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Impact of large-scale irrigation on agricultural yields and farm income in Burkina Faso: evidence from the Sourou Valley

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Abstract

This study assesses the impact of large-scale irrigation on farm productivity and income in northwestern Burkina Faso. Using household survey data from 1,080 farmers in the communes of Di (irrigated) and Kassoum (rainfed), we estimate an endogenous switching regression model to address selection bias. Results show that irrigation significantly increases both physical yields and net income per hectare. On average, irrigated farms earn 762,435 CFA francs more per hectare – a 177% increase compared to non-irrigated farms. Irrigation also boosts physical yields across crop categories, especially fruits and vegetables, with gains exceeding 5 tons per hectare. Robustness checks using propensity score matching confirm the consistency of results. Access to credit and agricultural cooperative membership significantly influence irrigation adoption. These findings underscore the transformative potential of irrigation for improving agricultural performance and farmer livelihoods in the Sahel, and provide evidence to support public investment in irrigation infrastructure.

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1. Introduction

The 2008 food crisis severely impacted Africa, exposing significant dysfunctions in the agricultural sector. This is concerning as global food demand is expected to increase by 60% by 2050 (Alexandratos & Bruinsma, 2012). Prices of staple goods surged by 93% to 157% (FAO, 2022), significantly affecting purchasing power in Africa, where poverty is widespread, particularly in sub-Saharan Africa, where 60% of the population lives on less than $2.15 per day (World Bank, 2022).

In response to the crisis, measures such as tax exemptions for certain agricultural products and subsidies were introduced. In sub-Saharan Africa, where two-thirds of the workforce is employed in agriculture, low agricultural income, caused by extensive, low-profit farming, limits economic growth (Goyal & Nash, 2020). Improving agricultural yields is crucial not only for food security but also for economic growth and poverty reduction by transitioning the workforce to more productive sectors (Gollin et al., 2014).

Significant investments in irrigation since the 1970s have boosted productivity, contributing to about 92% of global food production (Hasnip et al., 2001). Sub-Saharan African countries have integrated irrigation into their agricultural policies, but large agricultural projects are often criticized for low profitability.

Burkina Faso, affected by recurrent climatic events, adopted irrigation to counter climate uncertainties. Despite 63% of the active population being employed in agriculture, the sector's contribution to GDP has been limited. Over the past five years, agriculture has contributed only 32% to GDP, while rural areas represent 91.8% of the national poverty rate, due to low income levels in a predominantly subsistence farming system.

The country has invested in hydro-agricultural projects and lowland irrigation to enhance agricultural yields and economic growth, crucial for poverty alleviation. Key projects, such as the Sourou Valley Agropole, are part of this initiative. These efforts aim to demonstrate the profitability of irrigation over rain-fed agriculture given the significant investments made.

Our research aims to analyze the impact of large-scale irrigated areas, particularly in Di, a component of the Sourou Agropole, on the livelihoods of beneficiaries. Specifically, we assess the impact of irrigation on the per-hectare incomes of farmers. Our findings will guide future decisions on the relevance of large-scale irrigation projects as a driver of agricultural and economic growth.

2. Brief review of the literature

Irrigation is closely linked to improvements in agricultural productivity, household incomes, and employment opportunities. Research by Fikirie and Mulualem (2017) shows that irrigated crop yields are 2.3 times higher than those from rainfed agriculture, helping farmers shift from subsistence farming to market-oriented production. In Ghana, Akudugu et al. (2021) found that irrigation increased annual farm incomes, averaging USD 713.29 compared to USD 493.91 in non-irrigated areas. Irrigation also extended employment from 13 to 20 weeks, highlighting its positive impact on household consumption and food security.

In South Africa, the Revitalization of Irrigation Schemes program resulted in an annual gross margin of ZAR 2,652,067, benefiting farmers by enhancing incomes, asset ownership, and food access (Maepa et al., 2014). Zimbabwe's Panganai project showed similar results, creating jobs and boosting incomes through irrigation (Chazovachii, 2012).

