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Amy Faye and Joachim von Braun

Small-Scale Irrigation in the Sahel: Adoption Trends, Profitability, and Challenges

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Zentrum für Entwicklungsforschung (ZEF)
Center for Development Research
Genscherallee 3
D – 53113 Bonn
Germany
Phone: +49-228-73-1861
Fax: +49-228-73-1869
E-Mail: zef@uni-bonn.de
www.zef.de

The authors:
Amy Faye, Center for Development Research, University of Bonn. Contact: afaye@uni-bonn.de
Joachim von Braun, Center for Development Research, University of Bonn. Contact: jvonbraun@uni-bonn.de

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Abstract

This paper analyzes the current uptake of small-scale irrigation (SSI[1]), its profitability, and the constraints to its broader adoption in the Sahel using literature and survey data from Burkina Faso, Mali, Niger, and Senegal. Unlike most of the literature on irrigation in Sub-Saharan Africa (SSA), this analysis distinguishes unambiguously between farmer-led SSI (FSSI) and non-farmer-led SSI (NFSSI) and analyzes labour profitability of SSI. Inverse probability weighing techniques are used to balance covariates between SSIs and non-SSIs and between FSSIs and non-FSSIs.

The results show very low SSI adoption rates in the Sahel region. With the highest rates, Mali outperforms its neighbours, despite its political instability. However, FSSI is more common than NFSSI in Niger and Burkina Faso and less common in Mali and Senegal. Profitability analysis at the plot level shows that SSI is a more profitable land use activity compared to rainfed cropping. However, the two approaches complement each other as SSI mainly occurs during the dry season in the Sahel. On the other hand, FSSI is more profitable than NFSSI except in Mali where NFSSI has historically been a pathway to irrigation development through public irrigation schemes aiming for rice cultivation. Yet, FSSI generally has higher variable costs which could be reduced by promoting solar-powered technologies that could lead to irrigation expansion, especially for individual FSSI, provided that financial mechanisms are developed to enable the required initial investments. Results further show that for SSIs, irrigated high value crops such as vegetables are more profitable and require less land than the traditionally promoted rice in these Sahelian countries. Finally, the comparison of SSIs and non-SSIs and of FSSIs and NFSSIs shows that investments in irrigation development and adoption should account for the specificities of SSIs compared to non-irrigators and larger scale irrigators as well as the heterogeneity of SSIs that can be farmer-led or not.

Keywords: Sahel, Irrigation, Small-scale irrigation, Farmer-led irrigation, Irrigation technology, Profitability, labour productivity

JEL Codes: D13, Q12, Q15, Q25, Q42, Q55

[1] For ease of writing, SSI (resp. FSSI) refers to small-scale irrigation (resp. farmer-led small-scale irrigation) or small-scale irrigators (resp. farmer-led small-scale irrigators). Where it refers to the former, we simply write SSI (resp. FSSI), while for the latter, we use SSIs (resp. FSSIs).

1. Introduction

Small-scale irrigation expansion in Africa has been listed among the low-cost options with a large potential to reduce global hunger (Chichaibelu et al., 2021). In Sub-Saharan Africa (SSA), agriculture is mainly rainfed, despite a demonstrated potential for developing irrigation (Xie et al., 2014). In politically fragile countries like many Sahelian countries, irrigation might be a promising way to enhance the resilience of vulnerable rural communities that evolve in semi-arid to arid environments characterized by low levels of annual rainfalls.

In the Sahel, irrigation has been promoted through different pathways, including large and small-scale irrigation schemes and private individual initiatives (Barbier et al., 2011; Aarnoudse et al., 2018; Durga et al., 2023). However, irrigation is still limited in this region (van der Wijngaart et al., 2019) compared to South Asia (Haile et al., 2022). Recently, international and local attention has refocused on investing in irrigation in SSA, partly due to the food and energy price crises, climate change, and variability (Haile et al., 2022; McCarthy et al., 2023). However, due to the failure of numerous past initiatives (Higginbottom et al., 2021; Higginbottom et al; 2022), it is critical to investigate the most effective pathways to develop irrigation for enhanced productivity, food security, and poverty reduction in rural areas. As part of that objective, "Farmer-led irrigation" is more and more promoted by donors, including the World Bank, the International Water Management Institute (IWMI), and the Alliance for a Green Revolution in Africa (AGRA) to expand irrigation in SSA (Izzi et al., 2021).

This paper scrutinizes that objective by analyzing the current uptake of small-scale irrigation (SSI), its profitability, and the constraints to its wider adoption in the Sahel using the literature and recent nationwide survey data spanning four countries: Burkina Faso, Mali, Niger, and Senegal. This paper focuses particularly on farmer-led SSI (FSSI), as compared to non-farmer-led SSI (NFSSI). As noted up front, the two different institutional arrangements – FSSI and NFSSI – are not straightforward choices for farmers, as appropriate choices can vary depending on credit markets, water and land related property rights, and public policies on finance, extension, and R&D.

The empirical literature on irrigation in Africa has focused on the performance of irrigation schemes (You et al., 2011; Borgia et al., 2013; Sakurai, 2023) that provide key insights on why there is an untapped irrigation potential in SSA and key factors to consider for SSI expansion. Additionally, literature on irrigation technologies is abundant (Dittoh et al., 2010; Xie et al., 2014; Xie et al., 2021; Tadesse et al., 2024a,b) and shows a low uptake of mechanized and solar-powered technologies that can help expand irrigated areas. However, a critical look at this literature and how it can be leveraged to expand SSI in SSA is still lacking. Papers on SSI adoption and impacts inform on the drivers of adoption (Haile et al., 2022; Olayide et al., 2022; Assefa et al., 2022). However, they do not systematically distinguish between FSSI and NFSSI, which is important (Durga et al., 2023; Sakurai, 2023). Instead, irrigation is frequently compared to no irrigation, thereby hiding potential heterogeneities within the group of irrigation adopters, which can lead to inappropriate policy measures. Osewe et al (2020) assessed the drivers and impact of farmer-led irrigation in Tanzania. However, they compared adopters of farmer-led irrigation to non-adopters, which might include both non-farmer-led irrigators and non-irrigators.[2] Furthermore, ex-post analysis of the effects of irrigation shed light on household welfare effects (e.g., food consumption, income, and nutrition) or on-farm performance (e.g., gross margin and land productivity), but often ignores labour productivity. Additionally, there is often an absence of clear accounting for the differences between FSSI and NFSSI (Burney and Naylor, 2012; Nkonya et al, 2022; Kafle and Balasubramanya, 2022; Dillon et al., 2011; Assefa et al., 2022).

This research fills these identified gaps by reviewing the literature and using survey data. It addresses the following questions:

1. Why is there an untapped irrigation potential in the Sahel and what can be learned from existing SSI pathways?
2. Under what circumstances do technological choices found in the Sahel perform best and how can they be leveraged to expand SSI?
3. Why are solar-powered irrigation technologies hardly adopted among SSIs?
4. What specificities of FSSI and NFSSI should be accounted for in SSI expansion?
5. How does profitability differ between alternative land and water uses and between SSIs and non-SSIs and between FSSIs and NFSSIs?

In addition to filling the identified literature gaps, this paper aims to contribute to the policy discourse on irrigation, in general, and "farmer-led irrigation," in particular, in SSA.

The paper is organized as follows. Section 2 suggests a conceptual framework for defining SSI that actually distinguishes between FSSI and NFSSI. Section 3 presents the survey data and the weight adjustments made for the analysis. Section 4 analyses how SSI can be expanded through a critical review and case study analysis. Section 5 investigates SSI prevalence, its constraints, and profitability by distinguishing between FSSI and NFSSI and accounting for labour productivity.

[2] They first purposively sampled districts within which they selected farms randomly, independent of their irrigation status. This indicates that their group of non-adopters might be heterogeneous.

2. Conceptual framework and definitions

2.1 Conceptual framework

A conceptual framework of irrigation adoption can help define SSI better. In SSA, irrigation is promoted to improve productivity, food self-sufficiency and reduce rural poverty (Redicker et al., 2022). These metrics are first measured at the farm and household levels and aggregated at higher levels (regional, national, etc.). Therefore, decisions to participate in irrigation happen at the farm-household level.

Motivation to participate in irrigation may differ across farm-households because of the availability and accessibility of water resources, the enabling institutional and policy environment (e.g., access to markets and financing, access to energy and irrigation technology, etc.) (Falchetta et al., 2023; Durga et al., 2024), farm-households characteristics and objectives (Nkonya et al., 2022). For instance, the availability of water resources may affect the pathways through which farm-households participate in irrigation. Indeed, where water resources are difficult to access (e.g., when groundwater is too deep), farm-households might likely participate in irrigation through non-farmer-led initiatives as farmer-led initiatives might be too costly to undertake. Similarly, farmers' motivation to participate in irrigation may change according to the crops cultivated (high or low-value crops), access to markets (Nkonya et al., 2022), energy, and technology. Participation in irrigation, in turn, is expected to affect farm-households' input demand and labour allocation among crop and non-crop income earning activities. Both will affect crop production, which will affect home consumption and commercialization rates (Kafle and Balasubramanya, 2022), thereby increasing crop and household income, nutrition, and food security (Dillon, 2011; Mekonnen et al., 2022; Nkonya et al., 2022). Figure 1 provides a conceptual framework of irrigation adoption and impact pathways, highlighting the factors influencing adoption and its implications on farm profitability and household welfare.

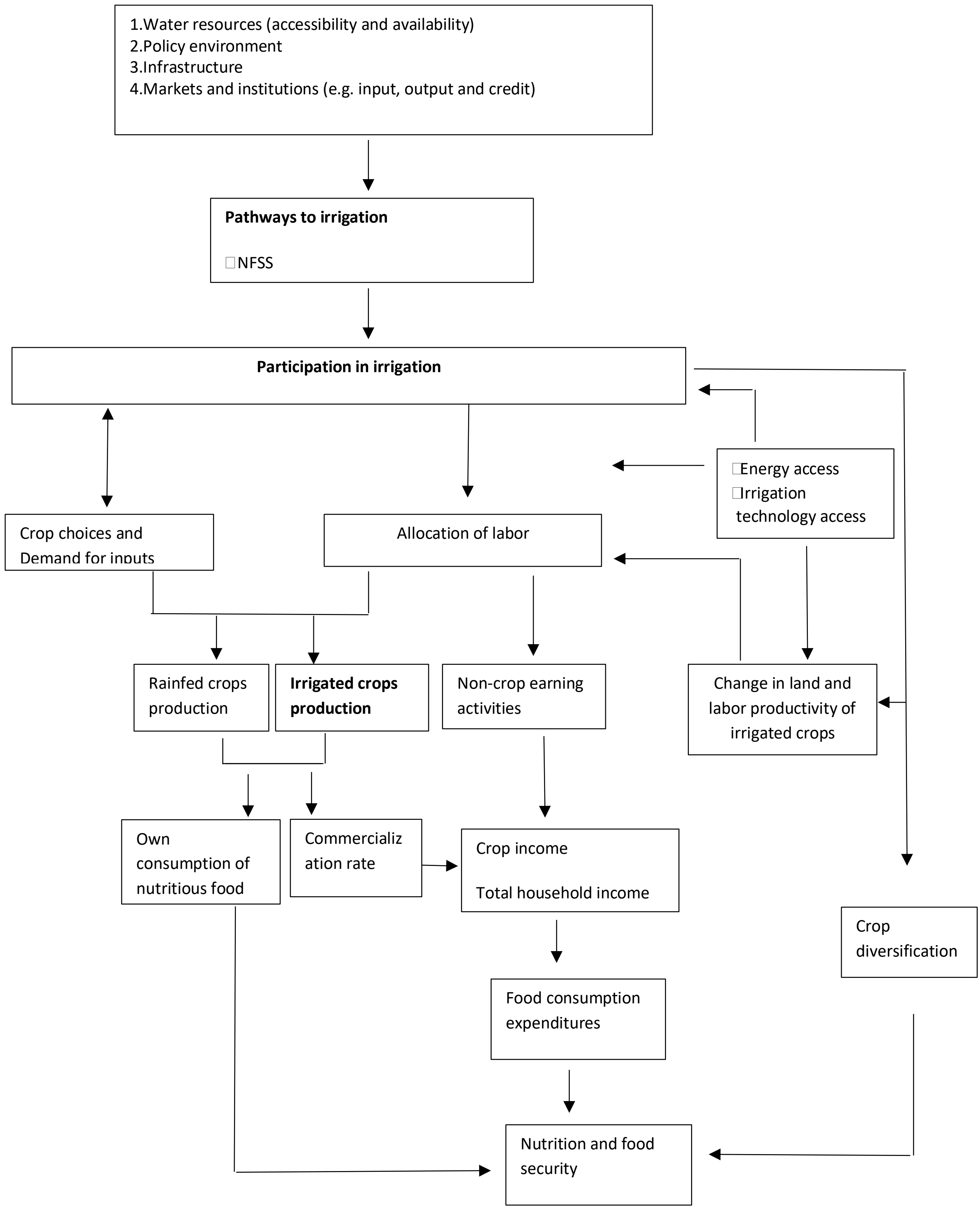

Figure 1: Conceptual framework of irrigation adoption and impacts

Source: Authors' elaboration inspired by von Braun et al. (1989)

Although some of these factors influencing irrigation adoption and its implications are explored in the literature, this study explores them through a different angle by distinguishing between the endogenous choices of FSSI and NFSSI. The implications of SSI on labour productivity and its consequences on labour allocation to farm and off-farm economic activities, which is often overlooked in the literature, are also explored.

2.2 Definitions

In SSA, irrigation has been promoted through collective large-scale schemes where management is centralized (Haile et al., 2022) or small-scale schemes where farmers ensure management through water user associations (Aarnoudse et al., 2018). Besides, individual farm-households engage in irrigation using their own means (Durga et al., 2024). Depending on the pathway to irrigation, four factors have been considered in defining “small scale irrigation”: irrigation scheme size, initiator (farmer-led or non-farmer led), management (centralized, decentralized, or individual), and size of technology (Adams and Carter, 1987; Sakaki and Koga, 2013; Kamwamba-Mtethiwa et al., 2016; Olayide et al., 2020; Haile et al, 2022; etc.). Despite the importance of these factors, existing definitions are unclear about the decision-making units participating in and benefiting from SSI (i.e., farm-households). The conceptual framework in Figure 1 illustrates the importance of considering end-users when designing and evaluating irrigation initiatives.

The units of analysis in these studies, mostly collective irrigation schemes or individual farm-households, explain the considered factors. When the former is the entry point, assimilating scheme size with small- or large-scale irrigation (e.g., Olayide et al., 2020) is misleading. Indeed, in both large- and small-scale collective schemes, the end users are farm-households sharing the total irrigated area, usually subdivided into small plots or one collective plot. Consequently, the actual irrigated area per farm-household is very small (see Table S2 in supplementary materials). Furthermore, the benefits of these schemes happen at the farm-household level. Therefore, the relevant size to consider should be the area irrigated at the farm-household level, possibly even distinguishing the intra-household arrangements when irrigated plots are more a men’s or a women’s domain.

Alternatively, when farm-households are considered as units, definitions usually associate SSI with farmer-led irrigation (Haile et al., 2022), where farmers initiate and control it individually (either one household member or a group of household members)[3] or collectively (with farms from other households). However, SSI can be farmer-led or non-farmer-led. At this scale, SSI is also characterized by the use of simple technologies, such as manual or motorized pumps, to access irrigation water (Kamwamba-Mtethiwa et al., 2016). Sakaki and Koga (2013) classified SSI into three types based on (i) location in urban or peri-urban areas and simple technology use (watering can or treadle pumps); (ii) farmer-led or not; and (iii) use of

[3] Individually refers to individual farm-households that may have several irrigated plots managed by one or multiple household members.

improved traditional irrigation material. However, size is not clearly defined in these technology-focused definitions. The phrase "smallholder irrigation" is also used to refer to SSI (Burney and Naylor, 2012; Xie et al., 2017). Yet, medium or large-scale farm-households can practice irrigation on a small scale.

The ambiguous implications of various SSI realities make them complex for the data used. Indeed, the research entry point is rural farm-households that may or may not participate in irrigation and, if they do, they could belong to a small- or large-scale collective scheme or be individual irrigators. Therefore, a practical definition of small-scale irrigation would ideally emphasize its small-scale nature depending on the area irrigated per farm-household. Once it is small-scale, other terminologies can be added to specify whether it is farmer-led or non-farmer-led and the management options. These latter characteristics mainly highlight the structure in which farm-households participate in SSI. In this direction, Adams and Carter (1987) define small-scale irrigation as "the management of the supply of water to crops or other economically useful plants, which is initiated organized and controlled by the landholder or groups of landholders; the extent of such activities does not normally exceed 10 ha per farm family, and may be as little as 0.1 ha." However, in addition to focusing only on FSSI, they are not clear about what they mean by "landholders." Furthermore, the 10 hectares threshold seems too high for small-scale farming defined with a farm size lower than 2 hectares (Ricciardia et al., 2018). Additionally, such a broad threshold might hide heterogeneities in participating farm-households.

Consequently – and for practical purposes – SSI, FSSI, and NFSSI are defined as follows:

- **Small-Scale Irrigation (SSI)**: "SSI" farm-households engage in irrigation in at least one of their cultivated plots during at least one season of the year and the total area under irrigation does not exceed 2 hectares per farm-household.
- **Farmer-led Small-Scale Irrigation (FSSI)**: When the irrigation is SSI and managed by an individual or groups of farm-households it is considered to be "FSSI" (Woodhouse et al., 2016; Shah et al., 2018; Kafle et al., 2020; Izzi & Veldwisch, 2021; Durga et al., 2023).[4]
- **Non-Farmer-led Small-Scale Irrigation (NFSSI)**: Farm-households not participating in FSSI but participating in SSI are considered as participating in "NFSSI."[5]

[4] More specifically, because we are using micro data at the farm-household level, it is not possible to determine whether the initiative comes from a single farm-household or a group of farm-households. However, conditional on small-scale irrigation, FSSI is considered to occur when farm-households use private wells as their source of irrigation for at least one irrigated plot. If the source of irrigation on an irrigated plot is other than private wells (e.g., wetlands or canal irrigation), the farm-household should own a private pump.

[5] This paper, only analyses individual FSSI, which may underestimate the collective farmer-led initiatives. Unfortunately, the data do not allow for the inclusion of these collective initiatives. However, such initiatives are investigated in El Ouaamari et al. (2019).

3. Survey data

The empirical analysis in this study relies on two groups of surveys: (i) the Harmonized Surveys on Households Living Standards 2018-2019 (HSHLS) in Senegal, Mali, Burkina Faso, and Niger; and (ii) surveys from the "*Projet d'Appui aux Politiques Agricoles*" (PAPA), an initiative of the Government of Senegal funded by USAID under the "Feed the Future" initiative and implemented for a period of 3 years (2015–2018) by the Ministry of Agriculture and Rural Equipment, in collaboration with local research institutions, the International Food Policy Research Institute (IFPRI) and the Michigan State University.

3.1 The Harmonized Surveys on Households Living Standards

3.1.1 Data

The HSHLS are the first edition of nationally-representative household surveys conducted within the West Africa Economic Monetary Union (WAEMU) through the household survey harmonization project, a joint program by the World Bank and the WAEMU Commission that aims at producing household survey data in member countries. These surveys were administered in two waves during the 2018/2019 agriculture year following a two-stage sampling procedure. The first stage consisted of selecting enumeration areas (EAs) from a sampling frame, and the second stage consisted of randomly selecting 12 households in each selected EA. Subsequently, each EA was randomly divided into two equal groups. The first group was interviewed in wave one, and the second in wave two. The surveys are composed of two strata, divided into rural and urban households. Table 1 summarizes the samples. The data contains (i) information on households' demographic and socioeconomic characteristics, (ii) agricultural activities (including information on crop production, inputs, equipment use, and sales), (iii) plot-level information on irrigation water sources and water-lifting technologies that are used to define SSI variables, and (iv) livestock and off-farm economic activities, and expenditures.

