5.67	18.00	43.43	27.53	6.18	15.27	43.43
PK2O	1000 VND kg^{-1}	24.99	7.24	12.73	35.64	28.28	6.02	13.82	36.36	26.63	6.84	12.73	36.36
PNIT	1000 VND kg^{-1}	29.73	10.57	15.22	43.48	32.59	8.84	16.52	44.57	31.16	9.82	15.22	44.57
PLAB	1000 VND $hour^{-1}$	94.93	26.34	46.89	184.97	91.44	32.45	49.79	213.14	93.19	29.53	46.89	213.14
PMAC	1000 VND $hour^{-1}$	395.71	101.14	216.10	668.83	458.87	140.11	222.33	971.70	427.29	125.92	216.10	971.70
PPES	1000 VND g AI^{-1}	1.19	0.84	0.12	4.33	1.09	0.85	0.14	5.97	1.14	0.84	0.12	5.97
PWAT	1000 VND m^{-3}	0.10	0.05	0.04	0.25	0.15	0.05	0.07	0.28	0.12	0.05	0.04	0.28
PPAD	1000 VND kg^{-1}	6.41	0.49	4.50	7.00	6.61	0.40	4.60	7.00	6.51	0.46	4.50	7.00
STD	Centimeter	3.05	1.53	0.81	8.93	1.99	0.92	0.59	6.00	2.52	1.36	0.59	8.93
CRO	=1: Crop time 2021 =0: Crop time 2022	0.38	0.49	0.00	1.00	0.32	0.47	0.00	1.00	0.35	0.48	0.00	1.00
VAR	=1: if >95 days =0: otherwise	0.62	0.49	0.00	1.00	0.76	0.43	0.00	1.00	0.69	0.46	0.00	1.00
LLL	=1: LLL =0: Non LLL	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.50	0.50	0.00	1.00

Table 4 presents comprehensive descriptions of the variables in the regression analysis. The standard deviation of the paddy land surface is calculated based on height measurements taken at 10 to 45 locations per plot, varying according to the size of the plot, thereby providing insights into the variation within the paddy land surface (Fig. 5). A decrease in the mean value of the standard deviation of the paddy land surface following the LLL adoption within the treatment group indicates the effectiveness of the LLL intervention, suggesting a reduction in field surface variation exceeding 5 cm. Furthermore, T-test results reveal no significant differences in the mean values of the standard deviation between the two assigned groups (Table SI.3 and Table SI.4).

The T-test was employed in the balance test to verify the adequacy of the randomization process. Baseline data from the Winter-Spring crop of 2020 on regression variables were utilized in the balance test to examine the mean differences between those in the assigned treatment group versus those in the control group. The variables include the two dependent variables on volumes of irrigation water and net water use and independent ones of input prices and others (Table SI.4). The p-values exceeded the 10% threshold, confirming no statistically significant differences between the two groups for the two variables on the water volumes. For the price variables, the results of balance test indicated that most variables exhibited equality of means, except for the prices of P_2O_5 and K_2O. The inclusion of dummy variables for crop type and paddy variety further confirmed consistent distribution across the groups, with Chi-square tests showing no significant differences. Overall, apart from the minor deviations in the prices of P_2O_5 and K_2O, the lack of significant differences in the majority of variables supports the validity of the randomization process. This verifies that the observed effects can be attributed to the intervention of LLL implementation rather than pre-existing differences between the two groups.

Local average treatment effects of laser land leveling on water usage

The regression results are presented in Table 5 and Table 6. The models' statistical robustness and explanatory power are further validated by high R-squared values, which indicate that a significant portion of the variability in the volumes of irrigation water and net water use is explained by the independent variables in the regression models. Furthermore, the F-statistics in the two regression models are statistically significant at the 0.000 level, highlighting the overall significance of the models in predicting the effects of LLL implementation on irrigation water volumes for paddy production in the Mekong Delta Region.

Table 5 Local average treatment effects of LLL adoption on the irrigation water volume

Variables	Notation	Coefficient	Robust Std. Err.	t	P>|t|
Constant		9.3546***	0.5297	17.66	0.000
Actual adoption	LLL	-0.2052***	0.0344	-5.96	0.000
Seed price	PSEE	0.0241	0.0449	0.54	0.592
Fertilizer price					
-Phosphorus	PP20	-0.0115	0.0901	-0.13	0.899
-Potassium	PK20	0.0414	0.0704	0.59	0.557
-Nitrogen	PNIT	-0.0968	0.0672	-1.44	0.151
Labor price	PLAB	-0.0583	0.0434	-1.34	0.181
Machine price	PMAC	-0.1240***	0.0461	-2.69	0.008
Pesticide price	PPES	-0.0329	0.0224	-1.47	0.144
Water price	PWAT	-0.5382***	0.0509	-10.57	0.000
Paddy price	PPAD	-0.1774	0.1578	-1.12	0.262
Land surface	STD	0.1031***	0.0343	3.01	0.003
Crop time	CRO	-0.1321***	0.0413	-3.20	0.002
Paddy varieties	VAR	-0.0353	0.0353	-1.00	0.318
Observations: 194			*R-squared = 0.7658*		
F (13, 180) = 48.64			*Prob > F = 0.0000*		