Studies in Ethiopia confirm irrigation's role in boosting the national economy. Hagosa et al. (2010) found that irrigated agriculture generated an average income of USD 323 per hectare, compared to USD 147 for rainfed farming. The study highlighted irrigation's growing contribution to agricultural GDP, stressing its role in economic development.

In Asia, Hussain and Wijerathna (2004) emphasized irrigation's role in reducing poverty by increasing productivity, creating jobs, and allowing households to diversify into higher-value crops. Similar trends were observed in China, where irrigation improved crop yields by 70.9% and farm incomes by 93% (Huang et al., 2006).

Our study addresses a gap in understanding the economic impact of large-scale irrigation in Burkina Faso, focusing on the Sourou Agropole. Using an endogenous switching regression model, we show that irrigation significantly increases net agricultural income per hectare, demonstrating its potential to transform rural livelihoods and contribute to food security in the Sahel. This research provides valuable insights for policymakers aiming to enhance food security and economic resilience through irrigation.

3. Study area and data collection

3.1. Study area

Our study is conducted in the commune of Di, located in the Sourou province in northwestern Burkina Faso. This rural area spans 306.66 km² and is home to 38,087 inhabitants distributed across 17 administrative villages (INSD, 2022). Di is situated in the Sourou Valley, the country's largest wetland, irrigated by the Sourou River, a tributary of the Mouhoun River that flows along the border with Mali (Bethemont & Faggi, 2003).

The region is characterized by a Sudano–Sahelian climate, with temperatures ranging from 21°C to 45°C and annual rainfall fluctuating between 511.8 mm and 701.3 mm (PCD, 2013a). The rainy season lasts approximately 4.5 months, from mid-May to September, while the dry season spans the remaining 7.5 months. Given the limited and irregular rainfall, irrigated agriculture has become essential for sustaining agricultural production and ensuring household food security.

The Sourou River, around which the irrigation perimeters have been developed, has a storage capacity of approximately 600 million cubic meters (Drabo, 2021), supporting the expansion of modern irrigation systems. The local soils are mainly raw mineral and brunified types, enriched with iron and manganese sesquioxides, as well as hydromorphic soils, offering relatively favorable conditions for crop cultivation (PCD, 2013a).

Irrigation in Di has a long history, beginning with pilot programs in 1952. A major institutional shift occurred in 1987 with the establishment of the Authority for the Development of the Sourou Valley (AMVS), which now oversees large-scale irrigation infrastructure. By 2021, over 9,000 hectares of land were irrigated, benefiting more than 7,000 farmers (AMVS, 2022). The area is equipped with gravity-fed and sprinkler irrigation systems, supported by a dense hydrographic network. These systems make year-round irrigation possible. However, water distribution is not always uniform: plots located downstream in the canal system may experience lower pressure or delivery delays, particularly during peak demand periods.

To serve as a control zone, we also collected data from the commune of Kassoum, a neighboring area with similar agroecological and socioeconomic conditions. As of 2019, Kassoum had 25,694 inhabitants (INSD, 2022). Its climate blends sub-Sahelian and northern Sudanian features, with annual rainfall between 650 and 800 mm and temperatures ranging from 23.3°C to 35.9°C. The soils are diverse: raw mineral soils (7.32%), hydromorphic soils (39.50%), weakly developed soils (50.55%), and vertisols (2.63%) (PCD, 2013b). Agriculture is the main livelihood activity, centered on maize, sorghum, and rice, with limited livestock farming.

Seasonal variation in water availability plays a key role in determining production dynamics. During the dry season, when rainfall is absent, irrigation becomes the primary source of water, enabling farmers to cultivate high-value crops such as fruits and vegetables, which would otherwise not be viable. This seasonal access to irrigation has a significant impact on cropping calendars, yields, and household incomes. The year-round availability of water through irrigation enhances income diversification, reduces climate-related risks, and improves the resilience of farming households in the region.