However, for some rural households, plot-level information was entirely missing, likely due to the fact that they did not cultivate that specific survey year or they are not agricultural households. Since SSI is defined based on plot-level information, only the rural strata with farm-households with non-missing plot-level data are considered. These deletions have implications, specifically visible in the case of Mali, where rural households without plot information are mainly located in the regions of Kidal (where only three had such data) and Taoudnit (the Southern area of Timbuktu where no household had such data).

Similarly, village-level variables, such as the existence of markets and banks, were missing for some villages. Since across-villages differences cannot be ignored, using other village information to impute such missing values would be inappropriate. Therefore, these observations along with unrealistic outliers were deleted. Lastly, while computing variables such as the costs and values of outputs and net returns per unit of land and labour, some plots did either not have any information on the type of crop (reported as "other" and unspecified) to calculate the value of output or the units associated with a given quantity of input (also reported as "other" and unspecified) to calculate the costs. Therefore, the information provided was insufficient to impute the missing values. These observations were deleted since both information on output value and costs are needed per plot.

Table 1: HSHLS Sample

	Burkina Faso	**Mali**	**Niger**	**Senegal**
Total sample	7010	6602	6024	7156
Rural	3861	3850	4447	3215
Urban	3149	2752	1577	3941
Excluding urban and non-agricultural rural households	3592	2623	3416	2280
Excluding missing values or unrealistic outliers	**3374**	**2586**	**3380**	**2280**
Number of plots in the used sample	9433	5994	6280	6500
Excluding missing values or unrealistic outliers	**7779**	**5158**	**5449**	**5317**

Source: Authors based on HSHLS (2018-2019)

Descriptive information on the country samples by SSI adopters and non-adopters is provided in Table S4 of the supplementary materials. The definition of all variables used in the descriptive analysis and estimations is also presented in detail in Table S3 of the supplementary materials.

3.1.2 Weight adjustments to balance control and treated groups

The HSHLS served for two analyses: (i) compare SSIs and non-SSIs and FSSIs and NFSSIs and (ii) analyze the plot-level profitability and productivity of alternative water and land uses for SSIs and FSSIs in the four countries. The plot-level analysis particularly compares SSI and rainfed plots as well as FSSI and NFSSI plots. The first analysis is based on a constructed metadata set that pooled information on the four countries' SSIs and non-SSIs. The second analysis is done separately for each country using farm-households from the metadata set.

To construct the meta dataset, we first built country-level datasets containing the variables of interest at the farm-household level. We then pooled the Country datasets. Given the low uptake of SSI in each country, a statistical comparison of SSIs and non-SSIs would not yield meaningful results. Therefore, constructing a metadata set increases the statistical power and allows for more heterogeneity. However, some adjustments in household weights are required for more robust comparisons.

First, because weights have the same scale in the different countries, population size must be corrected, although country-size effects might be small. Here, the population size considered is the number of households in countries, as the secondary sampling units are households. The population size weight calculated for each country c is

$$pweight_{c} = [number\ of\ rural\ households_{c}]/ \\ (number\ of\ rural\ households\ in\ sample_{c}) * 1000] \quad (1)$$

Each household weight ($hweight_{ic}$) is then multiplied by the corresponding population size weight in the metadata set, which gives the population-adjusted weight for each household i in country c:

$$phweight_{ic} = pweight_{c} * hweight_{ic}. \quad (2)$$

Second, the constructed metadata set leads to clustered data structures, where participation in SSI happens at the household level and is influenced by both household and country-level variables. The latter includes pathways to irrigation expansion, available water resources, policy environment or infrastructure (see conceptual framework in Figure 1). Therefore, the differences between SSIs and non-SSIs might be due to confounding factors and not necessarily participation in SSI. Therefore, it is necessary to ensure that the compared treatment and control groups are as similar as possible and only differ due to their treatment status. In such non-experimental settings, this can be achieved by either defining a counterfactual group to be compared to the treatment group using matching techniques (such as propensity score matching, exact matching or Coarsened Exact Matching (CEM)) or by using the inverse probability weighing (IPW) method to balance covariates between compared groups (Chesnaye et al., 2022). Here, we opt for the IPWs as our attempt to implement propensity score matching and CEM led to a significant loss of observations that fell out of the common support. Such a sample reduction renders the comparison of FSSIs and NFSSIs less appealing as the treatment groups would be too small.

To calculate the IPWs, we must estimate a logit model to predict the propensity scores (pscore), reflecting the probability of participation in SSI. However, in this case, one of the conditions to be considered as SSI is that total area irrigated is less than or equal to 2 hectares. Therefore, the group of non-SSIs is heterogeneous and composed of larger scale irrigators (LSIs) and non-irrigators. Consequently, we estimate a multinomial logit instead of a logit to calculate the pscores of participation in SSI, LSI, or non-irrigation. The pscores are then used to calculate the inverse probability weights of both treated (SSIs) and untreated units (LSIs and non-irrigators). The calculated IPWs are then multiplied with the country-adjusted household weights. The descriptive statistics uses these weights to balance the compared and treated groups. The IPWs are calculated using the entire meta dataset to balance SSI and non-

SSI groups. Since we also compare FSSI and NFSSI, the same procedure is repeated by estimating a logit model in the first step using the sub-sample of SSIs to balance FSSI and NFSSI groups.

The multinomial and logit models are simply specified in equations 3 and 4:

$$I_i = \beta_0 + \beta_n X_i + u_i \quad (3)$$

Where I_i is a categorical "choice" variable representing the irrigation status, equals to 1 if household i participates in SSI, 2 if household i participates in LSI, and zero if household i does not participate in irrigation.

$$FSSI_i = \delta_0 + \delta_n K_i + v_i \quad (4)$$

Where $FSSI_i$ is a binary "choice"[6] variable representing farmer-led small-scale irrigation, equals to 1 if household i participates in FSSI, and zero otherwise. X_i and K_i are vectors of n observable covariates that explain the treatment. Both vectors include country fixed-effects to account for the differences between countries related to biophysical characteristics or the policy environment. Other covariates include household socio-demographic characteristics such as age and gender of the household head, household size, wealth index variables (number of durables and number of livestock units), land security, access to markets and cities, farm size, and access to basic services such as electricity grid and tap water. βs and δs represent the estimated parameters and u_i and v_i the error terms.
After the multinomial logit estimations, the IPWs are calculated as the inverse propensity score of household i's participation in an irrigation treatment (p_{I_i}) :

$$IPW_{I_i} = \frac{1}{p_{I_i}} \text{ for each } I_i = 1, 2, 3 \quad (5)$$

After the logit model, the IPWs are calculated as

$$IPW_i = \frac{1}{p_i} \text{ if } FSSI_i = 1 \text{ and } IPW_i = \frac{1}{(1-p_i)} \text{ if } FSSI_i = 0 \quad (6)$$

where $p_i \in [0,1]$ is the predicted propensity score post-logit.

Therefore, participating individuals with a low probability of participation and non-participating individuals with a high probability of participation receive higher weights. This increases their relative influence (Chesnaye et al., 2022). Taking the weights into account in the analysis minimizes the imbalance between the treatment and control groups for the vector of covariates considered in the logit or multinomial logit estimations. The ultimate adjusted household weights are:

[6] Note that there is no presumption that engagement in FSSI versus NFSSI is strictly speaking a choice but rather endogenous. This is discussed later in more detail.

$ipwhweight_i$=$phweight_{ic} * IPW_{I_i}$ (7) in the comparison of SSIs and non-SSIs and

$ipwhweight_i$=$phweight_{ic} * IPW_i$ (8) in the comparison of FSSIs and NFSSIs.

The results of the estimated multinomial logit and logit models are shown in Tables S5 and S7 in the supplementary materials. Results of both models seem to be plausible in terms of the observable factors affecting the participation in the different irrigation regimes[7].

To be consistent with the household-level analysis, we also use the IPWs at the plot-level for each country to ensure the balance between compared SSI and rainfed plots.[8] The plot-level logit model is written

$$I_{ki} = \propto_0 + \propto_n Z_{ki} + w_{ki}, \quad (9)$$

where I_{ki} is a binary choice variable representing plot-level small scale irrigation (SSI_{ki}) or farmer-led small-scale irrigation ($FSSI_{ki}$) equal to 1 if plot k of household i is under SSI or FSSI, respectively, and zero otherwise. Z_{ki} are plot-level characteristics, including plot soil, plot fertility, intra-household plot management mode, plot security, and time to plot (see Table S3 in the supplementary materials for the description of variables). $\propto$s and v_{ki} represent the estimated parameters and the error term, respectively.

Not all the covariates were included in the logit estimation for all countries. Indeed, to fit the logit model, we adjusted covariates for Mali, Senegal, and Niger, as indicated in the logit estimation results in Table S9 of the supplementary materials. Because weights are not provided at the plot level, we compute plot-level weights as follows:

$$pweight_{ki} = hweight_i * \frac{area_{ki}}{farmsize_i}, \quad (10)$$

where $pweight_{ki}$ and $area_{ki}$ are plot ks weight and area for household i. $farmsize_i$ is the total area across all plots. After the logit, we estimate plot-level IPWs as follows:

$$IPW_{ki} = \frac{1}{p_{ki}} \text{ if } I_{ki} = 1 \text{ and } IPW_{ki} = \frac{1}{(1-p_{ki})} \text{ if } I_{ki} = 0 \quad (11)$$

where $p_i \in [0,1]$ is the predicted propensity score of a plot k being under SSI. The ultimate plot-level weights are calculated as:

$$ipwpweight_{ki} = pweight_{ki} * IPW_{ki} \quad (12)$$

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[7] For instance, compared to non-irrigators, both SSI and larger-scale irrigation are positively associated with formal education of the household head with a stronger effect size is for SSI adopters compared to LSI adopters. Also, both the presence of bank and land security are positively associated with SSI and LSI participation, compared to no irrigation. However, the effect size is larger for LSIs.

[8] The same procedure is not done for FSSI plots vs NFSSI plots due to their small sample size that does not allow for robust logit estimations. Therefore, for those plots, we only use the plot weights.

We use standardized means differences to check the balance between the compared groups at both household and plot levels. Tables S6, S8, and S10 show an acceptable balance between the compared groups in the three cases (i.e., SSI vs non-SSI, FSSI vs NFSSI at the household level, and rainfed vs. SSI plots). Furthermore, due to potentially high IPWs for observations with either very close to zero (for treated) or very close to one (for untreated) propensities, which could be a source of bias, we also calculate the stabilized IPWs as a robustness check. These are obtained by replacing the numerator in equations 5 and 11 by the raw propensity scores of participation in an irrigation treatment (I), and in equation 6, by the raw propensity scores of a household being FSSI or NFSSI or a plot being under FSSI or NFSSI. Raw propensity scores are obtained by estimating the multinomial and logit models in equations 3, 4, and 9 without the covariates. Standardized means difference obtained with stabilized weights are perfectly equal to the ones obtained with the standard IPW weights.

Because the HSHLS are nationally representative and based on a two-stage sampling procedure, the data analysis uses STATA survey data analysis commands to account for the survey design and weight adjustments.

3.2 The PAPA data

Given the absence of data on solar-powered irrigation technologies in the HSHLS, we use two datasets from the PAPA project to analyze the adoption of solar-powered irrigation technologies in Senegal. The PAPA project aimed to conduct comprehensive surveys and analyses of actors in agricultural value chains from producers to consumers, including agro-dealers and processors, to support policy design. Therefore, specific surveys were conducted on irrigated agriculture across the country. In this research we use two of the PAPA datasets. The first dataset is representative of irrigated farms located in the main agroecological zones of Senegal, where farm households mainly participate in irrigation agriculture: the coastal Niayes area and the Senegal River Valley. This dataset contains the same information as the HSHLS. It additionally contains details on irrigation, particularly water lifting and water distribution technologies, allowing for the identification of adopters of solar-powered irrigation technologies. The survey was administered during the dry season of 2017. Following a multistage sampling procedure, a total of 1,305 farm households were surveyed (see Faye et al. (2020) for the sampling procedure). Because we analyze the adoption of solar-powered irrigation technologies among SSI farm households, we removed observations that are not SSI, leading to a sample of 1,044 SSI farms.

The second dataset comprises 395 collective irrigation schemes randomly selected in rural areas of Senegal. This dataset contains general information on the schemes, their management, funding sources, production, inputs, technology use, etc.

4 SSI expansion opportunities and lessons from the literature

4.1 Untapped irrigation potential in the Sahel and lessons from current SSI pathways

In the Sahel, the cultivated area equipped for irrigation is far below the world average, especially in Burkina Faso and Niger. Mali outperforms its neighbors in terms of irrigation potential achieved, and area equipped for irrigation[9]. Additionally, there is a gap between the equipped area for irrigation and the equipped area actually irrigated (Figure 2) which is particularly striking in Mali and Senegal.

Mali's irrigation success is attributed to historical investments in the sector and its significant water resources, including the Niger River basin, the Senegal River basin, the Sourou basin, and several large lakes in the northern part of the country (Direction Nationale du Génie Rural, 2016; USAID, 2021; Houeto et al., 2022). Indeed, Mali initiated collective large-scale irrigation schemes in the 1920s that were managed by the Office du Niger, the largest public Irrigation Development and Management Agency (IDMA) in West Africa. The schemes were created to supply colonial industries and their colonies in West Africa with raw materials and rice, respectively (Zwart and Leclerc, 2010). In Senegal, Burkina Faso, and Niger, IDMAs were created later (in the 1960s and 1970s) to manage collective irrigation schemes of hundreds to thousands of hectares shared by thousands of farm-households. However, unsuccessful management and maintenance of irrigation facilities led to high rates of scheme failure and degradation over time (Houeto et al., 2022; Higginbottom et al., 2021; Redicker et al., 2022).

Transfer of management from IDMAs to producers through water user associations (WUAs) or cooperatives was initiated during the structural adjustment and economic restructuration plans in 1980 to improve schemes' performance by giving greater responsibility to producers for infrastructure and water management. Such transfers have had different degrees of success in the Sahel (Bazile et al., 2021). Besides, **smaller** public or donor-supported **collective initiatives** of less than 100 hectares have been promoted since the 1980s and 1990s with management operated by WUAs through village-level public irrigation and community-level private irrigation schemes that are farmer-led or non-farmer-led. However, these collective schemes also suffered from governance issues leading to infrastructure degradation, maintenance, and production constraints that reduced their performance (e.g., low productivity, abandonment) (García-Bolaños et al., 2011). These failures explain the gap between the equipped area for irrigation and the equipped area actually irrigated.

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[9] According to the FAO (2005), the *irrigation potential* corresponds to the "Area of land which is potentially irrigable. […] It includes the area already under agricultural water management". The *area equipped for irrigation* "consists of the areas equipped with hydraulic structures to provide water to the crops. It includes areas equipped for full control irrigation, equipped lowland areas, and areas equipped for spate irrigation. It does not include non-equipped cultivated wetlands and inland valley bottoms or non-equipped flood recession cropping areas."

SSI expansion via collective schemes can be done by equipping more land for irrigation and/or by irrigating more of the already equipped area. The former option might be costlier as it will require new public or private investments in irrigation infrastructure and technologies. The second option might be less costly as it would mainly require rehabilitation of failed schemes. However, both types of investments need to be well targeted to avoid past failures. According to the literature, relevant factors to consider when investing in irrigation expansion include: scheme size, type of management, and whether expansion should be farmer-led or not.

Concerning scheme size, both small- and large-scale collective schemes are profitable, although small-scale schemes offer larger potential benefits (You et al., 2011). However, large-scale schemes, usually non-farmer-led require higher investments but lead to higher paddy rice yields and water productivity (Barbier et al., 2011). Borgia et al. (2013) found that large and small-scale schemes performed equally along the Senegal River Valley in Mauritania, but small schemes had higher energy costs. Sakurai (2023) found that due to the economy of scale, scheme size is positively associated with investment performance up to a threshold of 1600 hectares, after which the association becomes negative.

Concerning the initiator, government-funded schemes perform worst (Sakurai, 2023). Dillon (2011) found that cost-benefit analysis does not inform spillover benefits of irrigation investments, such as village-level increase of food supply, asset accumulation, and informal sharing within villages, which helps households mitigate risk. Finally, management issues still remain of concern, independent of size (McCarthy et al., 2023).[10]

However, further considerations need to be accounted for. Indeed, most of these papers do not provide **variations in the metrics targeted**, even when the data allows for it (see McCarthy et al. (2023); Borgia et al. (2013)), which somehow hides within-scheme heterogeneity and the heterogeneity of targeted farm-households which are important to tailor investments as different schemes might suffer from different issues and different beneficiaries might have different constraints to participate in SSI. Also, an important factor not sufficiently explored in the literature is the implication of SSI adoption on **labour productivity**, which affects labour allocation among crop and non-crop activities as illustrated by the conceptual framework in Figure 1. Some of these gaps are explored in Section 5.

[10] A synthesis of performance indicators from these studies is available in Table S11 in the supplementary materials.

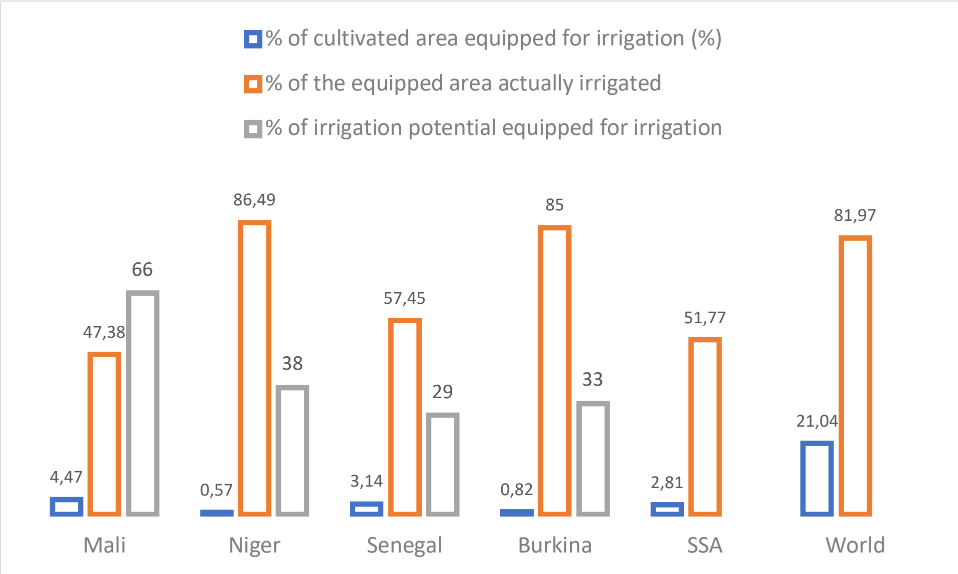

Figure 2: Irrigation in the Sahel (2020)
Source: Aquastat (2020), see Table S1 in the supplementary materials

4.2 Performance of technological choices found in the Sahel and implications on SSI expansion

In the Sahel, farmers use different irrigation technologies to lift and distribute water from canals, rivers, other surface water, and groundwater using wells or boreholes.

4.2.1 Water lifting technologies

Water lifting technologies include human-powered technologies, motor pumps, electric pumps, and solar pumps (Abric et al., 2011; Kane et al., 2018; Kergna and Dembele, 2018; Tadesse et al., 2024a).

Human-powered technologies are mainly constituted by the rope and bucket technology to lift water from shallow wells (Nkonya et al., 2022). However, manual and treadle pumps allow to lift water from a depth of up to 2.5 metres for the former and 15 metres for the latter. The main advantage of these technologies is their cost and their ease of use, handling, and transportation. However, they are labour-intensive, particularly the bucket-rope technology (Nkonya et al., 2022) and only suited to irrigate small areas (e.g., less than 0.5 hectares) (Abric et al., 2011; Kane et al., 2018; Tadesse et al., 2024a).