*** p<0.01, ** p<0.05, * p<0.1

In addition to concentrating mainly on the actual adoption of LLL, the two models also encompass other critical variables in compliance with the framework of the input demand function. This enables a more detailed comprehension of the impact of prices and farming conditions on the volumes of irrigation water and net water used for paddy production. For the irrigation water in the first model, the variable of particular interest of actual adoption LLL technology, shows a significant negative effect on irrigation water volume with the coefficient of -0.2052 and p value lower than 0.01 (Table 5). This indicates that the LLL adoption leads to a reduction in irrigation water volume. Other variables such as the prices of water and use of machines also show significant negative effects, highlighting cost-related incentives for reducing irrigation water for paddy production.

The standard deviation of the paddy land surface reflects the variation in field surface and the investment level in the LLL technology, particularly for the treatment group. A lower standard deviation indicates less surface variation, which prevents unnecessary water stagnation in the field. Further analysis demonstrates that the significant variation in land surface positively affects the volume of irrigation water, indicating that within the treatment group, higher LLL investment leads to a greater reduction in irrigation water volume. The crop time variable, which encompasses temporal factors, negatively affects the volume of irrigation water, indicating that the irrigation water volume was higher in the 2022 crop year compared to that in 2021.

Table 6 Local average treatment effects of LLL adoption on the net water use

Variables	Notation	Coefficient	Robust Std. Err.	t	P>|t|
Constant		7.2472***	0.9833	7.37	0.000
Actual adoption	LLL	-0.2864***	0.0660	-4.34	0.000
Seed price	PSEE	0.1750	0.1058	1.65	0.100
Fertilizer price					
-Phosphorus	PP20	0.3209*	0.1918	1.67	0.096
-Potassium	PK20	0.4524***	0.1267	3.57	0.000
-Nitrogen	PNIT	-0.4341***	0.1335	-3.25	0.001
Labor price	PLAB	-0.0822	0.0890	-0.92	0.357
Machine price	PMAC	-0.2822***	0.0887	-3.18	0.002
Pesticide price	PPES	-0.1103***	0.0355	-3.11	0.002
Water price	PWAT	-0.7206***	0.0915	-7.88	0.000
Paddy price	PPAD	-0.0038	0.2774	-0.01	0.989
Land surface	STD	-0.1100	0.0708	-1.55	0.122
Crop time	CRO	0.0093	0.0717	0.13	0.897
Paddy varieties	VAR	0.0787	0.0631	1.25	0.214
Observations: 194			*R-squared = 0.5313*		
F (13, 180) = 16.26			*Prob > F = 0.0000*		

*** p<0.01, ** p<0.05, * p<0.1

Unlike the focus of Table 5, Table 6 examines the impact of LLL adoption on net water use, which is defined as the difference between the volume of water irrigated onto the field and the volume that drains away. This metric captures the dual impacts on both irrigation and drainage volumes. The statistically significant coefficient for LLL in net water use is -0.2864, signifying a negative effect with a slightly larger absolute value compared to that observed in the irrigation water model. As net water use accounts for both irrigation and drainage volumes, this pronounced negative coefficient implies that LLL adoption not only diminishes the volume of irrigation water but also reduces unnecessary water stagnation and enhances water runoff through proactive drainage practices implemented by farmers during paddy cultivation.

The results from both models affirm the efficacy of LLL technology in enhancing water management within paddy production across the Mekong Delta region. Particularly, the net water use model underscores a more expansive influence, elucidating substantial benefits not only in diminishing the quantity of irrigation water utilized but also in reducing water stagnation, thereby optimizing the overall water usage in paddy fields. By establishing a more uniform land surface, the technology facilitates the precise application of water tailored to paddy production and improves drainage effectiveness. These outcomes advocate for the adoption of the LLL technology in the Mekong Delta region, especially in the face of climate change and water scarcity, where water conservation is paramount. The evident impact on both irrigation water and net water use substantiates the value of investing the LLL technology as a strategy for fostering sustainable agricultural practices.