3.2. Data collection

For the collection of primary data, a questionnaire was developed and validated by the national statistical system. The same questionnaire was administered in both zones. In the irrigated zone, the survey included 465 producer households in the developed perimeters of the villages of Di, Débé, and Niassan. In the control zone, the survey included 615 producer households engaged in rain-fed agriculture in the villages of Kassoum, Tiao, and Mara. These three villages are located 17 km, 20 km, and 23 km from the irrigated perimeter, respectively, to minimize any contagion effects from irrigation. The selection of control villages considered similarities in socioeconomic, geomorphological, and climatic characteristics, as well as the presence of basic social services such as education, health, potable water, and access to commercial markets. The survey was conducted simultaneously in both zones from November 2022 to July 2023.

4. Methods

4.1. Empirical model

The endogenous switching regression (ESR) model addresses self-selection bias in estimating the impacts of irrigation adoption. The ESR model is widely used in empirical studies (Di Falco et al., 2011; Ma & Abdulai, 2016). Unlike propensity score matching (PSM), which struggles with unobserved variables, the ESR model handles both self-selection bias and unobserved factors by using instrumental variables and counterfactual analysis.

The ESR model involves two stages: a Probit regression to predict irrigation adoption, followed by a second-stage regression to estimate outcomes for both adopters and non-adopters. To avoid inconsistent standard errors due to heteroskedastic residuals, the full information maximum likelihood estimator is used, simultaneously estimating both stages (Lokshin & Sajaia, 2004).

The conceptual framework used in this study assumes that farmers decide whether to adopt irrigation based on their agricultural activities. We presume that farmers are risk-neutral and consider the expected yields (D_{ir}^*) from using irrigation against the expected yields (D_{nir}^*) from not using it. The difference in expected yields between these two options is denoted as D_i^*, with $D_i^* = D_{ir}^* - D_{nir}^*$. If $D_i^* > 0$, farmers opt for irrigation in their agricultural practices. Since D_i^* is not directly observable, it can be expressed through observable variables in the latent variable model as follows:

$$D_i^* = Z_i\alpha + \mu_i \; with \; D_i = \begin{cases} 1 \; if \; D_i^* > 0 \\ 0 \; otherwise \end{cases} \tag{1}$$

where D_i is a binary variable that equals one if households *i* uses irrigation and 0 if not. $Z_i$is a vector containing factors that affect the decision to adopt irrigation, such as farm and household characteristics. α is a vector of unknown parameters to be estimated, and μ_i is an error term assumed to be normally distributed with a mean of zero. Accordingly, two separate outcome equations are specified for the irrigation and non-irrigation:

Regime 1 (irrigation)

$$Y_{ii} = X_i\beta_{ii} + \varepsilon_{ii} \; if \; D_i = 1 \tag{2a}$$

Regime 2 (non-irrigation)

$$Y_{ni} = X_i\beta_{ni} + \varepsilon_{ni} \; if \; D_i = 0 \tag{2b}$$

where, Y_{ii} and Y_{ni} represent yields outcome for irrigation and non-irritation, respectively. X_i is a vector of exogenous variables that may influence these outcomes, while ε_{ii} and ε_{ni} are random disturbance terms associated with the outcome variables. The variables Z_i in the selection equation (1) can overlap with the variables X_i in the outcome equations (2a) and (2b). In this analysis, the selection equation (1) is estimated using all explanatory variables specified in the outcome equations (2a) and (2b) plus one instrumental variable. The valid instrumental variable should influence the decision to adopt irrigation but not affect the outcome.