Motor pumps are fuel-powered pumps that allow for the irrigation of plots between 0.5 and 3 hectares (Abric et al., 2011). Compared to manual pumps, they have significant acquisition costs, and their spare parts can be hard to find in local markets, making maintenance difficult (Tadesse et al., 2024a). The availability and cost of fuel are also challenging, especially in remote areas. For instance, diesel fuel is the primary cost component in diesel-powered irrigation, accounting for 70% to 90% of the entire system's lifecycle cost (Xie and Ringler, 2021). Furthermore, motor pumps have negative climate impacts, and a relatively short service life (often less than five years).

Electric pumps are also inconvenient in rural areas due to sporadic grid presence and unreliable provision due to frequent power cuts or high tariffs. Both motor and electric pumps are more profitable for growing high-value crops. Additionally, their broad use could substantially increase groundwater demand, leading to resource depletion.

Solar pumps are becoming a viable alternative for pumping. Indeed, the Sahel has untapped solar energy potential that could be leveraged in rural areas without electricity access. Solar irrigation systems are further becoming more appealing due to their renewable nature, their increased affordability compared to the past, and their lower greenhouse gas emissions compared to fuel pumps (Xie and Ringler, 2022). Solar pump spare parts (controller and electrical wiring, panels) are also available in the local markets (Sarr et al., 2021). However, while they do not require fuel and electricity, they do require protection from thieves. In 2017, ten producers in Maradi (Niger) received credit from microfinance institutions and grants for the installation of solar irrigation systems. Still, the panels were not installed due to the need for guards, whose services sometimes cost more than the usual cost of buying fuel for a motor pump (Tadesse et al., 2024a). Small community schemes also face difficulties related to their size and management issues that disrupt the use of solar irrigation systems due to unrepaired breakdowns. However, these management issues are not specific to solar irrigation systems.

Concerning costs, Figure 3 displays a box plot of investment costs for water lifting technologies that are dependent on irrigation pump capacity (i.e., m^3/hour, number of irrigable hectares, depth of water). Therefore, direct comparisons of these capacity-invariant costs might be misleading. However, at first sight, solar pumps and motor pumps have the highest investment costs. Another important metric is the lifecycle cost of these technologies that could render solar pumps attractive, depending on pricing trends of solar energy and the price volatility of fossil fuels (Xie and Riungle, 2021).

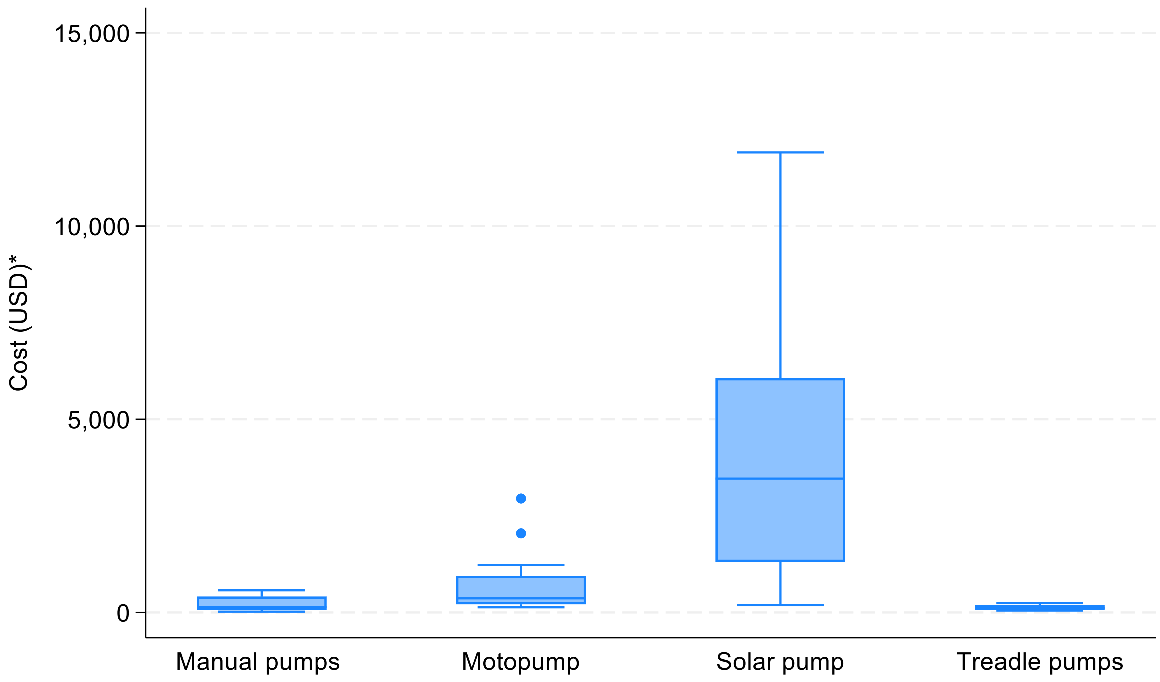

Figure 3: Cost of water lifting technologies in the Sahel
Source: Authors based on literature, HSHLS (2018/2019) and PAPA (2017) (see Table S12 in supplementary materials)

4.2.2 Water distribution technologies

Water distribution technologies include manual and mechanized water distribution techniques. Manual distribution is a cheap but labour-intensive process and is, thus, only suitable for small areas. Mechanized water distribution techniques are more appropriate for irrigating larger areas, improving irrigation efficiency, reducing labour time, and saving water. These mechanized techniques primarily include the Californian distribution network, drip irrigation, gravity irrigation, and sprinkler systems (Abric et al., 2011; Kane et al., 2018; Kergna and Dembele, 2018; Tadesse et al., 2024a).

Californian networks lower water loss through infiltration,[11] which reduces pumped water costs. These networks are appropriate for sandy soils and for irrigating slopes. As such, this technology is widespread in Niger, particularly in small-scale village-irrigated schemes and market gardens. Californian networks are easy to install, use, and maintain. Parts are affordable and available in local markets. Cultivating vegetables, rice, and arboricultural plots of 0.25 to 2 hectares are ideal uses for the Californian water distribution system. However, wandering animals (if plots are unfenced) and intense sunlight can damage the pipes (Tadesse et al., 2024a). **Drip irrigation** is an effective method for growing crops in water-limited areas. However, it is costly and requires continuous outreach to familiarize small producers with the equipment for its operation and maintenance, leading to its low uptake (Tadesse, 2024a; CIF,

[11] See Kane et al. (2018) for details on Californian networks.

2020). Furthermore, previous negative experiences have led to skepticism about drip irrigation (CIF, 2020). **Sprinkler systems** mimic natural rainfall and are suitable for vegetable crops. Sprinkler systems are particularly popular among small-scale commercial farms. Sprinkler systems are easy to use and maintain. They operate autonomously, reducing irrigation labour time. However, they should be selected wisely based on the size of water droplets and the type of cultivated soil that can both affect its suitability to a given area (Kane et al., 2018).

Among these technologies, the dot plot (Figure 4) clearly shows that the per hectare cost of Californian distribution systems is smaller than that of drip and sprinkler systems.

Other systems, such as the **remote irrigation system** developed by a Nigerien inventor to irrigate remotely connects farmers to a database managed by Tech Innov, the promoter of the technology, enabling them to operate the system via SMS or voice command. Although this system addresses manual irrigation labour challenges, its high cost and lack of statistics on its use hinder its adoption (Tadesse et al., 2024a).

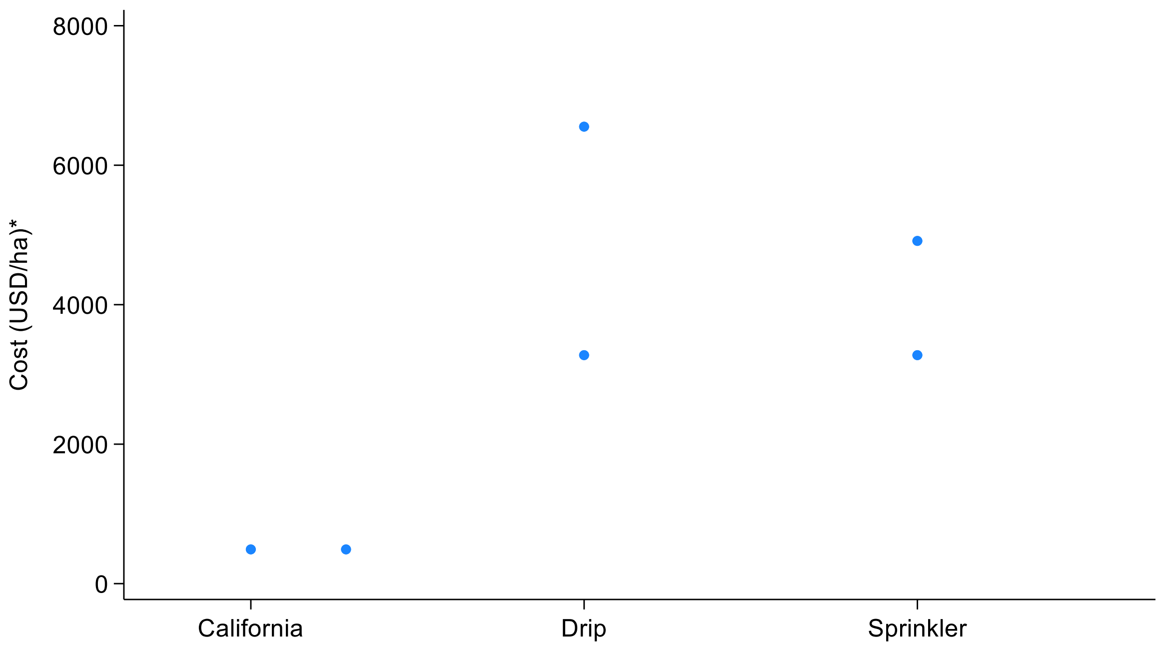

Figure 4: Upper and lower bound costs of selected water distribution technologies in the Sahel
Data source: literature (see Table S13 in supplementary materials)

4.2.3 Further considerations on the adoption of irrigation technologies to expand SSI

Improved irrigation technology allows for larger plot sizes, and reduced labour time, potentially leading to SSI expansion. As a result, adoption can increase farm output and income (Lipton et al. 2003). However, the indivisible feature of irrigation technologies should be further considered.

For indivisible technologies, when the gain from adoption is not affected by scale or ownership of the technology, independent technology dealers or larger farmers may buy the technology and rent it to farmers, or enable farmers to outsource the machine's services by supplying custom services (Lu et al., 2016). However, from the previous analysis, the gain from adoption of irrigation technologies is affected by both scale (here size) and ownership, implying that adoption and ownership decisions of technologies are linked, especially in the case of individually-initiated FSSI. Indeed, for the latter, ownership is crucial as irrigation requirements are daily across growing seasons. Consequently, these technologies are not just used during one cropping activity but throughout the season. Therefore, farmers would gain from owning the technologies as they will have unlimited access throughout the season compared to situations in which they rent it. Furthermore, owning the machine procures familiarity with the technology over time (Lu et al., 2016). Therefore, renting it could reduce possible gains from adoption, leaving farmers with the purchase option, which requires innovative financing mechanisms due to high investment costs.

Due to financial capacity limitations and land fragmentation, individually-initiated FSSI usually irrigate small scattered plots, making it difficult to share indivisible technologies across plots, especially when they are not easily transportable. Therefore, farmers irrigating small fragmented plots, typically less than 0.5 hectares might be more inclined to adopt human-powered irrigation technologies compared to farmers irrigating larger plots. However, improved technologies could be promoted among farmers participating in collective FSSI or NFSSI as they share common land with adjacent plots.

Some studies (Xie et al., 2014; Tadesse et al., 2024a) have looked at the potential for SSI expansion in Africa, comparing technologies including treadle pumps, motor pumps, and solar-powered pumps. Among these technologies, treadle pumps generate the highest net income per hectare. Small plots may not yield significant benefits from adopting improved mechanized technologies, as their gains are scale-dependent. Therefore, to ensure viable expansion of SSI, technology promotion should consider farm sizes and SSI pathways.

More research is needed on finding the optimal supply chains to promote the adoption of improved irrigation technologies when both costs and gains are scale dependent and ownership matters. Considering the case of solar pumps, initiatives for their adoption and ownership are encouraged through innovative financing mechanisms involving arrangements between technology suppliers and farmers, such as the "pay-as-you-go" and "pay-as-you-own" business models, which have been explored in Ghana since 2020 (Minh and Ofosu, 2022) and other areas of the world (IRENA, 2020). In Mali,[12] a partnership between the AICCRA Mali team and a company, ECOTECH, promotes the "pay-as-you-go" model, which allows farmers to pay in instalments, thus transferring ownership over time. The solar-

[12] https://aiccra.cgiar.org/news/pay-you-go-model-makes-solar-powered-irrigation-affordable-farmers-mali

powered system's functionality can be disrupted if timely payments are not made. In Senegal, farmers pay higher prices through local suppliers compared to e-commerce websites due to customs clearance and taxes. Reducing these costs could facilitate solar pump access (Sarr et al., 2018). Local development of irrigation technologies could also lower the prices.

4.2.4 Senegal case study on the adoption of solar-powered irrigation technologies

SSI farm-households adoption of solar-powered irrigation technologies

The PAPA farm-households dataset shows that among 1,305 irrigated farms, 80% are SSI. Also, among these SSI adopters, only 14 are adopters of solar pumps.

Adopters of solar pumps are mainly located in the coastal west (13 out of 14) where, as discussed, SSI is mainly farmer-led. Adopters have, on average, larger farms, slightly higher incomes, and much higher credit access rates (Table 2). However, they are less affiliated with farm organizations. Solar lighting at home is also more prominent among adopters of solar pumps.

Concerning irrigation, the main source of irrigation water for adopters is groundwater using their own wells followed by boreholes. They hardly use surface water bodies and shallow wells, contrary to non-adopters who, besides using their own wells, use surface water bodies, boreholes, and shallow wells. This is explained by their location in the coastal west where groundwater is the main source of irrigation. Adopters also use more mechanical lifting technologies with a larger share of them using motor pumps besides solar pumps, compared to non-adopters. However, no solar pump adopter uses drip irrigation, compared to 11% of non-adopters. Furrow irrigation is the main water distribution technology among solar pump adopters, followed by lance irrigation. Sprinkler irrigation is the least used.

However, adopters are less chemical input-intensive, probably due to larger farm sizes. Nonetheless, regarding labour inputs, the units of both paid and family labour used per hectare of land are higher for adopters compared to non-adopters. A higher share of adopters cultivates during the warm dry and rainy seasons. During the latter, there are higher risks of losses, highlighting a non-risk averse feature of adopters of solar pumps. This feature seems to be confirmed by their non-subscription to an agricultural insurance in the five years preceding the survey compared to non-adopters. This could, however, result from their lower exposure to flood risks the year preceding the survey.

Table 2: Comparison of adopters and non-adopters of solar pumps among SSI farm-households

	SSI adopters of solar pump	SSI non-adopters of solar pump
	Mean (SD)	Mean (SD)
Household characteristics		
Household size	12.07(4.39)	9.81(4.49)
Farm size	1.54(0.45)	0.84(0.57)
Agricultural insurance subscription	0.00(0.00)	0.06(0.23)
Domestic solar lighting	0.29(0.47)	0.15(0.36)
Exposure to drought	0.07(0.27)	0.05(0.23)
Exposure to flood	0.00(0.00)	0.06(0.24)
Total expenditures (USD)	2866.69(1396.35)	2512.24(2138.04)
Total other income (livestock, remittances, off-farm activities)	297.81(648.07)	301.88(918.72)
Access to credit	0.21(0.43)	0.12(0.33)
Membership to farm organization	0.07(0.27)	0.34(0.48)
Main source of irrigation water		
Wells	0.79(0.43)	0.51(0.50)
Boreholes	0.14(0.36)	0.13(0.34)
Shallow wells	0.00(0.00)	0.04(0.19)
Surface water bodies	0.07(0.27)	0.25(0.43)
Tap water	0.00(0.00)	0.06(0.24)
Water lifting Technics		
Manual	0.57(0.51)	0.53(0.50)
Mecanical	0.64(0.50)	0.52(0.50)
Motopomp ownership	0.57(0.51)	0.38(0.48)
Water distribution technology		
Drip irrigation	0.00(0.00)	0.11(0.31)
Furrow irrigation	0.57(0.51)	0.27(0.45)
Sprinkler irrigation	0.00(0.00)	0.03(0.17)
Lance irrigation	0.14(0.36)	0.12(0.32)
Input use per hectare		
UREA (kg/ha)	178.44(152.99)	216.62(193.92)
NPK (kg/ha)	181.49(198.35)	242.26(219.38)
Family labor (number/hectare)	7.37(13.96)	5.00(15.18)
Paid labor (number/hectare)	9.71(19.65)	3.63(10.18)
Seasons of cultivation		
Cold dry season	0.86(0.36)	0.91(0.29)
Warm dry season	0.71(0.47)	0.62(0.49)
Rainy season	0.21(0.43)	0.06(0.24)
Observations	14	1030

Source: Authors using PAPA farm-household data

Regarding the cultivated crops (see Figure 5), both groups primarily cultivate high-value horticulture crops. However, the proportions of the main high-value crops consumed in Senegal are higher in the group of adopters. Also, irrigated rice, which has a lower value compared to fruits and vegetables, is not grown by any adopter, which is again explained by their location.

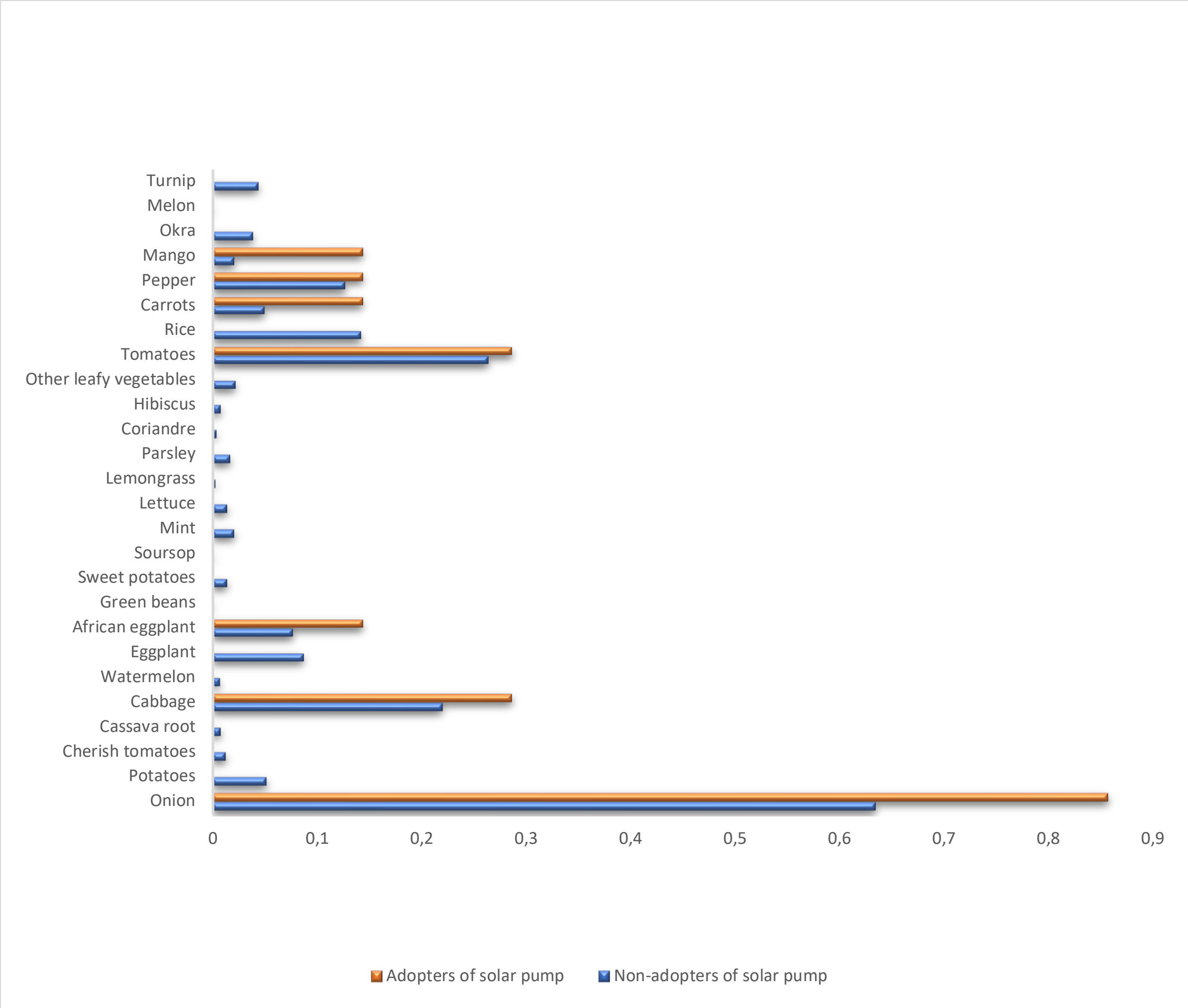

Figure 5: Cultivated crops of adopters and non-adopters of solar pumps in Senegal (shares)
Source: PAPA farm-household data

Adoption of solar-powered irrigation technologies among SSI adopters: The case of collective initiatives

Among 395 collective irrigation schemes, six are adopters of solar pumps, 11 adopt solar panels, and nine drip irrigation, among which only two have solar-powered drip irrigation (see Table 3). All these schemes fulfill the SSI definition as the area per member is below 1 hectare. However, most of these schemes are non-farmer-led, as donors or government institutions primarily initiated them. However, in solar panels-adopting schemes, farmers were more involved in their initiation. However, management of activities, such as input purchase, labour, water management, post-harvest activities (marketing, transport, packaging, and storage), etc., is mainly collective in these schemes. These activities are also primarily funded by members through regular financial contributions or from sales revenues. The second – more prominent – source of funding is credit. However, access to credit is very limited for these solar technology adopters and, where it exists, the credit mainly comes from banks, microfinance institutions, or rarely from farm organizations.