Projection of water savings from the implementation of LLL in the Mekong Delta Region

For a comparative analysis of water use, paddy yield, and water efficiency in paddy production with and without the implementation of LLL technology in the Mekong Delta Region. The LLL implementation significantly reduces the average irrigation water and water use volumes and concurrently, paddy yield for the treatment group increases compared to the control group (Table SI.5 and Fig. 6). The statistical analysis reveals a notable improvement in water efficiency, with the mean values of irrigation water and water use volumes decreasing respectively from 1.27 and 0.59 $m^3\ kg^{-1}$ for the control group to 0.71 and 0.31 $m^3\ kg^{-1}$ for the treatment group, indicating a more efficient use of water in paddy production under the LLL practice. These findings highlight the effectiveness of LLL technology in optimizing water resource management in paddy production and thereby conservating water and supporting sustainable agricultural practices in water-scarce regions like the Mekong Delta.

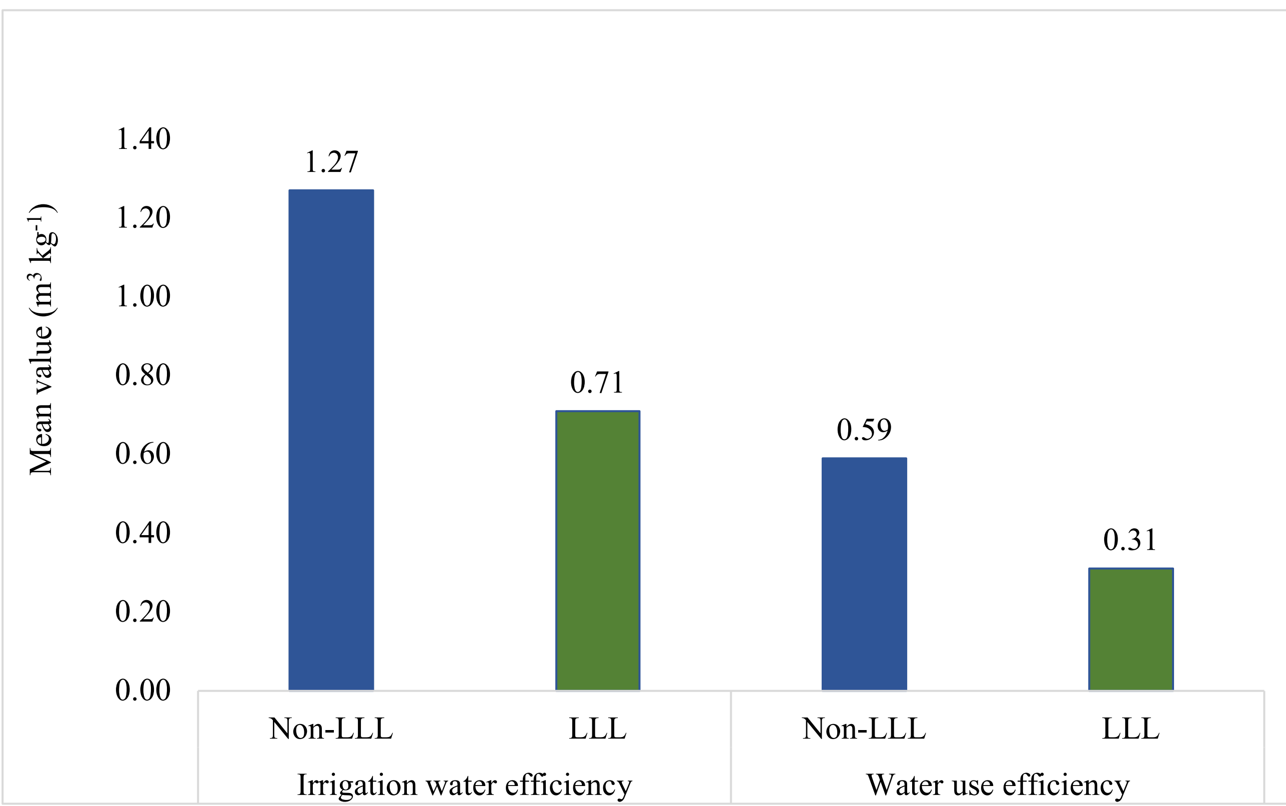


Fig. 6 Water efficiency in paddy production

Table 7 Projected savings of irrigation water and water use from LLL adoption in the Mekong Delta Region

Scenarios on the percentage paddy area applied LLL technology in the MDR (%)	Average irrigation water saved (million m^3 ha^{-1})	Average water use saved (million m^3 ha^{-1})
5	-375.51	-247.05
10	-751.02	-494.09
20	-1,126.53	-988.18
30	-1,877.56	-1,482.27
40	-2,628.58	-1,976.36
50	-3,379.60	-2,470.45

Note: Based values for projection include the mean values of irrigation water and water use in the control group of 9,623.90 m^3 ha^{-1} and 4,536.12 m^3 ha^{-1}, the estimated coefficients of LLL variable of -0.2052 and -0.2864 in the two models, the product of these two estimates is -1,975.03 m^3 ha^{-1} and -1,299.35 m^3 ha^{-1} being as the savings of irrigation water and net water use, respectively. These based values are then applied for the Mekong delta region with the paddy area of 3,802.6 thousand hectares. The scenarios are built on different percentage area applied LLL technology in the MDR.