The three error terms μ_i, ε_{ii}, and ε_{ni} in equations (1), (2a), and (2b) are assumed to follow a trivariate normal distribution with a mean of zero and a covariance matrix (Lokshin & Sajaia, 2004):

$$\Omega = \begin{bmatrix} \sigma_\eta^2 & \sigma_{i\eta} & \sigma_{n\eta} \\ \sigma_{i\eta} & \sigma_i^2 & . \\ \sigma_{n\eta} & . & \sigma_n^2 \end{bmatrix}$$

where, σ_η^2 represents the variance of the error term in the selection equation (1), while σ_i^2 and σ_n^2 denote the variances of the error terms in the outcome equations (2a) and (2b). The covariance between μ_i and ε_{ii} is given by $\sigma_{i\eta}$, and the covariance between μ_i and ε_{ii} is represented by $\sigma_{n\eta}$. Note that Y_{ii} and Y_{ni} are not observed simultaneously, meaning the covariance between ε_{ii} and ε_{ni} is undefined and thus indicated as dots in the covariance matrix (Lokshin & Sajaia, 2004; Akpalu & Normanyo, 2014). Assuming that the error term in the selection equation (1) is correlated with the error terms in the outcome equations (2a) and (2b), the expected values of ε_{ii} and ε_{ni}, given the sample selection, are non-zero and can be defined as follows:

$$E[\varepsilon_{ii}|D_i = 1] = \sigma_{i\eta}\frac{\oint(Z_i\alpha)}{\phi(Z_i\alpha)} = \sigma_{i\eta}\lambda_{ii} \quad (3a)$$

$$E[\varepsilon_{ni}|D_i = 0] = \sigma_{n\eta}\frac{\oint(Z_i\alpha)}{1-\phi(Z_i\alpha)} = \sigma_{n\eta}\lambda_{ni} \quad (3b)$$

where, $\oint(\cdot)$ represents the standard normal probability density function, and $\phi(\cdot)$ is the normal cumulative distribution function. The term $\lambda_{ii} = \frac{\oint(Z_i\alpha)}{\phi(Z_i\alpha)}$ and $\lambda_{ni} = \frac{\oint(Z_i\alpha)}{1-\phi(Z_i\alpha)}$. If the estimated covariances $\widehat{\sigma_{i\eta}}$ and $\widehat{\sigma_{n\eta}}$ are statistically significant, it indicates a correlation between the adoption of irrigation and the outcomes. This suggests evidence of endogenous switching, leading to the rejection of the null hypothesis, which assumes no sample selectivity bias is present.

The ESR model specifically tackles the issue of selectivity bias that arises from unobserved factors by treating it as a missing variable problem (Ma & Abdulai, 2016). Once the selection equation has been estimated, the inverse Mills ratios (λ_{ii} and λ_{ni}) and covariance terms ($\sigma_{i\eta}$ and $\sigma_{n\eta}$) are computed and incorporated back into equations (2a) and (2b). In this context, the inverse Mills ratios (λ_{ii} and λ_{ni}) are used to control for selectivity bias stemming from unobservable factors.

According to the method outlined by Lokshin and Sajaia (2004), the coefficients from the ESR model can be utilized to estimate the average treatment effect on the treated (ATT). The observed and unobserved counterfactual outcomes for irrigation are detailed as follows:

$$E[Y_{ii}|D_i = 1] = X_i\beta_{ii} + \sigma_{i\eta}\lambda_{ii} \quad (4a)$$

$$E[Y_{ni}|D_i = 0] = X_i\beta_{ni} + \sigma_{n\eta}\lambda_{ni} \quad (4b)$$

$$E[Y_{ni}|D_i = 1] = X_i\beta_{ni} + \sigma_{n\eta}\lambda_{ii} \quad (4c)$$

$$E[Y_{ii}|D_i = 0] = X_i\beta_{ii} + \sigma_{i\eta}\lambda_{ni} \quad (4d)$$

Equations (4a) and (4b) present the expected outcomes of irrigation adoption and non-adoption, respectively. Equation (4c) shows the expected outcome for non-adopters if they had adopted, thus constituting the counterfactual outcome for adopters. Equation (4d) illustrates the expected outcome for adopters if they had not adopted, also serving as the counterfactual outcome for non-adopters. By applying the methodologies of Heckman et al. (2001) and Di Falco et al. (2011), the expected outcomes from equations (4a) and (4c) are used to derive unbiased treatment effects on the treated (ATT). This is the difference between the earnings of adopters due to adoption and the earnings they would have realized without adoption.