On average, schemes using solar panels are larger both in terms of number of farmers and scheme size compared to schemes using solar pumps or solar-powered drip irrigation. However, they have the smallest area per member.

Wells are the main irrigation water source for all the solar technology adopters. Water lifting technologies are also mainly solar pumps. Surprisingly, for both solar pump and solar panel adopters, water distribution technologies are mainly watering cans. This may indicate that the pumps are used to lift and store the water in basins. Also, since the area per member and plot sizes are small, farmers probably irrigate their plots using manual tools once water is stored in basins.

Table 3: Adoption of solar-powered technologies in collective irrigation initiatives

	Solar pump	**Solar panel**	**Drip irrigation**	**Solar-powered drip irrigation***
Scheme characteristics	Mean (SD) [Min, Max]	Mean (SD) [Min, Max]	Mean (SD) [Min, Max]	Scheme 1; Scheme2
Number of farmers	13(13)	38(41)	31(34)	12; 10
	[4; 40]	[7; 152]	[10; 120]	
Scheme size (hectares) (a)	3.17 (3.60)	4.37(7.05)	10.44(11.77)	2.5; 4
	[0.5; 10]	[0.25; 25]	[2.5; 40]	
Area per member (ha)	0.25(0.2)	0.18(0.21)	0.33(0.13)	0.21; 0.4
	[0.06; 0.57]	[0.01; 0.57]	[0.17; 0.56]	
Number of plots (b)	7(4)	10(9)	5(6)	8; 5
	[3; 12]	[1; 27]	[1; 19]	
Plots size (=a/b, hectares)	0.79(1.26)	0.69(.83)	6.99(12.61)	0.31; 0.8
	[0.04; 3.33]	[0.03; 2.5]	[0.31, 40]	
	Number	Number	Number	1=yes, 0=No
Initiator of collective scheme				
Third-party (donors, government…)	5	5	9	1; 1
Farmers	2	6	1	0; 1
Irrigation water source				
Wells	5	11	2	1; 1
Boreholes	1	1	7	0; 0
Retention pond	2	1		0; 0
Water lifting technologies				
Motorpump	0	1	0	0; 0
Solar pump	6	2	1	1; 0
Solar panels	2	11	2	1; 1
Water distribution technology				
Watering cans	6	10	5	1; 1
Drip irrigation	2	3	9	1; 1
Gravity irrigation	0	1	0	0; 0
Access to credit	1	2	4	0; 0
Source of credit				
Bank		1	4	
Microfinance institutions		1		
Farm organization	1			
Access to advisory services	2	5	4	0; 1
Observations	6	11	9	2

Source: Authors using PAPA-collective
*Note: Adoption of solar-powered drip irrigation is calculated using the information on solar pump, solar panel and drip-irrigation adoption.

5 Uptake of SSI in the Sahel

5.1 Prevalence of irrigation in the sample

In line with Aquastat data (Figure 2), in the country samples, participation in irrigation, area and the share of land irrigated, are higher in Mali, followed by Senegal (see Tables 4 and 5).

Among irrigated plots, private wells are the primary source of irrigation in Niger and Burkina Faso. Alternatively, stream and canal irrigation are almost equally used as the primary source for Mali, while canal irrigation is the main source in Senegal. This confirms the substantial dominance of surface water resources in Mali and Senegal reported by Aquastat data (Table S1 in supplementary materials). In terms of irrigation technology adoption, in Niger, motor pumps are more prominent than manual pumps, despite their higher cost. The opposite is noted in Burkina Faso and Mali while they are almost equally used in Senegal.

The main irrigated crops are unsurprisingly paddy rice and onion in all the countries. In comparison, Aquastat data (Table S1 in supplementary materials) shows that rice is the main irrigated crop in all four countries and Mali has the largest area under irrigated rice, followed by Senegal. However, the data shows that in Niger and Burkina Faso, the share of onion among irrigated plots is slightly higher compared to that of paddy rice. This is not surprising for Niger as in the period 2018-2022, the country was the second largest producer of onion in West Africa, after Nigeria, and the biggest exporter of onion in West Africa (FAOSTAT, 2024).

Table 4: Sahel irrigation overview (irrigated land, water source, irrigation technologies and crops)

	Burkina	Mali	Niger	Senegal
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Households' irrigated land (across all plots)				
Share of land irrigated	0.012 (0.075)	.118(.31)	.018(.118)	.081(.263)
Total irrigated area(ha)	0.047 (0.39)	.40(4.89)	.026 (.194)	.312(6)
Number of plots irrigated	202	802	291	424
Household irrigation technology adoption				
Motopump	0.020 (.141)	.027(.163)	0.031(.173)	0.026(.159)
Manual pump	0.045 (.208)	.067(.25)	0.006(.08)	0.018(.134)
Primary source of irrigation (across irrigated plots) (%)				
Private wells	47.52	21.32	69.35	29.25
Canal irrigation	31.68	38.15	19.03	52.12
Brook/stream irrigation	15.84	38.40	10.65	14.86
Wetlands	4.95	2.12	0.97	3.8
Main irrigated crops (share of irrigated plots)				
Rice	0.18	0.77	0.21	0.46
Onion	0.28	0.08	0.27	0.09
Observations				
Plots	9433	5994	6280	6500
Households	3374	2586	3380	2280

Data source: Authors calculation using HSHLS (2018/2019)

Among the irrigating farms, farm-households with less than 2 hectares of total area irrigated are more prominent (Figure 6). Therefore, irrigation expansion in the Sahel should account for the specificities of SSI, which is explored further in the following sections.

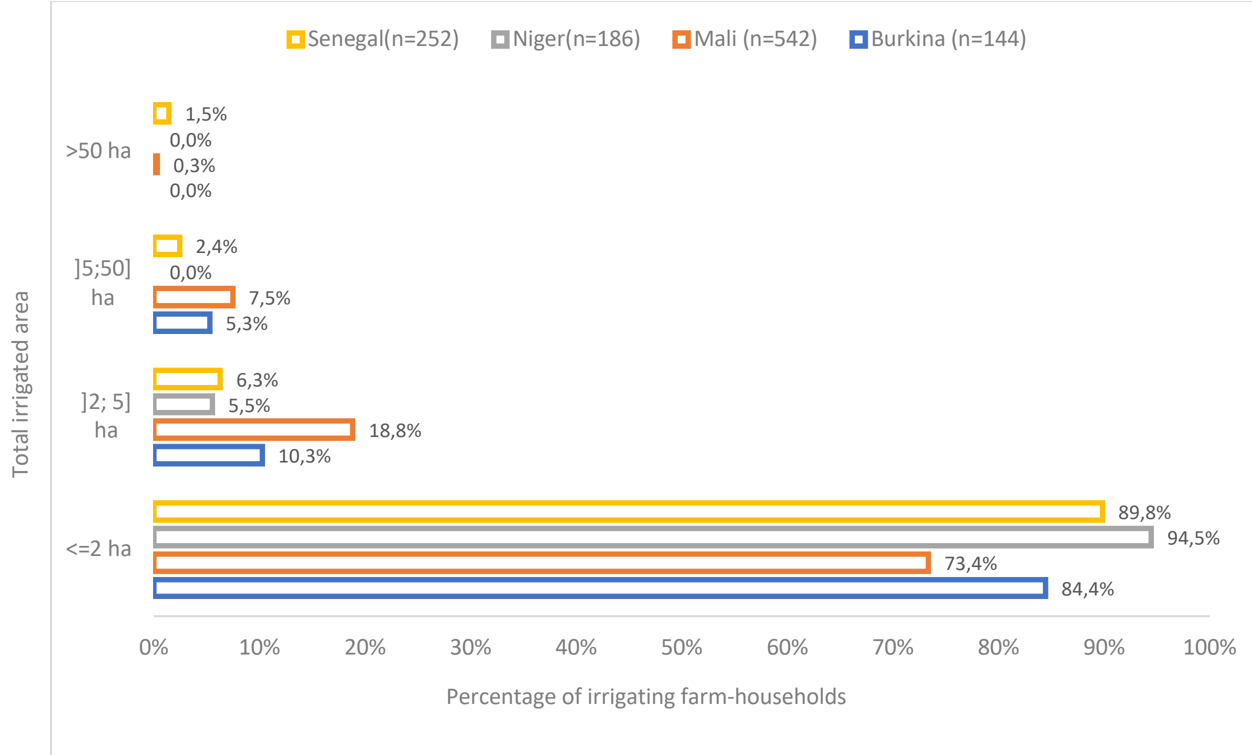

Figure 6: Share of irrigated farms by range of total area irrigated among irrigating farms

Source: Authors based on HSHLS (2018/2029)

5.2 Adoption of SSI in Burkina Faso, Mali, Niger, and Senegal

Table 5 shows that the adoption of SSI is very low in the Sahel, with a minimum of around 4% in Niger and Burkina Faso and a maximum of around 12% in Mali. Despite having the highest rates of SSI adoption, Mali and Senegal have the lowest rates of FSSI. Indeed, among small-scale irrigators, 64% are farmer-led in Niger, 58% in Burkina Faso, 46% in Senegal, and 38% in Mali.

Table 5: Adoption rates of SSI in the Sahel

	Mean	SD	Linearized std. err.	[95% conf. interval]		Observations
Burkina						
Irrigation	0.042	0.200	0.001	0.039	0.045	3374
SSI	0.035	0.185	0.001	0.033	0.037	
FSSI	0.58	0.495	0.01	0.56	0.601	132
Mali						
Irrigation	0.162	0.369	0.002	0.158	0.166	2586
SSI	0.119	0.324	0.001	0.116	0.122	
FSSI	0.376	0.485	0.006	0.364	0.387	419
Niger						
Irrigation	0.039	0.193	0.001	0.037	0.041	3380
SSI	0.037	0.188	0.001	0.035	0.038	
FSSI	0.635	0.483	0.007	0.620	0.649	175
Senegal						
Irrigation	.114	.317	.002	.110	117	2280
SSI	.102	0.303	0.002	0.099	0.105	
FSSI	0.462	0.500	0.008	0.447	0.477	227

Data source: Authors calculation using HSHLS (2018/2019)

The prevalence of private wells in Niger and Burkina Faso as primary sources of irrigation could explain the higher rates of FSSI in these countries. Furthermore, the higher rates of SSI and lower rates of FSSI in Senegal and Mali could be explained by the early irrigation investments in non-farmer-led collective large-scale irrigation schemes in these countries. On the other hand, in Niger, irrigation started to occupy a noticeable position in policies mainly from the 1990s (see Tadesse et al., 2024a). Furthermore, in Niger, efforts to develop smallholder private irrigation that started as early as 1995 were successful. Indeed, the Pilot Private irrigation Project and its succeeding scale-up project in 2002 promoted low-cost irrigation technologies by enhancing the supply chain for irrigation technologies and advisory services. However, this success relied heavily on project support (Abric et al., 2011).

The variances in the different samples show heterogeneity of SSI adoption rates confirmed by the regional analysis illustrated in Figures 7 to 10. Tables S16 to S17 in the supplementary materials show the data used to generate the maps.

In Mali, for instance, the divide is clear, with higher adoption rates of SSI in the northern regions (Gao and Timbuktu) and lower rates in the southern regions (e.g., Koulikoro, Kayes, Sikasso), which correspond to areas with higher rainfalls compared to the north. Mopti and Segou have higher rates of adoption compared to Koulikoro and Kayes, likely due to the presence of collective schemes exploiting the Niger river (see Table S2 in the supplementary materials), which can also explain the low rates of FSSI. Despite their lower adoption of SSI, there is potential to develop SSI in southern regions due to the presence of water resources (Figure 7) and suitability for solar-irrigation (IWMI, 2019, 2021; Xie and Ringler, 2022). Regarding FSSI adoption, rates are generally higher in regions with lower prominence of SSI.

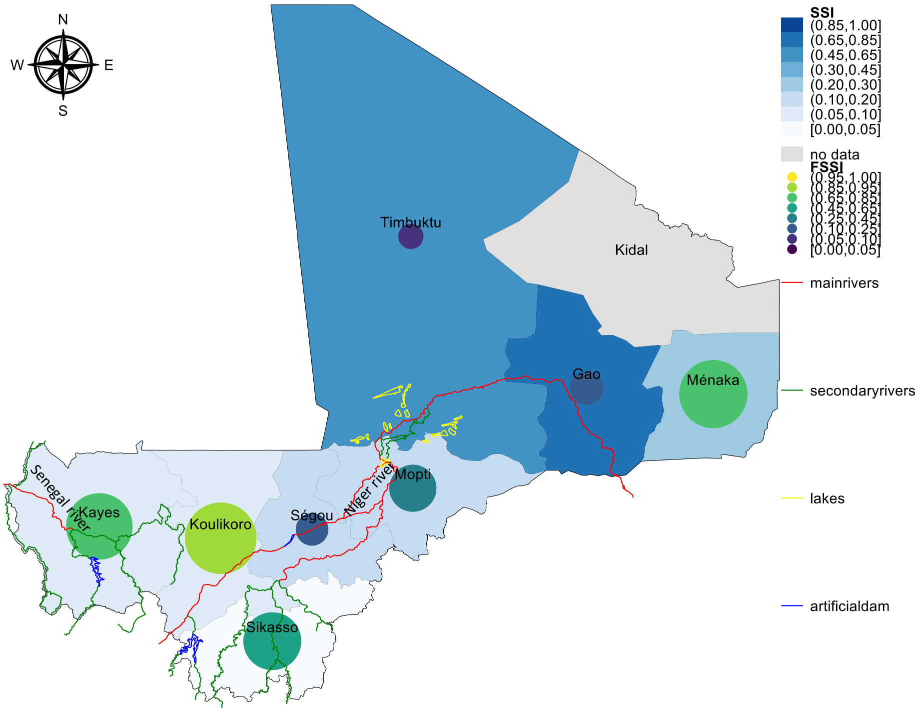

Figure 7: Adoption rates of SSI and FSSI in Mali

Source: Authors' elaboration based on DIVA-GIS spatial data (Accessed, 19.03.2024), https://data.humdata.org/dataset/mali-water-bodies-water-courses? for water bodies (accessed 14.06.2024)

Similarly, in Senegal, the highest rates of adoption are found in the north (St-Louis and Matam), with moderate rates in the coastal west. However, as in Mali, regions with the highest adoption rates of SSI have a lower presence of FSSI, except in the coastal west. In Senegal, SSI appears to be mainly farmer-led. These results can be explained by the presence of large permanent rivers, lakes, and canals in the north (including the Senegal River; Figure 8), allowing farmers to mainly grow irrigated rice and vegetables. Lastly, the coastal west (Niayes) is characterized by the presence of shallow groundwater that enables FSSI, thereby making this area the main hub supplying the country with irrigated fruits and vegetables. Surprisingly, Tambacounda and Kedougou have low rates of both SSI and FSSI, despite the presence of main and/or secondary rivers.

In both Mali and Senegal, annual rainfalls decrease from south to north. Therefore, the areas with the highest SSI rates correspond to those with the lowest annual rainfalls.

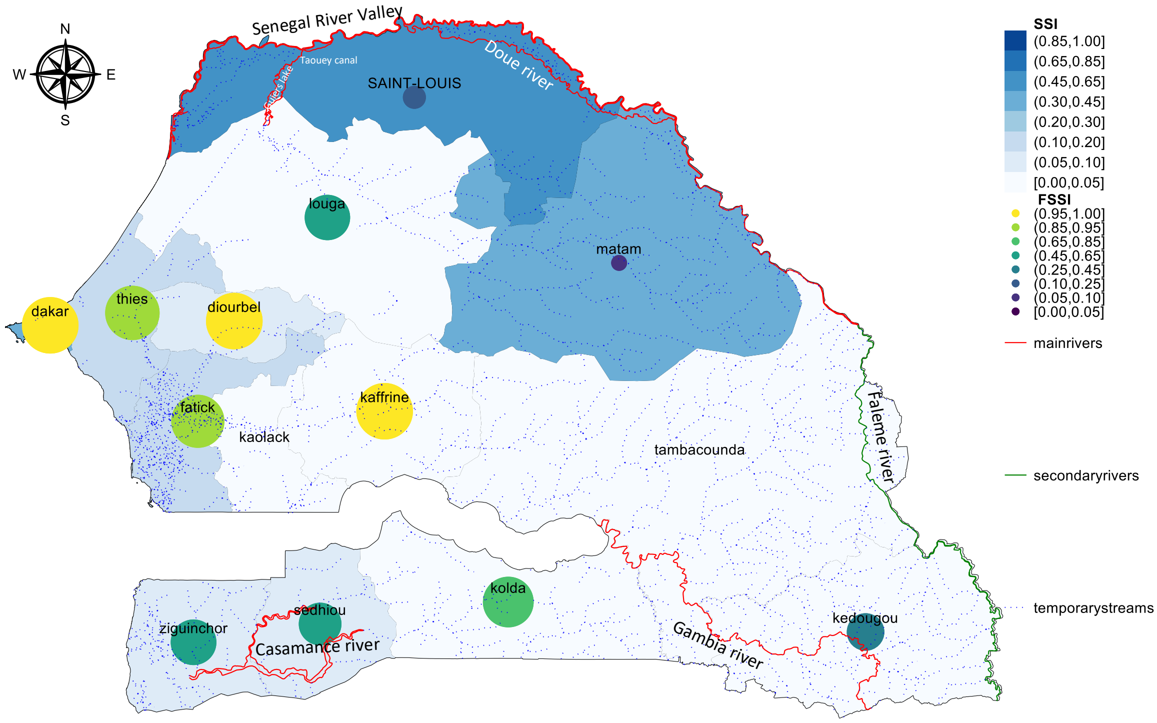

Figure 8: Adoption rates of SSI and FSSI in Senegal

Source: Authors' elaboration based on DIVA-GIS spatial data for regions (Accessed, 19.03.2024); https://data.humdata.org/dataset/senegal-water-courses? for water bodies (accessed 13.06.2024)

Contrary to Mali and Senegal, in Burkina Faso, adoption rates of SSI are highest in the centre and south-western regions, with the highest rates in the Hauts-Bassins (Figure 9). The lowest rates are noted in the northern regions. Adoption rates of FSSI are highest in the centre-west, centre-south and Hauts-Bassins. In Burkina Faso, rainfalls increase from north to south. Therefore, in contrast to Senegal and Mali, the areas with the highest rates of SSI are not necessarily the ones with the lowest annual rainfalls.