The analysis of projected water savings from the LLL implementation in the Mekong Delta region reveals substantial potential for water conservation (Table 7). Based on the estimated coefficient of the LLL adoption variable, the mean value of water use in the control group, and the paddy area of the Mekong Delta region, the further analysis in Table 7 explores various scenarios of LLL adoption rates and their corresponding water savings. Specifically, at a 5% adoption rate of LLL technology, the projected irrigation water and water use savings are 375.51 and 247.05 million m^3, respectively. As the adoption rate increases, the water savings grow proportionally, with a 50% adoption rate potentially saving 3,379.60 and 2,470.45 million m^3 for irrigation water and net water use volumes, respectively. These projections highlight the scalability of the LLL technology's benefits and underscore the potential for significant environmental impact if adoption rates can be increased in the coming years.

The lower and upper bounds of estimated coefficient within the 95% confidence intervals provided in the analysis offer insights into the variability and reliability of the projected water savings (Table SI.6). This range suggests that while there is some uncertainty in the exact amount of water savings, the overall trend remains robust across different levels of LLL adoption. With the savings amounting to 20.52% of the total irrigation water and 28.64% of net water use, the technology adoption in the Mekong Delta enhances water efficiency and improves resilience against climate change impacts by ensuring precise water distribution, reducing irrigation needs, and preventing waterlogging, thereby supporting sustainable paddy production. This analysis underscores the importance of promoting and supporting the adoption of the LLL technology to achieve significant environmental benefits in the Mekong Delta Region. Policies should focus on providing financial assistance, ensure the availability of LLL service providers, and organizing the season appropriately to support the effective adoption of this technology.

Conclusions and policy implications

This study examines the impact of LLL adoption on irrigation water use and efficiency in Mekong Delta paddy production. The descriptive analysis underscores the potential for water reuse facilitated by farmers' drainage practices. However, the reliance on experiential methods for technology application in paddy production presents challenges that may impede long-term sustainability. Additionally, the predominance of individual pumping systems for irrigation in most paddy plots indicates a deficiency in cooperative irrigation infrastructure, posing challenges related to water scarcity that farmers are likely to encounter under the pressures of climate change in the Mekong Delta region. The regression analysis indicates that the LLL treatment results in significant savings of 1,975 m^3 ha^{-1} and 1,299.35 m^3 ha^{-1} for irrigation water and net water use in paddy production, respectively, when compared to the control. These savings represent 20.52% and 28.64% of the total irrigation water and net water use, respectively. Consequently, if 5% of the paddy area in the Mekong Delta region adopts the LLL technology, the projected average savings are estimated at 375.51 million m^3 for irrigation water and 247.05 million m^3 for net water use, respectively.

The research findings offer significant insights for agricultural policymakers in the Mekong Delta region, emphasizing the environmental benefits of the LLL technology. Policies should prioritize financial support, the availability of LLL service providers, and the establishment of appropriate seasonal regulations to facilitate the implementation of this technology. The analysis highlights the necessity of promoting and supporting LLL adoption to achieve water savings and conservation in paddy production. It advocates for the technology adoption in response to climate change and water scarcity, suggesting that policymakers use these insights to incentivize LLL adoption among farmers, thereby enhancing sustainable agricultural practices and economic outcomes. Future research should assess the role of social networks, including peer learning models, in facilitating the adoption of sustainable agricultural technologies. It is also crucial to investigate the long-term effects of technologies such as laser land levelling on soil health and water conservation. Furthermore, integrating sustainable technologies with climate-smart practices and examining the role of cooperatives, as well as region-specific challenges, will offer valuable insights for promoting technology adoption and improving climate resilience across varied agricultural systems.

Acknowledgements

This research is funded by the University of Economics Ho Chi Minh City, Vietnam (UEH). The authors gratefully acknowledge the provision of data from Project MS-546, funded by the Swedish International Development Cooperation Agency (SIDA) through the Environment for Development (EfD) Initiative in Vietnam.

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