$$ATT = E[Y_{ii}|D_i = 1] - E[Y_{ni}|D_i = 1] = X_i(\beta_{ii} - \beta_{ni}) + \lambda_{ii}(\sigma_{i\eta} - \sigma_{n\eta}) \quad (5a)$$

ATT measures the effects of irrigation on the farm incomes of households that actually used irrigation. Similarly, the average treatment effect on the untreated (ATU) for households not using irrigation is reflected by the difference between the expected outcomes in equations (4d) and (4b). This illustrates the difference between the potential earnings of non-adopters if they had adopted irrigation and their actual earnings by not adopting it.

$$ATU = E[Y_{ii}|D_i = 0] - E[Y_{ni}|D_i = 0] = X_i(\beta_{ii} - \beta_{ni}) + \lambda_{ni}(\sigma_{i\eta} - \sigma_{n\eta}) \quad (5b)$$

Finally, the average treatment effect (ATE) measures the average effect of the treatment for the entire population, regardless of whether they used irrigation or not. The ATE can be considered a weighted average of the ATT and ATU, considering the proportion of units in each regime. The ATE is expressed as:

$$ATE = P(I = 1) \cdot ATT + P(I = 0) \cdot ATU \quad (5c)$$

4.2. Variables and descriptive statistics

Table 1 shows that net income per hectare, measured in CFA francs, is the primary outcome variable, while irrigation is the treatment variable indicating whether a household practices irrigation.

To address potential endogeneity in the irrigation adoption decision, we use agricultural cooperative membership as an instrumental variable (IV) in the selection equation of the ESR model. This instrument satisfies the two main conditions for validity: relevance and exogeneity. First, relevance is supported by empirical evidence and the local institutional context: agricultural cooperatives in the study area play a key role in disseminating agricultural technologies, facilitating access to credit, organizing collective purchases of equipment, and providing technical training. These mechanisms significantly influence the likelihood of adopting irrigation. Second, for exogeneity, we argue that cooperative membership affects net income per hectare only indirectly – primarily through its effect on irrigation adoption. While members may benefit from better access to information or financial services, these advantages do not systematically translate into higher income unless they enable the use of productivity-enhancing technologies such as irrigation. This assumption is further supported by a falsification test (see Table 3), which confirms that cooperative membership has a significant impact on irrigation adoption but no direct effect on income outcomes.. Control variables include household head gender, marital status, education, access to credit, plow usage, fertilizer application, agricultural experience, and household size. Table 2 reveals significantly higher net income for households practicing irrigation. Additionally, irrigating households tend to have male heads, higher education, more credit access, and agricultural experience, highlighting potential self-selection bias addressed by the ESR model.

Table 1

Definition of variables and descriptive statistics.

Variable	Variable definition	Units	Obs.	Mean	Std. Dev.	Min	Max
incomeperhect	Net earnings per hectare	CFA/ha	1080	588 237	437 623	155 714	2 700 000
irrigation	= 1 if the observation i practices irrigation, = 0 otherwise	n.a.	1080	0.43	n.a.	0	1
gender	= 1 if the household head is a man, =0 otherwise	n.a.	1080	0.93	n.a.	0	1
matstat	= 1 if the household head is being in a marital or cohabiting relationship, = 0 otherwise	n.a.	1080	0.76	n.a.	0	1
educ	The educated years of the household head	years	1080	2.55	3.64	0	12
credit	= 1 if the household has access to credit, = 0 otherwise	n.a.	1080	0.41	n.a.	0	1
plow	= 1 if the household uses plow in the farm, = 0 otherwise	n.a.	1080	0.71	n.a.	0	1
fertilizer	= 1 if the household applies mineral fertilizer on the farm, = 0 otherwise	n.a.	1080	0.97	n.a.	0	1
expagr	The number of years the household head has been practicing agriculture.	years	1080	28.15	17.58	2	80
housesiz	The number of family members	heads	1080	5.79	2.35	2	22
agrcoopmemb	Instrumental variable. 1 if the household head is a member of an agricultural cooperative, = 0 otherwise.	n.a.	1080	0.43	n.a.	0	1

Source: survey data.