Most of these regions, especially the Boucle du Mouhoun, the centre-west, the Hauts-Bassins, and the north are considered suitable for small-scale irrigation. The profitable areas (IRR > 10%) are in the northern parts of Boucle du Mouhoun, in the southern part of the north region and in the central part of the centre-west region (Tadesse et al., 2024b).

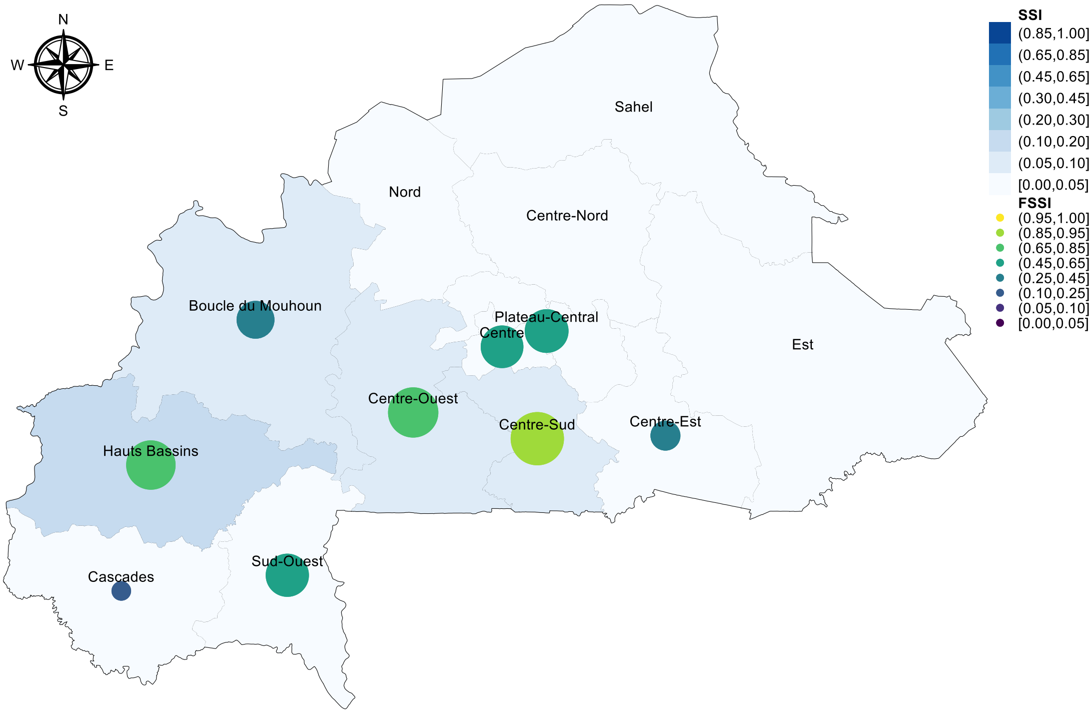

Figure 9: Adoption rates of SSI and FSSI in Burkina Faso

Source: Authors' elaboration based on DIVA-GIS spatial data (Accessed, 19.03.2024)[13]

In Niger, the Agadez region has the highest adoption of SSI (Figure 10). Adoption of FSSI is highest in Agadez and Zinder. However, in the latter, only 0.7% of farmers practice SSI.

The high performance in Agadez might stem from an exponential uptake of motor pumps over the past decade. However, potential feasible areas for SSI expansion are primarily located in western Niger, where most potentially feasible areas generate an IRR of 30% to 50%. Indeed, all feasible small-scale irrigation areas are found in Tillaberi and Dosso. Tahoua and Maradi have low but profitable irrigation potential (Tadesse et al., 2024a).

[13] The maps for Burkina Faso and Niger do not include water bodies as the various shapefiles available online are inconsistent.

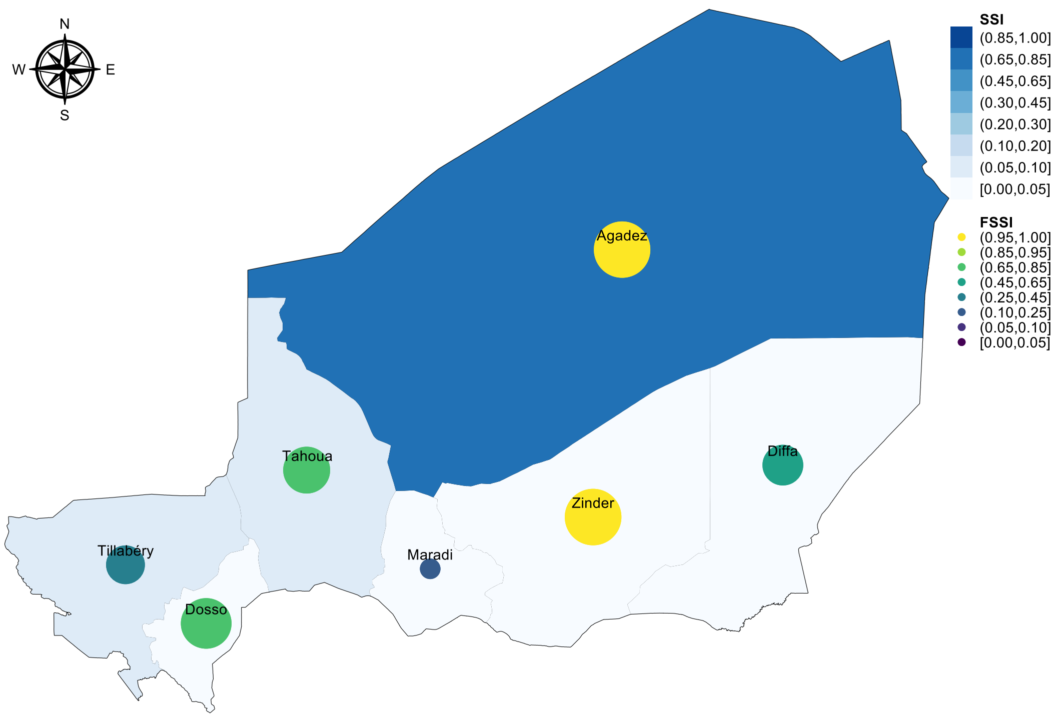

Figure 10: Adoption rates of SSI and FSSI in Niger

Source: Authors' elaboration based on DIVA-GIS spatial data (Accessed, 19.03.2024)

5.3 Comparison of small-scale irrigators and non-small-scale irrigators

Tables 6 and 7 compare SSIs and non-SSIs and FSSIs and NFSSIs, respectively. The comparison of SSIs and non-SSIs accounts for the heterogeneity within the two groups. Non-SSIs are subdivided into non-irrigators and larger scale irrigators. In general, household socio-demographic characteristics such as age, gender, and education show noticeable and significant differences between SSIs and non-SSIs with stronger differences between SSIs and LSIs compared to SSIs and non-irrigators. For instance, SSIs household heads are younger compared to non-SSIs with at least four years (resp. less than a year) of difference between SSI and LSI (resp. between SSI and no-irrigation). SSI households are more frequently male-headed compared to non-irrigators but more frequently female-headed compared to LSIs. Concerning education, household head alphabetization in a local language displays the most significant difference with SSI household heads being more frequently alphabetized compared to non-irrigators but less frequently alphabetized compared LSIs.

Compared to non-SSIs, SSIs have higher incomes compared to both non-irrigators and LSIs, although there are much larger differences between SSI and non-irrigators. This is in line with the positive effects of irrigation on household welfare. It also suggests a larger effect of SSI on household income, compared to LSI. Nevertheless, because we use expenditures as an income proxy, savings and credit might affect the differences. Credit access does, however, not seem to play a role in the difference between SSI and non-SSI. Concerning the other sources of income, the existence of livestock income seems to deter participation in SSI compared to no irrigation but plays no difference between SSIs and LSIs. However, the magnitude of the income is significantly larger for non-SSIs with a much higher difference between LSIs and SSIs. Therefore, when the difference in livestock income is relatively small between irrigators and non-irrigators, households might not be interested in irrigation. However, high livestock income differences might lead to the choice of LSI. Regarding off-farm income, its magnitude also seems to play a higher role than its mere existence. A larger share of non-SSIs has off-farm income. However, the magnitude is higher in the SSI group, with substantially higher differences between SSIs and LSIs. The relative importance of off-farm income in total household income is also higher for SSIs compared to LSIs, while it is higher for non-irrigators compared to SSIs.

SSIs tend to be smaller farms compared to non-SSIs. Indeed, farm size is almost two times larger in non-irrigators and more than four times larger in LSIs, compared to SSIs. However, areas cannot be directly compared between these groups. For instance, non-irrigators tend to practice rainfed agriculture which mainly focuses on cereals that are usually cultivated on larger areas of land compared to irrigated crops such as fruits and vegetables. Concerning technologies, a higher share of SSIs uses chemical fertilizers with expectedly larger differences between SSIs and non-irrigators. Furthermore, motor pumps are more prominent among SSIs than manual pumps. Also, the minor differences in the use of irrigation technologies compared to non-SSIs is not significant between SSI and LSI. SSI farms more frequently use renewable energy sources such as solar energy at the domestic level compared to non-irrigators, showing familiarity and awareness of the benefits of solar power. However, their use of domestic solar energy is much lower compared to LSIs.

Comparison of village characteristics, shows that SSIs are, by far, less likely to be located in villages where rainfed agriculture is dominant, compared to non-irrigators and to a lesser extent compared to LSIs. They, however, tend to be less likely to be located in villages with banks, markets and tap water, compared to non-irrigators and LSI. Therefore, improving access to these services might play in favor of SSIs to render their activity more profitable, particularly access to markets which seems to be the most constraining. Indeed, SSIs have higher fuel expenses for vehicles with a stronger gap between SSIs and LSIs. This shows the presence of means of transportation that could contribute to easing access to markets and information. However, higher fuel expenses also suggest higher transaction costs, especially since SSIs are located in villages that are farther from the closest cities compared to non-irrigators and farther from the closest roads compared to both non-irrigators and LSIs. The stronger difference with LSIs might further indicate the presence of selling contracts between LSIs and input/output dealers, which could reduce their need to travel to access to markets. Yet commercialization rate of SSIs is 16% and 8% higher compared to non-irrigators and LSIs, respectively. This could be related to the higher share of land cultivated under fruits and vegetables for SSIs, which tend to be high-value crops.

These findings highlight that access to infrastructure, education, use of productivity-enhancing technologies, and the presence of off-farm and non-crop income may drive (or be affected by) irrigation in general. However, the extent to which they may drive SSI, compared to LSI is less straightforward. These results further suggest the need to account for the heterogeneity of irrigation treatments when analyzing irrigation in Africa.

Table 6: Comparison of SSIs and non-SSIs

	SSI vs. no irrigation		SSI vs. LSI	
	Means Diff	T-stat.	Means Diff	T-stat.
Household characteristics and assets				
Household size	0.123	-3.537512***	0.326	-5.254276***
Gender of household head	0.026	-12.0664***	-0.070	25.74508***
Age of household head	-0.631	5.144815***	-4.418	13.52685***
Education of household head	0.002	-0.8925437	0.001	-0.0788529
Household head alphabetization	0.019	-6.146351***	-0.092	8.185177***
Household head has high school diploma	0.001	-3.012562**	0.002	-7.950776***
Total fuel expenses for vehicles (USD)	0.222	-8.917193***	0.537	-13.89062***
Total expenditures (USD)	344.485	-23.05521***	108.752	-3.513961***
Domestic use of solar energy (=1 if yes)	0.034	-6.173302***	-0.246	22.88863***
Farm size (hectares)	-1.517	48.61758***	-4.497	30.36418***
Land security	0.001	-0.9788118	0.005	-4.723208***
Share of land under cereals crop	-0.098	35.79906***	-0.144	35.51871***
Share of land under fruits and vegetables	0.168	-65.39151***	0.132	-46.48127***
Durables	0.014	-3.03063**	-0.037	3.541748***
Number of livestock units	-0.256	1.218112	0.953	-2.069592*
Use of technologies				
Uses chemical fertilizer	0.455	-133.3778***	0.105	-9.238455***
Owns motorized pump	0.251	-60.64623***	0.013	-1.314421
Owns manual pump	0.070	-21.24809***	0.001	-0.15786
Funding sources				
Contracted credit for the last 12 months	0.001	-0.1985213	0.005	-0.7213619
Existence of livestock income	-0.032	7.601***	0.005	-0.3478771
Net income from livestock (USD)	-4.932	4.449857***	-20.930	3.728745***
Existence of off-farm income	-0.150	30.78062***	-0.057	5.61518***
Off-farm income (USD)	18.085	-0.6943986	279.207	-8.177855***
Share of off-farm income in total expenditures	-0.067	13.11273***	0.052	-6.487621***
Commercialization rate	0.157	-38.19925***	0.083	-11.94541***
Village characteristics				
Location in rainfed agriculture village	-0.511	126.0739***	-0.108	9.610295***
Existence of bank	-0.016	9.240306***	-0.009	2.977523**
Existence of market	-0.043	7.381298***	-0.066	5.420446***
Distance to closest city (km)	1.753	-2.92514**	-24.005	14.97793***
Distance to closest road (km)	2.028	-10.0949***	1.273	-3.905557***
Presence of electricity grid	0.027	-5.717876***	-0.041	4.013337***
Presence of tap water	-0.027	5.870811***	-0.033	3.167905**
Observations	**11450**		**1123**	

Data source: Authors calculation using HSHLS (2018/2019); * p<0.05, ** p<0.01, *** p<0.001

Note: See in Table S19 in supplementary materials the means and standard deviations for each group.

Table 7 compares FSSIs and NFSSIs. Interestingly, more NFSSIs are located in villages with enabling conditions such as the presence of markets and an electricity grid. However, electricity might not be the first choice of energy source for FSSIs due to frequent power cuts and high tariffs in these countries. Furthermore, NFSSI is usually funded by donors or government. Their location may be the result of a selection based on the existence of enabling factors that can be leveraged to settle irrigation infrastructures and ease access to funding and markets. NFSSIs closeness to cities and roads compared to FSSIs also demonstrates less costly access to markets, likely also explaining the substantially higher transportation-related fuel expenses of FSSIs. Yet, FSSIs have higher commercialization rates, which is consistent with their higher share of land under fruits and vegetables. On the other hand, NFSSIs allocate more land to cereals than FSSIs. The higher cultivation of irrigated paddy rice in NFSSIs is understandable as multiple government or donor-funded irrigation schemes targeted rice production historically.

NFSSIs have lower income in general. Access to credit is significantly more important for NFSSIs than FSSIs. This can be explained by the support that NFSSIs benefit from. Concerning the other funding sources, NFSSIs have higher livestock income. However, their off-farm income and its share in the total expenditures is much lower than that of FSSIs.

Concerning technologies, despite their potential assistance in terms of access to inputs, surprisingly lower proportions of NFSSIs use chemical fertilizers compared to FSSIs.

These results suggest the need to further account for the heterogeneity of SSI when analyzing its drivers and impacts. Specifically, the analysis of the drivers and impacts of FSSI might require correcting for potential self-selection into FSSI and NFSSI once SSI occurs. SSI could also be considered as a simultaneous decision, where households have to choose between SSI, LSI or non-irrigation, or as a two-step decision, where farmers first choose to irrigate or not, before choosing between SSI and LSI. These distinctions are essential in microdata analysis but are hardly done in the literature on SSI in Africa, primarily due to the associations of SSI with farmer-led irrigation, which ignores the NFSSI (Haile et al., 2022) or to the consideration of SSI as a binary choice (irrigation or no irrigation) (Assefa et al., 2022; Nkonya et al., 2022) or to the comparison of adopters of farmer-led irrigation to non-adopters which can be composed of both non-farmer-led irrigators and non-irrigators (Osewe et al, 2020). Results also hint that NFSSI results from a non-random selection of areas with enabling village-level characteristics that can be leveraged to develop irrigation. This indicates the need to correct for a potential placement effect in impact analyses of SSI.

Table 7: Comparison of FSSIs and NFSSIs

	NFSSI		FSSI		
	Mean	**Std. dev.**	**Mean**	**Std. dev.**	**T-stat.**
Household characteristics and assets					
Household size	6.775	3.748	7.403	3.982	-13.86586***
Gender of household head	0.911	0.299	0.913	0.268	-0.5613542
Age of household head	45.529	14.582	45.924	13.785	-2.312083*
Education of household head	0.140	0.363	0.146	0.336	-1.684833
Household head alphabetization	0.284	0.473	0.318	0.443	-4.879836***
Household head has high school diploma	0.003	0.060	0.004	0.058	-1.069266
Total fuel expenses for vehicles (USD)	0.795	1.980	1.846	5.033	-29.43883***
Total expenditures (USD)	2758.998	2017.450	2931.123	1864.808	-7.804662***
Domestic use of solar energy (=1 if yes)	0.252	0.456	0.342	0.451	-15.31731***
Farm size (hectares)	2.536	2.484	3.057	2.850	-12.20612***
Land security	0.026	0.167	0.027	0.154	-0.7870663
Share of land under cereals crop	0.846	0.260	0.674	0.321	35.87048***
Share of land under fruits and vegetables	0.098	0.222	0.233	0.305	-30.86943***
Durables	0.318	0.625	0.370	0.625	-6.271756***
Number of livestock units	14.856	23.110	18.436	27.533	-13.58154***
Use of technologies					
Uses chemical fertilizer	0.705	0.478	0.805	0.377	-14.15784***
Owns motorized pump			0.428	0.470	-65.73357***
Owns manual pump			0.169	0.356	-34.51881***
Funding sources					
Contracted credit for the last 12 months	0.172	0.396	0.093	0.276	8.306802***
Existence of livestock income	0.443	0.521	0.473	0.475	-4.164835***
Net income from livestock (USD)	28.540	168.990	14.623	127.421	8.774663***
Existence of off-farm income	0.497	0.524	0.420	0.469	10.92416***
Off-farm income (USD)	460.549	2944.788	864.272	6339.848	-11.0327***
Share of off-farm income in total expenditures	0.167	0.565	0.235	0.803	-9.505745***
Commercialization rate	0.223	0.316	0.393	0.592	-40.39539***
Village characteristics					
Location in rainfed agriculture village	0.242	0.449	0.242	0.407	-0.0154696
Existence of bank	0.050	0.229	0.048	0.203	0.8450904
Existence of market	0.286	0.474	0.302	0.437	-2.123258*
Distance to closest city (km)	32.027	34.137	35.316	40.881	-5.324518***
Distance to closest road (km)	7.052	7.623	12.186	20.294	-19.21593***
Presence of electricity grid	0.190	0.411	0.169	0.356	3.379257***
Presence of tap water	0.202	0.421	0.197	0.378	0.9057946
Observations	**953**		**953**		

Data source: Authors calculation using HSHLS (2018/2019). * p<0.05, ** p<0.01, *** p<0.001

5.4 Profitability of alternative land, labour and water uses: Plot-level analysis

5.4.1 SSI profitability compared to alternative land and labour uses

Table 8 compares the per hectare costs and net returns, as well as land and labour productivity of plots under SSI and rainfed plots[14] and for the particular case of paddy rice.

Per hectare input costs, land, labour productivity, and net returns are consistently and significantly higher for irrigated plots compared to rainfed plots in all four countries. These findings are in line with most of the literature looking at another metric of land productivity in the Sahel (output per unit of land) (Tadesse et al., 2024a,b; Dillon, 2011; Olayide et al., 2022). Similarly, irrigated paddy rice plots have higher values for almost all these metrics in all the countries. Where some metrics are higher for rainfed plots, the differences are not statistically significant. This is particularly the case for net returns or land productivity in Burkina Faso and Niger where the number of irrigated or rainfed paddy plots might be too low to detect statistical significance.

Looking at specific indicators, net returns appear low compared to the cost of irrigation technologies in Figure 3. These low returns are particularly pronounced for solar-powered technologies, drip, and sprinkler irrigation systems, highlighting the cost constraint of acquiring technologies. Plot sizes further reveal small SSI plots, typically less than 0.6 hectares on average, which, as discussed, could explain the low uptake of modern indivisible irrigation technologies.

[14] It is worth noting that in the Sahel, rainfed plots are only cultivated during the rainfed season while SSI plots are mainly cultivated during the dry season which is much longer than the rainy season.

Table 8: Profitability of land under SSI to alternative land uses in the 2018/2019 agriculture year in the Sahel

	Burkina			Mali			Niger			Senegal		
	Rainfed	SSI		Rainfed	SSI		Rainfed	SSI		Rainfed	SSI	
	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.
All plots												
Input cost (USD/ha)	65.69	325.96	***	169.93	434.87	***	65.56	1407.12	***	255.55	603.93	***
	(127.83)	(48.53)		(475.71)	(185.62)		(265.49)	(850.19)		(1317.15)	(250.75)	
Land productivity (USD/ha)	265.94	1154.28	***	340.09	1335.82	***	125.54	3305.38	***	404.07	2699.33	***
	(643.28)	(273.58)		(1163.09)	(722.39)		(645.19)	(1202.24)		(1631.46)	(863.23)	
Net return (USD/ha)	200.25	828.32	***	170.16	900.95	**	59.98	1898.26	***	148.52	2095.40	***
	(626.21)	(258.39)		(1016.09)	(708.66)		(580.68)	(1113.55)		(1958.27)	(768.48)	
Labor productivity (USD/unit of labor)	2.94	6.93	***	4.88	11.19	***	2.52	8.50	***	3.24	6.74	***
	(5.55)	(1.55)		(12.18)	(6.51)		(4.08)	(2.45)		(7.61)	(2.26)	
Plot size (ha)	1.58	0.53	***	3.20	0.76	***	2.33	0.39	***	3.84	0.53	***
	(3.26)	(0.08)		(14.12)	(0.21)		(10.31)	(0.12)		(44.13)	(0.13)	
Observations	7588	167	7755	4145	339	4484	5005	241	5246	4989	208	5197
Rice plots												
Input cost (USD/ha)	124.10	204.37	***	176.28	385.09	***	191.72	739.37	**	468.43	510.65	ns
	(131.86)	(89.22)		(277.92)	(392.23)		(395.49)	(659.87)		(912.07)	(536.84)	
Land productivity (USD/ha)	618.80	582.80	ns	339.34	1076.37	***	436.58	810.59	ns	1343.50	2194.06	*
	(881.13)	(355.62)		(495.79)	(1103.02)		(894.61)	(574.41)		(2752.71)	(1760.01)	
Net return (USD/ha)	494.71	378.43	ns	163.06	691.27	***	244.86	71.22	ns	875.07	1683.41	**
	(892.65)	(342.42)		(517.58)	(1049.34)		(700.43)	(809.05)		(2473.19)	(1402.10)	
Labor productivity (USD/unit of labor)	5.52	8.02	ns	6.29	15.62	***	3.50	7.82	*	2.56	9.88	***
	(7.06)	(3.04)		(9.83)	(19.81)		(6.26)	(6.41)		(4.66)	(7.71)	
Plot size (ha)	1.29	0.61	*	2.18	0.94	***	0.65	0.64	ns	2.83	0.57	ns
	(1.80)	(0.22)		(1.88)	(0.60)		(0.83)	(0.45)		(26.16)	(0.26)	
Observations	410	29	439	289	283	572	35	51	86	355	86	441

Data source: Authors calculation using HSHLS (2018/2019). * p<0.05, ** p<0.01, *** p<0.001, ns= not significant

Labour productivity figures should be analyzed with caution, as labour has an opportunity cost. The latter can be proxied by estimating production functions to obtain the shadow wage of labour (von Braun et al., 1989) or by considering the rural and urban wages a household member could obtain in the labour market. Figure 11 compares the average rural daily wages over several years per economic activity and labour productivity in the different countries. In Niger and Mali, SSI labour productivity is substantially higher than agriculture wages and moderately higher than the wages in non-agriculture economic activities. In contrast, in Burkina Faso and Senegal, SSI labour productivity is close to agriculture wages and generally lower than the wages in non-agriculture economic activities.

Therefore, SSI seems a reasonable labour allocation activity compared to agriculture activities in Niger and Mali. Concerning the non-agriculture activities, the direct comparison of wages and labour productivity might not be sufficient to support this conclusion. Indeed, non-agriculture economic activities are usually found in urban areas in these Sahelian countries, implying that migration might be necessary to earn these wages. Consequently, migration-related costs of living might lead to lower earnings. For the case of Senegal and Burkina Faso both agriculture and non-agriculture economic activities seem to compete with SSI for labour.

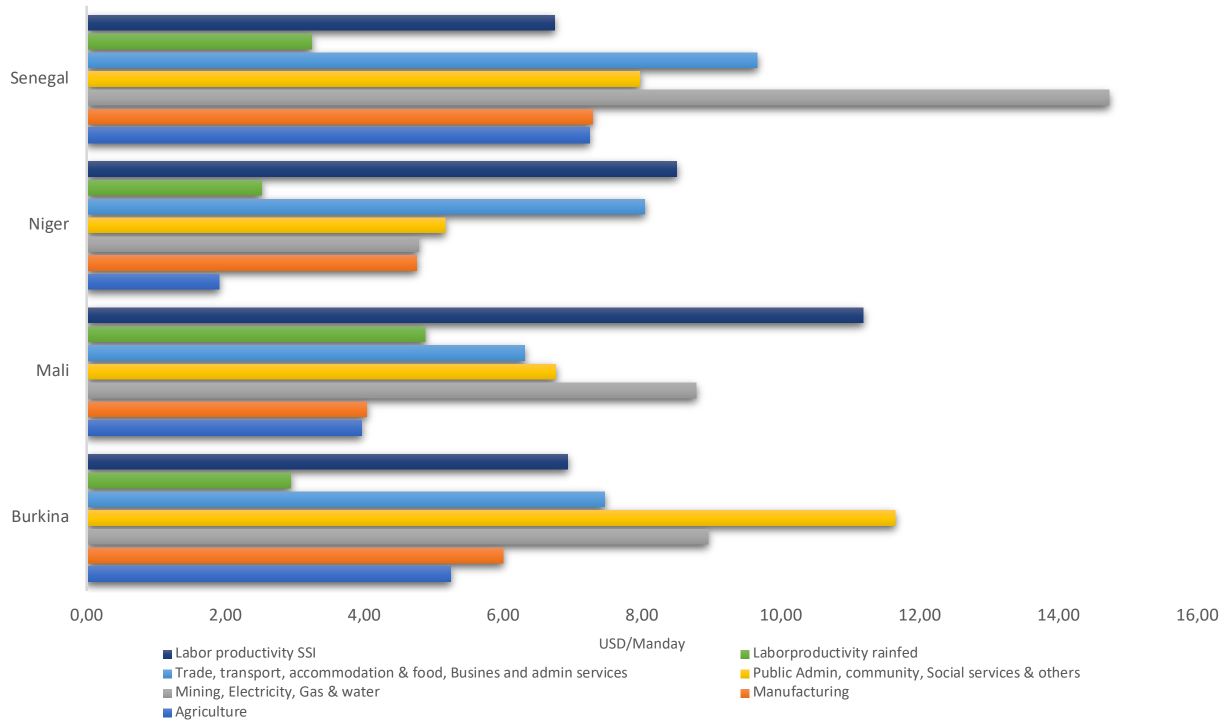

Figure 11: SSI labour productivity and wages in the Sahel

Source: Authors calculation based on HSHLS and ILO data (2013-2022- see Table S11 in Supplementary materials)

5.4.2 Comparative profitability of alternative SSI water uses

Table 9 compares the same metrics for onion and paddy rice for irrigated plots of SSIs in the four countries.

As expected, onion is more productive and profitable than paddy rice. This can be explained by the significantly higher onion yields in the Sahel compared to paddy rice, demonstrating that water use approaches are critical when promoting SSI. However, despite the higher performance of onion, rice has historically benefited from more interventions on SSI. These interventions have been relatively successful in reducing import dependence in some countries, especially in Mali. Indeed, the share of consumption supplied by local production is 93%, 38%, and 32% in Mali, Burkina Faso, and Senegal, respectively (IPAR, 2016). However, Table 10 also hints that to reach the objective of productivity (both land and labour) enhancement and poverty reduction in rural areas, besides irrigated rice, interventions to promote SSI should further target higher value crops such as vegetables that appear to have greater potential to increase such metrics without requiring large areas of land.

Table 9: Comparative profitability of land under SSI for different crops in the 2018/2019 agriculture year in the Sahel

	Burkina Faso			Mali			Niger			Senegal		
	Onion	Paddy Rice		Onion	Paddy Rice		Onion	Paddy Rice		Onion	Paddy Rice	
	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.
Input cost (USD)/ha	416.66 (355.41)	204.37 (89.22)	**	325.56 (482.20)	385.09 (393.35)	ns	1728.70 (2919.40)	739.37 (625.08)	**	1641.47 (3177.95)	510.65 (792.97)	ns
Land productivity (USD/ha)	3261.64 (2058.02)	582.80 (355.62)	***	2770.40 (3874.46)	1076.37 (1106.17)	ns	6466.60 (4281.08)	810.59 (544.12)	***	3359.42 (4261.75)	2194.06 (2599.71)	ns
Net return (USD)/ha	2844.98 (2237.72)	378.43 (342.42)	***	2444.85 (3803.80)	691.27 (1052.34)	ns	4737.90 (4235.75)	71.22 (766.39)	***	1717.95 (3511.38)	1683.41 (2071.04)	ns
Labour productivity (USD/unit of labour)	17.63 (12.89)	8.02 (3.04)	***	13.77 (26.16)	15.62 (19.87)	ns	13.69 (9.69)	7.82 (6.07)	**	6.22 (10.29)	9.88 (11.38)	ns
Plot size (ha)	0.58 (0.47)	0.61 (0.22)	ns	0.46 (0.57)	0.94 (0.60)	***	0.21 (0.31)	0.64 (0.43)	***	0.54 (0.57)	0.57 (0.39)	ns
Observations	49	29	78	23	283	306	68	51	119	19	86	105

Data source: Authors calculation using HSHLS (2018/2019). * p<0.05, ** p<0.01, *** p<0.001, ns= not significant

5.4.3. Comparative profitability of FSSI and NFSSI

To further look at the important factors in SSI promotion, we compare FSSI and NFSSI profitability in Tables 11 and 12).

Table 10 shows that variable input costs are much higher in FSSI compared to NFSSI. The latter usually gets support for input access or benefit from collective input acquisitions that might give them the opportunity to benefit from reduced transaction costs while FSSI might rely more frequently on their own means. Similarly, we found that NFSSI happens in location-privileged villages, easing access to markets and reducing transaction costs. This result might, however, be different if FSSI is collective, which is not studied here due to data limitations. Also, our previous comparison of FSSIs and NFSSIs shows that FSSIs use higher amounts of inputs such as chemical fertilizers. Finally, FSSIs have higher variable costs associated with their higher use of motor pumps.

However, all plots considered, FSSI generally performs better except in Mali, where NFSSI is more profitable, although the differences are not all significant (Table 10). This could be related to Mali investments in NFSSI via the promotion of rice.

Furthermore, when specific crops such as onion and rice are analyzed, NFSSI performs better in terms of lower input costs, per hectare value of output and net returns per hectare, particularly in Burkina Faso and Mali (see Table 11). This could be related to public and donor interventions in the different countries. For instance, as discussed, in Mali pathways to irrigation have mainly been non-farmer led with investments on collective large-scale or small-scale third-party-funded irrigation schemes. Also, as discussed, through those interventions, NFSSIs usually receive support for input access, production techniques, commercialization, etc., and are strategically located.

These results challenge the current trend towards FSSI, which is considered as a viable alternative to the traditional NFSSI (Durga et al, 2023), and suggest that both FSSI and NFSSI could be pathways to irrigation depending on the context and crops considered. However, further case studies using larger samples of both FSSI and NFSSI are needed to challenge the current findings.

Table 10: Comparative profitability of FSSI and NFSSI in the 2018/2019 agriculture year in the Sahel

	Burkina Faso			Mali			Niger			Senegal		
	NFSSI	FSSI		NFSSI	FSSI		NFSSI	FSSI		NFSSI	FSSI	
	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.	Mean (SD)	Mean (SD)	T-stat.
Input cost (USD)/ha	186.42 (112.12)	394.38 (265.54)	***	361.24 (352.29)	519.00 (685.12)	ns	436.90 (304.75)	1553.17 (3032.01)	***	585.31 (1371.01)	716.04 (971.10)	ns
Land productivity (USD/ha)	1058.18 (1102.34)	1345.07 (1623.00)	ns	1180.47 (1271.02)	912.31 (1326.83)	ns	891.61 (1056.06)	3911.11 (4434.26)	***	1949.45 (2515.24)	3495.31 (3658.51)	**
Net return (USD)/ha	871.76 (1080.64)	950.70 (1532.41)	ns	819.23 (1222.00)	393.31 (1188.84)	**	454.71 (968.75)	2357.94 (4232.83)	***	1364.13 (1934.35)	2779.27 (3406.06)	**
Labour productivity (USD/unit of labour)	7.72 (6.42)	9.12 (8.70)	ns	16.43 (19.28)	8.39 (17.48)	**	6.91 (5.20)	9.42 (9.22)	ns	8.16 (10.11)	7.89 (10.18)	ns
Plot size (ha)	0.66 (0.32)	0.53 (0.37)	ns	0.95 (0.57)	0.68 (0.69)	*	0.54 (0.28)	0.37 (0.52)	ns	0.60 (0.42)	0.46 (0.44)	ns
Observations	55	112	167	244	95	339	49	192	241	126	82	208

Data source: Authors calculation using HSHLS (2018/2019). * p<0.05, ** p<0.01, *** p<0.001, ns= not significant

Table 11: Comparative profitability of FSSI and NFSSI for different crops in the 2018/2019 agriculture year in the Sahel

	Burkina Faso		Mali		Niger		Senegal	
	Onion	**Rice**	**Onion**	**Rice**	**Onion**	**Rice**	**Onion**	**Rice**
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
FSSI								
Input cost (USD)/ha	524.97	256.96	314.99	616.41	1882.66	1116.00	968.21	1150.55
	(337.46)	(47.10)	(407.38)	(508.99)	(2855.41)	(766.54)	(1067.61)	(1237.81)
Land productivity (USD/ha)	2734.73	354.09	1174.64	784.49	6974.52	953.72	3693.82	5546.51
	(2099.14)	(91.34)	(1070.31)	(781.33)	(3603.73)	(633.36)	(4824.08)	(2834.44)
Net return (USD)/ha	2209.76	97.14	859.64	168.08	5091.86	-162.28	2725.61	4933.01
	(2196.91)	(85.82)	(939.64)	(729.56)	(3798.19)	(1052.86)	(4395.96)	(1601.86)
Labour productivity (USD/unit of labour)	13.98	9.91	3.93	9.84	14.86	7.15	8.34	12.93
	(12.25)	(1.65)	(4.09)	(14.20)	(8.78)	(4.71)	(14.22)	(11.92)
Plot size (ha)	0.47	0.82	0.46	0.81	0.21	0.81	0.47	0.19
	(0.41)	(0.15)	(0.48)	(0.62)	(0.30)	(0.52)	(0.42)	(0.07)
Observations	42	10	19	51	64	20	15	3
NFSSI								
Input cost (USD)/ha	229.76	176.88	360.16	364.16	597.22	518.32	2535.79	474.90
	(109.79)	(103.36)	(41.68)	(382.32)	(356.27)	(424.19)	(3249.42)	(719.05)
Land productivity (USD/ha)	4170.80	702.33	7995.66	1102.79	2733.64	726.58	3034.41	2018.42
	(594.21)	(447.01)	(564.39)	(1144.62)	(3849.43)	(512.24)	(3017.55)	(2500.77)
Net return (USD)/ha	3941.04	525.45	7635.50	738.63	2136.42	208.26	498.62	1543.52
	(672.12)	(402.71)	(563.24)	(1080.76)	(3496.61)	(450.29)	(415.53)	(2055.07)
Labour productivity (USD/unit of labour)	23.91	7.04	45.97	16.14	5.07	8.21	3.40	9.71
	(5.36)	(3.45)	(23.78)	(20.54)	(2.76)	(7.85)	(1.23)	(11.38)
Plot size (ha)	0.76	0.51	0.49	0.96	0.24	0.54	0.64	0.59
	(0.34)	(0.18)	(0.08)	(0.61)	(0.15)	(0.36)	(0.52)	(0.40)
Observations	7	19	4	232	4	31	4	83

Data source: Authors calculation using HSHLS (2018/2019)

Note: Due to small sample sizes, mean differences were not tested for.

6 Conclusion and policy implications

Microdata analysis shows that irrigation is still uncommon among farm-households in the Sahel. Indeed, irrigation adoption rates, are as low as 4% in countries such as Burkina Faso and Niger. Despite its prolonged political instability, Mali outperforms its counterparts with the highest adoption rate of 16% followed by Senegal, with 11%. Among the irrigating farms, small scale irrigators (irrigating farm-households with less than two hectares of total area irrigated) are more prominent.

In the HSHLS country samples, SSI adoption is highest in Mali (12%) followed by Senegal (10%) and lowest in Burkina Faso and Niger (around 4%). However, among SSIs, FSSI is more common than NFSSI in Niger and Burkina Faso (64% and 58% of SSIs, respectively) and less common in Mali and Senegal (38% and 46% of SSIs, respectively). Both SSI and FSSI show regional heterogeneity. In Mali and Senegal, northern regions have more adopters of SSI. Additionally, in Senegal, the coastal west has moderate rates of adoption. In Burkina Faso, it is rather the southwestern and central regions that have higher rates of SSI, while in Niger, the rates are high in Agadez compared to the other regions.

These results confirm the low prevalence of irrigation in SSA (Durga et al., 2023) and highlight the need for more investment in irrigation development and adoption, particularly due to the low adoption rates of SSI that could potentially improve household welfare. However, investments to expand irrigation should learn from the past performance of irrigation pathways, particularly collective large-and-small-scale irrigation schemes and private farm-households initiatives. Evidence shows that, although some differences in performance exist, both schemes can be economically viable pathways to SSI (You et al., 2011), provided that efficient management and maintenance of irrigation infrastructure is ensured. Besides scheme size, the farmer-led or non-farmer-led nature of SSI is an important feature to consider.

Concerning private farm-households initiatives, the comparison of SSIs and non-SSIs highlights that SSIs are less likely to be located in villages with services such as banks, markets, and tap water, compared to non-irrigators and LSIs. Their villages are also farther from cities and roads compared to non-SSIs, which could increase transaction costs. Therefore, improving joint access to these services might render SSI more profitable. Other factors that could be improved to expand SSI are education and access to productivity-enhancing technologies that may drive SSI.

However, despite being less privileged in terms of access to enabling conditions, SSIs have higher commercialization rates compared to non-SSIs (16% higher than that of non-irrigators and 8% higher than that of LSIs). This could be related to their higher shares of cultivated land under fruits and vegetables, which tend to be high-value crops. Concerning income, SSI seems to be positively associated with income as SSIs have higher income compared to both LSIs and non-irrigators. On the other hand, although livestock and off-farm income seem to be positively associated with irrigation compared to no-irrigation, the magnitude of livestock income seems to be positively associated with LSI compared to SSI, while the magnitude of off-farm income seems to be positively associated with the choice of SSI, compared to LSI.

The results further show that there may be specific drivers for different groups of small-scale irrigators, depending on whether they are farmer-led or not. For instance, access to credit does not appear to be the ideal channel to fund SSI[15]. However, when comparing FSSIs and NFSSIs, the latter have significantly higher access to credit. This could be explained by the support usually offered to NFSSIs that tend to be collective and supported by donors. Also, although SSIs are not located in privileged villages, NFSSIs are more likely to be located in villages with enabling conditions such as the presence of markets, an electricity grid, and close proximity to cities and roads. Yet, FSSIs have higher commercialization rates, which is consistent with their higher share of land under high value crops.