Table 2

The differences in all the variables between irrigation products and nonirrigation.

Variable	Irrigation (n=465)		Non-irrigation (n=615)		Diff in mean
	Mean	Std. Dev.	Mean	Std. Dev.	
incomeperhect	988048	377054	285941	128549	702 107***
gender	0.963	0.188	0.904	0.295	0.06***
matstat	0.776	0.417	0.748	0.435	0.03
educ	2.787	3.795	2.371	3.517	0.42*
credit	0.935	0.246	0.016	0.127	0.92***
plow	0.723	0.448	0.701	0.458	0.02
fertilizer	0.97	0.171	0.969	0.173	0.00
expagr	29.568	16.388	27.088	18.383	2.48**
housesiz	5.806	2.106	5.787	2.519	0.02
agrcoopmemb	0.968	0.177	0.034	0.182	0.93***

Note: *, **, and *** denote $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

Source: survey data

5. Results
5.1. Instrumental variable

In this study, agricultural cooperative membership (agrcoopmemb) is used as an instrumental variable to address endogeneity between irrigation and net income per hectare. A falsification test confirms its validity, following the methodology of (Di Falco et al., 2011) and Shiferaw et al. (2014). Agrcoopmemb significantly increases the likelihood of irrigation adoption but does not directly impact net income per hectare for non-irrigating households. This confirms agrcoopmemb as a valid instrumental variable, influencing irrigation adoption without affecting income outcomes directly.

Table 3
The results of the falsification test on the instrumental variable.

	Irrigation	Log(incomeperhect)
agrcoopmemb	**2.413*****	**0.106**
	(10.59)	(1.366)
gender	0.707	-0.307***
	(1.372)	(-5.216)
matstat	-0.128	0.103***
	(-0.471)	(2.624)
educ	-0.0923***	0.00445
	(-3.151)	(1.057)
credit	2.475***	-0.0580
	(9.360)	(-0.517)
plow	-0.262	-0.00769
	(-1.174)	(-0.251)
fertilizer	-0.186	0.237***
	(-0.351)	(3.068)
expagr	-0.00993	-0.00215**
	(-1.380)	(-2.353)
housesiz	-0.0946**	0.0181***
	(-2.055)	(3.164)
Constant	-1.471**	12.41***
	(-2.151)	(141.3)
Observations	1080	615
R-squared		0.116

Note: t statistics based on robust standard errors in parentheses. *, **, and *** denote p<0.10, p<0.05, and p<0.01, respectively.
Source: authors' calculations

5.2. Impact of irrigation on farm income

The ESR model analyzes factors influencing households' decisions to adopt irrigation and its impact on net income per hectare (incomeperhect). Using the full information maximum likelihood estimator, both selection and outcome equations are estimated jointly. The Wald test confirms their correlation, validating the joint estimation approach. The significant ρ_{ii} coefficient suggests that households practicing irrigation have higher net incomes per hectare than randomly selected households, while the ρ_{ni} coefficient is not significant for non-irrigators.

Several factors influence irrigation adoption (Table A1 in appendices). Male-headed households are more likely to adopt irrigation due to greater access to resources, while education negatively affects adoption, possibly due to diversifying into non-agricultural activities. Access to credit positively influences adoption, highlighting the need for financial support. Fertilizer use is negatively associated with adoption, suggesting a substitution effect. Larger households are less likely to adopt irrigation, possibly due to resource constraints, while membership in agricultural cooperatives increases the likelihood of adoption.