Profitability is another factor that could motivate SSI adoption. The analysis of land and labour profitability performed at the plot-level shows that SSI is more profitable than rainfed agriculture. Therefore, in addition to possibly allowing to smooth farm-households consumption across seasons by providing additional income, SSI could play a role in providing job opportunities in rural areas during the dry season. Indeed, comparison of labour productivity and wages in agriculture and non-agriculture sectors shows that SSI can be competitive compared to other economic activities in countries such as Mali and Niger. Within the SSI plots, the profitability analysis shows that FSSI performs better or worse compared to NFSSI, depending on crop types, third-party support and country specificities.

Improved irrigation technologies also could help expand SSI by reducing irrigation labour time and saving water, thereby allowing for the irrigation of larger areas of land. However, compared to SSI profitability, irrigation technologies are expensive, leading their low uptake. For instance, average net returns of irrigated plots were found to appear low compared to the cost of irrigation technologies, particularly solar-powered technologies, drip, and sprinkler irrigation systems. Furthermore, SSI farms cultivate very small plots, while irrigation technologies are indivisible and land is frequently fragmented in Sahelian countries. Therefore, sharing a technology across plots is notably useful, particularly for individual FSSI.

For individual FSSI, solar-powered irrigation technologies could be a way of improving irrigation expansion. Indeed, individual FSSIs have higher variable costs compared to NFSSIs as our results show. Improving the accessibility of such technologies through innovative financing mechanisms, such as the pay-as-you-go, could improve individual FSSIs' profitability by reducing their variable costs associated with motor pumps.

[15] The main channels to access to credit in these countries are informal channels such as "tontines", and formal channels such as cooperatives, banks, microfinance institutions, national funds, etc. (e.g. see in Mathurin et al. (2024)).

A Senegal case study of adoption of solar-technologies shows how limited it is compared to fuel-based technologies in both farm-household initiatives and collective small-scale irrigation schemes. In general, the few farm-households adopting solar pumps in the Senegal case study are mainly farmer-led small scale irrigators, that seem less risk-averse, have higher incomes, easier access to credit, and use groundwater resources for irrigation. Among small-scale collective irrigation schemes, solar-powered drip irrigation is the least adopted solar irrigation technology, compared to solar pumps, and solar panels. Public-private partnerships seem to have a critical role to play in the future of irrigation in the Sahel as they could ease the affordability of solar technologies.

Policy challenges relate mostly to maintaining and improving the progress in areas with high rates and ensuring spatial (across regions) and temporal (across seasons) extension of irrigation, mainly in areas where rainfed agriculture is still dominant and farmers primarily cultivate during the rainy season, which reduces their livelihoods during the off-season.

To complement policy implications provided in the literature (Malabo Montpellier Panel, 2018; You et al., 2011), the sequencing of actions to promote higher uptake of SSI in the Sahel seems important. Indeed, enhancing SSI in a given context needs to be based on planned sequential actions:

- identify potential areas for different irrigation pathways;
- use available data and research outputs on the drivers of SSI adoption to identify the combined set of complementary investments needed in the potential areas, as the needs are different depending on whether the adoption of SSI is already happening or not and the types of adopters;
- implement the identified investment mix, prioritizing areas where gains are higher.

Besides, in areas where water resources are easily accessible (not too deep groundwater or existing surface water resources), farmer-led individual irrigation initiatives should be prioritized by accompanying farmers in acquiring affordable irrigation technologies and accessing input and output markets. In such areas, resource management should also be planned to avoid overexploitation. In areas where water resources are not easily accessible (e.g. when groundwater is too deep or surface water is not present), irrigated agriculture development must be non-farmer-led through large or small-scale collective initiatives supported by public means or donors as irrigation investments are not affordable to individual farm-households. However, such initiatives must be revisited to solve the existing governance issues.

Lastly, in addition to the traditional focus on irrigated rice, irrigation investments should target more high-value crops that are more profitable and require less land.

In terms of research, the availability of irrigation data could be greatly improved by including some minor details on irrigation technologies and costs in the agricultural modules of national surveys. This could help to better guide decision making on irrigation in the Sahel. Last but not least, further research based on an unambiguous definition of SSI that investigates the drivers and impacts of SSI, distinguishing between FSSI and NFSSI using larger samples of the latter is needed to challenge the current findings and better target irrigation interventions.

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Appendix: Supplementary materials

Table S12: Irrigation in the Sahel in 2020

	Mali	Niger	Senegal	Burkina	SSA	World
Cultivated area[a](x1000ha)	8302	17813	3830	6614	242284.35	1575907.9
Area equipped for irrigation (x1000ha) (A)	371.07	101.59	120.1	54.27	6816.16	331497.94
% of irrigation potential equipped for irrigation	65.56	37.63	29.36	32.89		
% of cultivated area equipped for irrigation (%)	4.47	0.57	3.14	0.82	2.81	21.04
% of groundwater in A	0.27	1.35	8.33	5.53	9.55[b]	36.54
% of Surface water in A	99.98	71.16	91.34	40.54	66.62[b]	59.11
% of mixed surface and groundwater in A	0	nd	nd	0	0.11[b]	4.36
Area equipped for irrigation actually irrigated (x1000ha)	175.8	87.87	69	46.13	3528.82	271717.10
% of the equipped area actually irrigated	47.38	86.49	57.45	85	51.77	81.97
Harvested irrigated temporary crop area(x1000)						
Maize	0.44	0.42	2.97	2.730		
Other crops	106.94	4.41	1.81[c]	2.02[c]		
Rice	105.3	13.54	80.68	15		
Sugarcane	5.04	0.053	10.75	3.9		
Vegetables	60	0.16	13.61	10		
Sorghum	1.51	1.54	nd	4		
Total	205.2	17.75	106.2	37.65		
Total harvested irrigated permanent crop area	4.37	nd	nd	1.45		

Source: AQUASTAT (2020), accessed 27 May 2024
See https://www.fao.org/4/v8260b/V8260B03.htm for the definition of variables according to FAO
[a] Arable land + permanent crops
[b] Calculated using the area equipped for irrigation and area irrigated using the corresponding source of water
[c] Calculated using total- sum (Maize, rice, sugarcane, vegetables and sorghum).

Table S13: Characteristics of IDMAs in the Sahel

Country	IDMA	Acronym	Year of creation	Regions covered (examples)	Irrigated schemes	Total area covered by IDMA schemes	crops	Current management	Farmers invoved	Source
Burkina	BAGREPOLE	Société de Développement Intégré du Pôle de Croissance de Bagré	2011*	Centre-Est andCentre-South	>3	> 5500 ha	Rice, Maize, tomato, onion, ..., fruits	Producer organizations and IDMA	>4500 farmers and 20 agricultural entrepreneurs	AFD, AFEID & COSTEA (2021b)
	AMVS	Autorité de Mise en valeur de la Vallée du Sourou	1986**	Boucle du Mouhoun		30 000 ha potentially irrigable. 6558 ha equipped for irrigation	Dry season: Onion (3177 ha), Rice (715 ha), Tomato (308 ha); Maize (196ha); Green bean (48 ha); Humid season: Maize(4162ha), Rice (738 ha)	Cooperatives and associated WUAs supported by AMVS	>12.000 households and 20 agricultural entrepreneurs	GRET, SCP & COSTEA(2021); AFD, AFEID & COSTEA (2021a)
Mali	Office du Niger		1930	Segou						
Mali	ODRS	Office de Développement Rural de Sélingué	1996	Sikasso, Koulikoro	2	2 294 ha	IDMA dominantly			AFD, AFEID,COSTEA(2021c)
Mali	OPIB									
Mali	Office du Riz Segou (ORS)			Segou			Rice			
Niger	ONAHA	Office National des Aménagements Hydro-Agricoles	1978	Tillaberi	33	8473.78 ha (7581.3 ha exploitables)	Rice and polyculture (2 out of 33)	33 coopératives and WUAs	27 674 exploitants dont 616 femmes	GRET, SCP, COSTEA(2022)
				Niamey	6	752 ha (722,25 ha exploitable)	Rice	6 cooperatives	2 945 farmers (43 women)	
				Tahoua	16	113 371 km²	Polyculture			
				Dosso						
Senegal	SAED	Société d'Aménagement et d'Exploitation des Terres du	1965	St-Louis	6 (transfer between 1991 & 2017)		Rice and polyculture	Unions and WUAS		GRET, SCP, COSTEA(2021)

		Delta du Fleuve Sénégal	
	SODAGRI	Société de Développement Agricole et Industriel du Sénégal	Rice and polyculture

***, **Antecedents: see in Bazile et al (2020)**

Table S14: Key variables definition

Variables	Household-level	Plot-level
Treatments		
SSI	=1 if farm-households participate in small-scale irrigation and 0 otherwise. Farm households are considered to be participating in SSI if they use at least one source of irrigation that is different from rainfalls on at least one of their plots and their total irrigated area is less than 2 hectares.	= 1 if households participate in SSI and plot is irrigated using at least one source of irrigation that is different from rainfalls, 0 otherwise.
FSSI	=1 if farm-households participate in farmer-led small-scale irrigation and 0 otherwise. Conditional on SSI=1, farm-households are considered to participate in FSSI if (i) they reported “own wells” as their main source of irrigation for at least one irrigated plot or (ii) when they use other irrigation sources on a plot, they own a pump.	= 1 if plot is under SSI and plot is irrigated using “own wells” or when they use other irrigation sources on a plot, households own a pump, 0 otherwise.
Outcomes		
Input cost (USD)/ha	=average input cost across all plots	= sum (value of used chemical input/ha, value of used organic inputs/ha, value of used seeds/ha, cost of hired labor/ha, irrigation costs/ha). All the inputs used and for which a market exists are valued regardless of whether or not they are bought. This means that family labour is not valued. Irrigation costs include the depreciation cost of irrigation pumps and the operation and energy costs. The latter two costs were not available in the HSHLS datasets. Therefore, we used secondary data on small-scale irrigation schemes from Xie et al, (2011) for the operation costs. We applied the cost of 40$/ha/year to all the irrigated fields. The energy costs of 90.8 euros/ha were taken from Borgia et al. (2013) Cost of hired labour is composed of the cost of hired labour for land preparation and sowing, soil maintenance and harvesting. For each stage ($i = land\ preparation\ and\ sowing, soil\ maintenance, harvesting$) , labor cost_i= (male mandays_i* daily male wage_i) + (female mandays_i* $\text{daily female wage}_i$) + ($\text{boys mandays}_i$* daily boys wage_i) + (girls mandays_i* $\text{daily girls wage}_i$). Males and females are above 15 years old and boys and girls are below 15 years old. Daily wages correspond to the commonly paid wages in each village. We further add irrigation labor for pump owners from Nkonya et al (2022) who provided data on labor days per type of technology to irrigate 4 hectares per year and for 3-crop cycles each year. We applied 31.42 mandays and 4.66 mandays per ha and per crop for manual and motor pumps respectively.
Land productivity (USD)/ha		= value of output on plot /area of the plot
Labor productivity (USD/mandays)		= value of output on plot / sum (family and hired mandays used on plot)

Variables	Household-level	Plot-level
Net returns per hectare (USD)/ha		= value of output/ha - input cost/ha
Socio-demo characteristics		
Household size	Number of household members listed	
Gender of household head	=1 if man	
Age of household head	Age	
Household head alphabetization	= 1 if alphabetized	
Household head education	= 1 if household head has been to formal school	
Household head possession of high school diploma	= 1 if yes	
Farm size	= Total area across all plots, in hectares	
Total area irrigated	= Sum of the area over irrigated plots	
Share of land under irrigation	= Total area irrigated / Farm size	
Fuel expenses	= Total fuel expenses for vehicles in USD	
Domestic use of solar energy	= 1 if yes	
Land security	= 1 if household possesses land title for at least one cultivated plot	
Share of land under cereals (respectively fruits and vegetables)	= Total area under cereals (resp. fruits and vegetables) crops / Farm size	
Total annual expenditures (USD)	= Sum of food and non-food expenditures (excluding durable goods).	
Existence of livestock (resp. off-farm) income	=1 if the income type exists, 0 otherwise	
Livestock net income (USD)	= Total livestock revenue - Total livestock cost Cost of livestock includes the cost of feed, water, health (vaccines and others).	
Off-farm income (USD)	= Annual household income from wages + Annual net income from household enterprises + Annual remittances	
Share of off-farm income in total expenditures	= Off-farm income/ Total annual expenditures	

Variables	Household-level	Plot-level
Commercialization rate	= average of (value of output/ value of sales) across all plots	
Owns motor (respectively manual) pump	= 1 if household owns a motor (resp. manual) pump	
Use of chemical fertiliser	= 1 if household uses chemical fertilizer in at least one plot	
Durables	=number of durable goods that the household purchased the 12 months preceding the survey	
Livestock units	=Number of livestock units that the household owns	
Access to credit	= 1 if at least one household member contracted credit for the last 12 months preceding the survey	
Village characteristics		
Location in purely rainfed agriculture village	= 1 if farmers in the village do not usually practice irrigated agriculture. This variable was recorded during the survey at the village level.	
Presence of bank/ market/electricity grid/tap water	=1 if the service exists in the village	
Distance to closest city (km)	= distance to the closest city to the village	
Plot characteristics		
Primary source of irrigation		=private wells, canal irrigation, brook/stream irrigation, wetlands
Plot fertility		= respondent's perception of the fertility of the plot (good, medium, poor)
Soil type		= Type of soil on plot (Sandy, loamy, clay, glaze)
Plot security		= 1 if household possesses land title for the plot
Plot management		= 1 if plot is management by an individual household member, 0 if it is collectively management by multiple household members
Time to plot (minutes)		= time to reach plot with the usual mean of transportation

Source: Authors

Table S15: Description of country samples

Variables	Irrigation status	Senegal Mean	Senegal sd	Senegal obs	Niger Mean	Niger sd	Niger obs	Mali Mean	Mali sd	Mali obs	Burkina Mean	Burkina sd	Burkina obs
Household size	No irrigation	11.19	6.24	2028	6.28	3.08	3194	7.83	3.91	2,044	7.25	4.15	3232
	SSI	10.86	6.59	227	6.64	3.92	175	6.98	3.44	419	7.02	3.93	132
	LSI	11.67	5.58	25	4.80	1.90	11	8.61	5.89	123	9.72	4.52	11
Household head alphabetization	No irrigation	0.36	0.48		0.31	0.46		0.32	0.45		0.22	0.42	
	SSI	0.37	0.48		0.32	0.55		0.39	0.57		0.30	0.48	
	LSI	0.52	0.49		0.51	0.62		0.37	0.51		0.45	0.35	
Gender of household head	No irrigation	0.87	0.33		0.86	0.35		0.96	0.19		0.89	0.32	
	SSI	0.86	0.34		0.91	0.34		0.94	0.27		0.91	0.30	
	LSI	1.00	0.00		1.00	0.00		0.96	0.21		1.00	0.00	
Age of household head	No irrigation	51.73	13.56		43.88	14.47		49.49	14.44		46.86	14.64	
	SSI	48.84	14.76		43.59	15.82		49.32	17.00		44.67	14.57	
	LSI	50.72	10.12		42.79	10.56		51.62	16.90		54.71	8.98	
Farm size (hectares)	No irrigation	7.09	41.32		3.81	16.56		5.83	13.17		3.55	3.92	
	SSI	1.81	2.53		2.59	3.06		2.01	3.11		3.21	2.57	
	LSI	22.89	49.81		5.17	5.05		8.41	23.49		7.91	3.37	
Location in rainfed agriculture village	No irrigation	0.79	0.41		0.70	0.45		0.72	0.44		0.76	0.43	
	SSI	0.30	0.45		0.09	0.34		0.37	0.56		0.25	0.45	
	LSI	0.32	0.45		0.22	0.51		0.29	0.47		0.26	0.31	
Presence of bank	No irrigation	0.07	0.26		0.03	0.16		0.13	0.32		0.07	0.26	
	SSI	0.11	0.31		0.00	0.00		0.18	0.45		0.04	0.21	
	LSI	0.33	0.46		0.06	0.30		0.25	0.45		0.00	0.00	
Presence of market	No irrigation	0.32	0.47		0.17	0.37		0.35	0.46		0.59	0.49	
	SSI	0.39	0.48		0.06	0.28		0.33	0.55		0.69	0.48	
	LSI	0.64	0.47		0.31	0.57		0.28	0.47		0.30	0.32	
Distance to closest city (km)	No irrigation	18.67	18.81		35.22	27.19		38.79	33.10		30.03	23.59	
	SSI	13.41	11.50		35.97	57.16		31.33	43.56		45.08	38.93	
	LSI	8.24	8.01		51.99	78.66		30.39	37.26		77.26	25.41	

Distance to closest road (km)	No irrigation	0.67	1.45	14.53	10.45	8.16	4.90	2.04	2.15
	SSI	2.47	3.48	19.98	31.20	9.89	7.60	1.30	1.64
	LSI	2.30	2.94	13.18	21.14	9.30	5.79	0.63	0.50
Presence of electricity grid	No irrigation	0.39	0.49	0.15	0.35	0.06	0.24	0.17	0.38
	SSI	0.56	0.49	0.14	0.41	0.13	0.40	0.26	0.46
	LSI	0.55	0.48	0.38	0.60	0.02	0.15	0.15	0.25
Presence of tap water	No irrigation	0.73	0.44	0.28	0.44	0.13	0.33	0.12	0.32
	SSI	0.74	0.43	0.16	0.43	0.23	0.49	0.23	0.44
	LSI	0.81	0.38	0.21	0.50	0.06	0.24	0.13	0.24
Contracted credit for the last 12 months	No irrigation	0.09	0.29	0.20	0.40	0.06	0.23	0.03	0.17
	SSI	0.03	0.17	0.19	0.47	0.04	0.22	0.06	0.25
	LSI	0.24	0.42	0.20	0.50	0.04	0.22	0.00	0.00
Uses chemical fertilizer	No irrigation	0.40	0.49	0.12	0.32	0.54	0.48	0.48	0.50
	SSI	0.80	0.39	0.81	0.47	0.61	0.57	0.87	0.36
	LSI	0.78	0.40	0.64	0.59	0.75	0.46	0.95	0.16
Net income from livestock (USD)	No irrigation	-26.21	431.45	17.33	229.73	30.78	724.33	33.31	842.61
	SSI	-56.73	291.69	19.76	129.04	20.24	196.82	53.54	277.52
	LSI	-35.92	215.39	89.15	343.86	16.83	159.77	72.65	74.16
Existence of livestock income	No irrigation	0.35	0.48	0.45	0.49	0.42	0.48	0.63	0.48
	SSI	0.26	0.43	0.43	0.59	0.34	0.55	0.59	0.52
	LSI	0.19	0.38	0.46	0.61	0.24	0.45	0.91	0.20
Off-farm income (USD)	No irrigation	1672.42	9176.43	847.02	9300.79	500.86	4760.84	551.56	4886.87
	SSI	569.92	8150.37	950.50	8351.23	496.51	1782.01	679.55	3033.57
	LSI	605.64	1959.62	327.99	563.14	455.78	1162.24	1378.70	2833.36
Existence of off-farm income	No irrigation	0.70	0.46	0.67	0.46	0.54	0.48	0.52	0.50
	SSI	0.67	0.46	0.47	0.59	0.45	0.58	0.39	0.51
	LSI	0.66	0.46	0.68	0.57	0.44	0.52	0.57	0.35
Share of off-farm income in total expenditures	No irrigation	0.25	1.12	0.36	1.34	0.18	0.88	0.22	1.06
	SSI	0.14	1.01	0.22	0.96	0.16	0.61	0.24	0.72
	LSI	0.09	0.34	0.19	0.42	0.13	0.32	0.34	0.65
	No irrigation	5763.39	3490.83	1978.53	1109.18	3235.18	1835.76	2405.19	1477.40