For irrigating households, marital status and agricultural experience negatively impact income, while among non-irrigators, male-headed households see lower income, and education positively impacts income. Fertilizer use boosts income for non-irrigating households, emphasizing the importance of agricultural intensification.

Agricultural experience slightly reduces income, while larger households benefit from additional labor, positively affecting income.

The ATT estimates in Table A2 (in appendices) show the impact of irrigation adoption on net income per hectare, accounting for selection bias. Adopting irrigation significantly increases net income by 762,435 CFA francs, or 177%. For nonirrigated farms (ATU), adopting irrigation would have increased their net income by 637,874 CFA francs, a 120% rise. The ATE represents the overall effect of irrigation on all farms, with an average increase of 691,504 CFA francs per hectare. This translates to a 144% increase in net income per hectare across the population due to irrigation. These results underscore the significant economic benefits of irrigation adoption in enhancing farm productivity and incomes.

5.3. Impact of irrigation on physical yields by product category

Given the diversity of crops cultivated by farmers in the study area, where multiple crops are often grown on the same plot, it was not feasible to calculate yields for individual crop types. Instead, the analysis focused on physical yields per hectare by broad product categories, namely cereals, oilseeds and protein crops, and fruits and vegetables. During data collection, enumerators gathered information on net income by category. These income values were then converted into estimated yields (in tons per hectare) using the average farm-gate prices declared by producers.

The results in table 4 show that irrigation generates substantial gains in physical productivity across all product categories. For cereals, irrigating households obtain an additional 2.31 tons per hectare compared to what they would have produced under rainfed conditions. This confirms the capacity of irrigation to enhance productivity even in staple crop systems.

In the case of oilseeds and protein crops, irrigators benefit from a 0.89-ton increase per hectare, underscoring the potential of irrigation to intensify production in traditionally lower-yielding systems.

The impact is even more pronounced for fruits and vegetables, where irrigation results in an average gain of 5.55 tons per hectare relative to the counterfactual scenario without irrigation. This substantial increase reflects the high responsiveness of these high-value crops to water availability and controlled growing conditions.

The ATU estimates suggest that non-irrigating farmers could also benefit greatly from adopting irrigation. If they had access to irrigation, their yields could increase by 1.93 tons per hectare for cereals, 0.74 tons for oilseeds and protein crops, and 4.64 tons for fruits and vegetables. These figures highlight the productivity gap between irrigators and non-irrigators and point to a significant untapped potential for yield improvement.

Lastly, the ATE values – representing the average yield gain across the entire population - confirm the overall benefit of irrigation: 2.09 tons per hectare for cereals, 0.81 tons for oilseeds and protein crops, and 5.03 tons for fruits and vegetable

Table 4. Impact of Irrigation on Yields (tons per hectare) by Product Category – ESR Model

Product categories	ATT	ATU	ATE
Cereals	2.309 (0.000)	1.932 (0.000)	2.094 (0.000)
Oilseeds and protein crops	0.890 (0.000)	0.744 (0.000)	0.807 (0.000)
Fruits and vegetables	5.545 (0.000)	4.639 (0.000)	5.029 (0.000)

Note: *p-values are reported in parentheses.*

5.4. Robustness check

To assess the robustness of the ESR model results, Table 5 presents findings from propensity score matching (PSM). PSM compares treated and untreated units with similar observable characteristics, simulating a randomized controlled trial. Several matching methods were used: nearest-neighbor matching, radius matching, local linear regression matching, stratification matching, and kernel matching.

Nearest-neighbor matching pairs treated units with untreated ones based on covariate proximity. In this study, matching was done using one, two, and three nearest neighbors. Radius matching improves upon this by limiting matches to a predefined distance. We applied radii of 0.01, 0.05, and 0.1. Local linear regression matching adjusts covariate differences through regression models, while stratification matching divides the sample into homogeneous strata based on propensity scores. Kernel matching uses a weighted average of all untreated units, assigning higher weights to closer matches.

Depending on the estimator used, the number of observations in the treatment group ranged from 388 to 465, and the control group from 579 to 615. PSM results show that irrigation adoption increases income per hectare by 661,000 to 717,000 CFA francs, consistent with the ESR model's findings. While PSM only accounts for observable factors and may produce biased estimates, the ESR model remains more reliable for this analysis.

Table 5
The overall effects of irrigation on net incomes per hectare based on PSM approach (In thousands of CFA francs).

		Obs. Treated	Obs. Controls	ATT	500 bootstrapped t-stats
Nearest-neighbor matching	n=1	402	615	661***	16.12
	n=2	402	615	664***	17.27
	n=3	402	615	670***	18.44
Radius matching	r=0.01	388	615	668***	12.87
	r=0.05	402	615	679***	15.30
	r=0.10	402	615	681***	16.31
Local linear regression matching		465	579	717***	22.56
Stratification matching		465	579	693***	21.79
Kernel matching		402	615	678***	15.15

Note: *, **, and *** indicate the significance level of 10%, 5%, and 1%, respectively. For stratification matching, the number of strata is six and the level of significance is 0.01.

6. Conclusion and Policy Implications

Our study highlights the significant impact of irrigation on farmers' incomes in the commune of Di. Using an endogenous switching regression (ESR) model, we found that irrigation increased yields per hectare by an average of 762,435 FCFA. Both the average treatment effect on the treated (ATT) and untreated (ATU) showed substantial yield increases. Access to credit and membership in agricultural cooperatives were key factors in irrigation adoption and maximizing benefits. Supporting the development of cooperatives, improving access to agricultural credit, and providing training on effective irrigation practices are essential for enhancing productivity and improving farmers' livelihoods in rural areas.

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APPENDICES

Table A1

The determinants of adopting irrigation and its impacts on incomes per hectare.

	Selection equation		Outcome equations (log(incomeperhect))			
			Irrigation		Non-irrigation	
	Coef.	Robust std. err.	Coefficient	Robust std. err.	Coef.	Robust std. err.
gender	0.679**	0.270	0.023	0.121	-0.330***	0.070
matstat	-0.213	0.183	-0.171***	0.052	0.107***	0.039
educ	-0.063***	0.019	0.006	0.005	0.008*	0.004
credit	2.544***	0.217	0.037	0.117	-0.570***	0.082
plow	-0.174	0.134	-0.064	0.050	0.003	0.030
fertilizer	-0.667***	0.181	-0.142	0.120	0.233***	0.041
expagr	0.002	0.004	-0.005***	0.002	-0.002*	0.001
housesiz	-0.069**	0.029	-0.011	0.012	0.020***	0.006
agrcoopmemb	1.462***	0.291				
_cons	-0.890***	0.239	14.182***	0.179	12.380***	0.065
σ_i			0.325***	0.014		
σ_{ni}					0.369***	0.015
ρ_{ii}			-0.975***	0.017		
ρ_{ni}					0.066	0.123
Wald test of indep. eqns.	36.79***					
Log likelihood	-439.8727					
Obs.	1080		1080		1080	

Note: *, **, and *** denote p < 0.10, p < 0.05, and p < 0.01, respectively.

Source: authors' calculations.

Table A2

The overall effects of irrigation on net incomes per hectare based on ESR model.

	Percentage variation		Income per hectare in CFA francs	
	Estimations	Robust t-student	Estimations	Robust t-student
ATT	177***	132.35	762435***	130.88
ATU	120***	185.20	637874***	120.43
ATE	144***	134.86	691504***	159.06

Notes: *, **, and *** denote p < 0.10, p < 0.05, and p < 0.01, respectively. Given that the dependent variables in the ESR outcome equations are the logarithms of net income per hectare, the mean value of the outcome is obtained by raising e (approximately 2.718) to the power of the estimated parameter.

Source: authors' calculations.