Total expenditures (USD)	SSI	5573.38	3333.92	2755.97	1824.35	3409.88	2394.20	2328.85	1683.74
	LSI	6464.04	2732.26	2561.05	1335.07	4412.05	2980.07	2254.13	1076.73
Owns motorized pump	No irrigation	0.00	0.07	0.02	0.12	0.02	0.12	0.01	0.11
	SSI	0.20	0.40	0.40	0.58	0.08	0.33	0.20	0.42
	LSI	0.10	0.29	0.51	0.62	0.09	0.29	0.32	0.33
Owns manual pump	No irrigation	0.01	0.10	0.00	0.05	0.07	0.24	0.04	0.20
	SSI	0.07	0.26	0.09	0.34	0.07	0.30	0.12	0.34
	LSI	0.20	0.39	0.14	0.43	0.04	0.21	0.11	0.23
Domestic use of solar energy (=1 if yes)	No irrigation	0.26	0.44	0.04	0.19	0.68	0.45	0.35	0.48
	SSI	0.22	0.41	0.07	0.30	0.58	0.58	0.50	0.53
	LSI	0.23	0.41	0.39	0.60	0.83	0.39	0.75	0.31
Total fuel expenses for vehicles (USD)	No irrigation	1.28	6.00	0.35	2.62	2.25	3.08	1.73	2.68
	SSI	0.36	1.48	1.10	7.44	1.75	3.23	2.09	2.94
	LSI	0.34	1.32	0.00	0.00	2.90	3.86	1.91	1.24
Share of land under cereals crop	No irrigation	0.49	0.32	0.95	0.18	0.79	0.27	0.80	0.24
	SSI	0.59	0.41	0.73	0.43	0.82	0.37	0.75	0.22
	LSI	0.58	0.42	0.94	0.21	0.94	0.18	0.85	0.12
Share of land under fruits and vegetables	No irrigation	0.06	0.20	0.00	0.05	0.01	0.06	0.01	0.06
	SSI	0.26	0.40	0.23	0.41	0.13	0.33	0.12	0.15
	LSI	0.20	0.36	0.04	0.20	0.03	0.14	0.08	0.10
Land security	No irrigation	0.05	0.21	0.01	0.11	0.02	0.15	0.02	0.12
	SSI	0.09	0.28	0.09	0.34	0.16	0.43	0.10	0.31
	LSI	0.12	0.31	0.00	0.00	0.25	0.46	0.25	0.31
Household head has high school diploma	No irrigation	0.01	0.09	0.00	0.05	0.00	0.06	0.00	0.02
	SSI	0.01	0.09	0.00	0.00	0.01	0.14	0.00	0.00
	LSI	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.17
Commercialization rate	No irrigation	0.38	1.37	0.07	0.27	0.25	2.27	0.25	0.70
	SSI	0.33	0.37	0.40	1.78	0.13	0.26	0.44	0.32
	LSI	0.59	0.91	0.17	0.36	0.17	0.24	0.52	0.14
Durables	No irrigation	0.59	0.82	0.22	0.50	0.53	0.78	0.35	0.63
	SSI	0.63	0.91	0.32	0.67	0.51	0.90	0.32	0.62

	LSI	0.60	0.89	0.52	0.62	0.73	0.91	0.66	0.48
Livestock units	No irrigation	21.59	46.86	8.81	14.05	19.88	27.01	27.31	34.92
	SSI	20.57	40.07	10.97	20.17	14.24	33.08	28.14	33.33
	LSI	29.81	116.10	9.56	14.61	12.58	20.06	38.41	19.64
Education of household head	No irrigation	0.15	0.36	0.14	0.35	0.18	0.37	0.11	0.31
	SSI	0.18	0.38	0.14	0.42	0.21	0.47	0.17	0.40
	LSI	0.30	0.45	0.14	0.43	0.20	0.42	0.13	0.24

Source: Authors bases on HSHLS (2018/2019)

Table s16: mlogit results on the observable drivers of SSI

VARIABLES	SSI[a]	Larger-scale irrigation
Household head education	0.180***	0.0727***
	(0.0168)	(0.0263)
Household size centered[b]	-0.0238***	-0.00367
	(0.00240)	(0.00416)
(Household size centered)^2	-0.00121***	0.00600***
	(0.000226)	(0.000523)
(Household size centered)^3	3.46e-05***	-0.000139***
	(4.65e-06)	(1.29e-05)
Land security	1.914***	2.526***
	(0.0270)	(0.0403)
Durable centered	0.115***	0.745***
	(0.0179)	(0.0264)
(Durable centered)^2	-0.0825***	-0.490***
	(0.0188)	(0.0264)
(Durable centered)^3	0.00684*	0.0688***
	(0.00363)	(0.00438)
Log (distance to closest road)	0.0501***	-0.0781***
	(0.0122)	(0.0262)
Presence of bank	0.0607*	0.887***
	(0.0322)	(0.0539)
Presence of tap water	0.134***	-0.867***
	(0.0266)	(0.0470)
Country[c]		
2. Mali	1.117***	0.625***
	(0.0442)	(0.101)
3. Niger	-0.110***	-0.674***
	(0.0410)	(0.0721)
4. Senegal	1.191***	1.985***
	(0.0297)	(0.0550)
Constant	-3.404***	-5.118***
	(0.0291)	(0.0660)
Observations	11620	

Source: Authors bases on HSHLS (2018/2019)

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Notes: [a]no irrigation (N=10667) is the base outcome. [b] The variables household size and durables were centered by extracting their means to avoid potential multicollinearity between these variables and the calculated squared and cubed terms. [C] Burkina is the base country.

Table S17:Balancing of SSI and non-SSI groups before and after ipw

	Standardised diff. before ipw[a] (treated=LSI, untreated=no irrigation)	**Standardised diff. after ipw (treated=LSI, untreated=no irrigation)**	**Standardised diff. before ipw (treated=SSI, untreated=no irrigation)**	**Standardised diff. after ipw (treated=SSI, untreated=no irrigation)**	**Standardised diff. before ipw (treated 1=SSI, treated 2=LSI)**	**Standardised diff. after ipw (treated 1=SSI, treated 2=LSI)**
Quantitative variables						
Household size centered	0.315	**-0.041**	0.027	**0.026**	-0.297	**0.068**
(Household size centered)^2	0.207	**-0.022**	-0.017	**-0.008**	-0.235	**0.015**
(Household size centered)^3	0.174	**-0.021**	-0.003	**-0.004**	-0.205	**0.019**
Durable centered	0.461	**0.066**	0.126	**0.019**	-0.327	**-0.046**
(Durable centered)^2	0.213	**-0.047**	0.064	**0.003**	-0.152	**0.047**
(Durable centered)^3	0.144	**-0.03**	0.037	**-0.002**	-0.114	**0.03**
Log (distance to closest road)	0.023	**-0.086**	0.026	**-0.073**	0.006	**0.004**
Categorical variables						
Household head education (=0)	-0.125	**-0.004**	-0.111	**-0.006**	0.014	**-0.002**
Household head education (=1)	0.125	**0.004**	0.111	**0.006**	-0.014	**0.002**
Land security (=0)	-0.68	**0.029**	-0.425	**-0.005**	0.278	**-0.034**
Land security (=1)	0.68	**-0.029**	0.425	**0.005**	-0.278	**0.034**
Country (Burkina=1)	-0.364	**-0.108**	-0.283	**-0.006**	0.08	**0.102**
Country (Mali=2)	-0.003	**0.14**	0.165	**0.014**	0.168	**-0.126**
Country (Niger=3)	-0.951	**0.004**	-0.353	**0.015**	0.569	**0.01**
Country (Senegal=4)	1.269	**0.03**	0.562	**-0.019**	-0.598	**-0.05**
Presence of tap water (=0)	0.293	**-0.014**	-0.075	**0.067**	-0.368	**0.081**
Presence of tap water (=1)	-0.293	**0.014**	0.075	**-0.067**	0.368	**-0.081**
Presence of bank (=0)	-0.414	**0.031**	-0.126	**0.071**	0.292	**0.04**
Presence of bank (=1)	0.414	**-0.031**	0.126	**-0.071**	-0.292	**-0.04**
Observations						

Source: Authors based on HSHLS (2018/2019)
[a] Groups are balanced when the standardized means difference is less than 10% (Chesnaye et al., 2022)
See Table S5 for additional notes.

Table S18: logit results on the observable drivers of FSSI

VARIABLES	FSSI
Household head education	0.179***
	(0.0316)
Log (Age of household head)	-0.145***
	(0.0359)
Gender of household head	0.159***
	(0.0446)
Land security	-0.767***
	(0.0418)
Log (durable)	0.705***
	(0.0326)
Presence of market	0.0805**
	(0.0400)
Log (Livestock units)	0.135***
	(0.00898)
Log (distance to closest road)	-0.0137
	(0.0133)
Log (Farm size)	-0.119***
	(0.00749)
Presence of bank	0.436***
	(0.0667)
Presence of electricity grid	0.0884
	(0.0588)
Presence of tap water	-1.137***
Country	
	(0.0722)
2. Mali	-0.379***
	(0.0507)
3. Niger	0.220***
	(0.0678)
4. Senegal	-1.072***
	(0.0560)
Constant	0.540***
	(0.135)
Observations	11,620

Source: Authors based on HSHLS (2018/2019)
Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table S19: Balancing of FSSI and NFSSI groups before and after ipw

	Standardised diff. before ipw (treated=FSSI, untreated=NFSSI)	Standardised diff. after ipw (treated=FSSI, untreated=NFSSI)
Quantitative variables		
Log (Age of household head)	-0.088	0.017
Log (durable)	0.22	0.063
Log (Livestock units)	0.148	0.015
Log (distance to closest road)	0.037	0.042
Log (Farm size)	-0.013	0.005
Categorical variables		
Burkina	0.103	0.055
Senegal	-0.078	-0.002
Niger	0.242	-0.047
Mali	-0.376	-0.003
Presence of market (=0)	0.051	-0.036
Presence of market (=1)	-0.051	0.036
Gender of household head (=0)	-0.046	-0.009
Gender of household head (=1)	0.046	0.009
Household head education (=0)	-0.06	-0.019
Household head education (=1)	0.06	0.019
Presence of electricity grid (=0)	0.284	0.055
Presence of electricity grid (=1)	-0.284	-0.055
Land security (=0)	0.12	-0.006
Land security (=1)	-0.12	0.006
Presence of electricity grid x Presence of tap water (=0)	0.361	0.063
Presence of electricity grid x Presence of tap water (=1)	-0.361	-0.063
Presence of bank (=0)	0.077	0.01
Presence of bank (=1)	-0.077	-0.01

Source: Authors based on HSHLS (2018/2019)

See Table S6 for additional notes

Table S20: plot logit results for ipw

Variables	Burkina	Niger	Mali	Senegal
Plot security	2.325***	2.489***	2.671***	0.993***
	(0.521)	(0.384)	(0.314)	(0.285)
Soil type[a]				
2. Loam soil	0.357		1.064***	0.249
	(0.452)		(0.334)	(0.442)
3. Clay soil	0.360		1.777***	1.492***
	(0.319)		(0.240)	(0.195)
4. Glacis soil	-0.639		-1.948**	-4.534***
	(0.775)		(0.940)	(1.019)
Time to plot[b]	3.20e-05	-0.142**	0.693***	0.0158***
	(0.000207)	(0.0671)	(0.0903)	(0.00302)
Soil fertility[c]				
2. Medium	-1.083***	-0.849***		
	(0.335)	(0.239)		
3. Low	-1.654***	-1.169***		
	(0.450)	(0.348)		
Plot management	0.567*	0.744**		
	(0.316)	(0.316)		
Log (Time to plot)				
Constant	-4.223***	-3.675***	-6.068***	-3.839***
	(0.407)	(0.342)	(0.397)	(0.198)
Observations	7,761	5,252	4,497	5,245

Source: Authors based on HSHLS (2018/2019)

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

[a] Sandy soil is the base category. [b] For Niger and Mali, we used Log (Time to plot) instead of Time to plot. Good fertility is the base category.

Table S21: Balancing check for SSI and rainfed plot groups Burkina

	Standardised diff. before ipw (treated=SSI plot, untreated=Rainfed plot)	Standardised diff. after ipw (treated=SSI plot, untreated=Rainfed plot)
Variables		
Time to plot	0.011	0.000
Plot security (=0)	-0.38	-0.035
Plot security (=1)	0.38	0.035
Soil type (1=Sandy)	-0.14	-0.087
Soil type (2=Loam soil)	0.121	0.086
Soil type (3= Clay soil)	0.14	0.053
Soil type (4= Glacis soil)	-0.168	-0.043
Soil fertility (1=Good)	0.491	0.065
Soil fertility (2=Medium)	-0.227	0.015
Soil fertility (3=Low)	-0.315	-0.09
Plot management (=0)	-0.272	-0.073
Plot management (=1)	0.272	0.073

Source: Authors based on HSHLS (2018/2019)

Table S22: Synthesis of performance indicators of irrigated schemes in the Sahel

	Investment (FCFA/ha)	Operation and maintenance costs (FCFA/ha)	Energy costs (FCFA/ha)	Paddy yields (t/ha)	Water productivity (kg/m3)	Countries covered	Source
	Large Schemes						
Office du Niger rainfed season	>5000 000			5-6	0.20 0.08	Mali	Barbier et al (2011)
Office du Niger dry season				4-5		Mali	
	1 836 570*	18365.7				SSA	You et al (2011)
				15**			Zwart and Leclerc (2010)
			24534.4	3.15 to 3.72 t ha−1 (average 3.5)		Mauritania	Borgia et al. (2013)
	2 300 000 (5.4 millions)						Sakurai (2023)
	1 483 296						McCarthy et al. (2023)
	Medium to small-scale schemes						
Medium schemes	5 209 849						McCarthy et al. (2023)
Village schemes	<500 000			5.5		Mali	Barbier et al (2011)
	2.1 (3.3) millions						Sakurai (2023)
Small scale schemes	1 224 380	24487.6				SSA	You et al (2011)
	1000 000					Mali	Dillon (2011)
			59564.8	1.34-5.74 (average: 3.77)	0.30	Mauritania	Borgia et al. (2013) ***
	10 738 332.7						McCarthy et al. (2023)
Farmer-led SSS	0.8 (0.7) millions						Sakurai (2023)
Individual schemes	± 2000 000			5.5			Barbier et al (2011)

Note: *On-farm investment cost only per year. ** Biomass yield. ***Irrigation campaign 2008 for small-scale schemes and 2010 for Large-scale schemes.
1USD=610,41fcfa, date=19.06.2024.

Table S23: Cost of irrigation technologies

Water Lifting Technology	Cost (x1000FCFA)	Cost (USD)*	Source**
Manual pumps	80	131	Tadesse et al. (2024a)
	90	147	
	35	57	HSHLS 2018/2019 (Niger, Senegal, Mali, Burkina)
	150	246	
	37.6	62	
	300	491	
	23.81	39	
	350	573	
	13.503	22	
	250	410	
Treadle pumps	30	49	Abric et al. (2011); Tadesse et al. (2024a)
	120	197	Tadesse et al. (2024a)
	90	147	Abric et al. (2011)
	43	70	Adeoti et al., (2007)
	49	80	
	146.5	240	
Motor pump	250	410	Abric et al. (2011)
	177.9	291	HSHLS-Senegal
	750	1229	
	81.42	133	
	204.37	335	HSHLS-Mali
	1250	2048	
	241.5	396	PAPA collective
	100	164	
	400	655	
	1800	2949	HSHLS-Burkina
	125	205	
	132.85	218	
Solar pump	275	451	Sarr et al. (2018)
	457.5	749	PAPA collective
	115	188	
	800	1311	
	500	819.121574	Sarr et al. (2018)
	2500.17344	4095.892007	
	1500	2457.364722	
	3580.23152	5865.289756	
	3700.24016	6061.893088	
	4200.27616	6881.073639	

	7267.47632	11905.89328	
	3700.24016	6061.893088	
	1260	2064.186367	
	5500	9010.337314	
	420	688.0621222	
	1980	3243.721433	
	2850	4668.992972	
	3455	5660.130077	
	4260	6978.915811	
	1070	1752.920168	
	1750	2866.925509	
	2250	3686.047083	

Note: *1USD=610,41fcfa, date=19.06.2024. **For a given technology, prices from datasets consist of means, mins and max. Prices from the same literature source are costs of different capacity of the technology.

Table S24: Water distribution technologies

Water distribution technology	Cost (x1000Fcfa/ha)	Cost (USD/ha)*	Source
California	300	491	Abric et al. (2011); Tadesse et al. (2024b)
	350	573	Tadesse et al. (2024b)
Drip	2000	3276	Abric et al. (2011)
	4000	6553	
Sprinkler	2000	3276	Tadesse et al. (2024b)
	3000	4915	Tadesse et al. (2024b)

Note: *see Table S4

SSI and FSSI adoption rates

Table S25: SSI and FSSI adoption rates in Niger

Region	adoptionratessi	adoptionratefssi
agadez	0.7689046	0.9935109
diffa	0.0156735	0.5
dosso	0.0161694	0.7934429
maradi	0.0066305	0.111834
tahoua	0.0518972	0.6731071
tillaberi	0.0830168	0.4494516
zinder	0.0069941	1
niamey	0.4188702	0.5

Source: Authors based on HSHLS 2018/2019

Table S26: SSI and FSSI adoption rates in Mali

Region	adoptionratessi	adoptionratefssi
Kayes	0.0563242	0.7866319
Koulikoro	0.0785111	0.9153127
Sikasso	0.0496372	0.5874883
Ségou	0.1192744	0.1732453
Mopti	0.1364087	0.3817067
Timbuktu	0.5158088	0.098258
Gao	0.7375152	0.184554
Kidal		
Ménaka	0.2934836	0.8260389

Source: Authors based on HSHLS 2018/2019

Table S27: SSI and FSSI adoption rates in Burkina

Region	adoptionratessi	adoptionratefssi
Boucle du Mouhoun	0.0523019	0.4270307
Cascades	0.0224048	0.1001788
Centre	0.0472554	0.5520842
Centre-Est	0.040928	0.2588637
Centre-Nord	0.0062698	0
Centre-Ouest	0.0705222	0.7804505
Centre-Sud	0.0572587	0.8804241
Est	0.0021801	0
Hauts Bassins	0.1271246	0.752053
Nord	0	0.000
Plateau-Central	0.015452	0.5811136
Sahel	0.0205486	0
Sud-Ouest	0.00868	0.5657591

Source: Authors based on HSHLS 2018/2019

Table S28: SSI and FSSI adoption rates in Senegal

Region	adoptionratessi	adoptionratefssi
dakar	0.3164644	1
ziguinchor	0.0673416	0.6367525
diourbel	0.0598767	1
SAINT-LOUIS	0.6058049	0.1451531
tambacounda	0.016031	0
kaolack	0.0052178	0
thies	0.1395617	0.9221757
louga	0.0316461	0.6304928
fatick	0.1029015	0.8753656
kolda	0.0457675	0.7946985
matam	0.3341139	0.0617503
kaffrine	0.003834	1
kedougou	0.0412198	0.4198662
sedhiou	0.0778733	0.5529136

Source: Authors based on HSHLS 2018/2019

Table S29: Crops cultivated by solar pump adopters in Senegal

	Adopters		Non-adopters	
Crops	**Mean**	**SD**	**Mean**	**SD**
Onion	0.634	0.482	0.857	0.363
Potatoes	0.051	0.221	0	0
Cherish tomatoes	0.012	0.107	0	0
Cassava root	0.007	0.082	0	0
Cabbage	0.219	0.414	0.286	0.469
Watermelon	0.006	0.076	0	0
Eggplant	0.086	0.281	0	0
African eggplant	0.076	0.265	0.143	0.363
Green beans	0.001	0.031	0	0
Sweet potatoes	0.013	0.112	0	0
Soursop	0.001	0.031	0	0
Mint	0.02	0.141	0	0
Lettuce	0.013	0.112	0	0
Lemongrass	0.002	0.044	0	0
Parsley	0.016	0.124	0	0
Coriandre	0.003	0.054	0	0
Hibiscus	0.007	0.082	0	0
Other leafy vegetables	0.021	0.145	0	0
Tomatoes	0.263	0.441	0.286	0.469
Rice	0.141	0.348	0	0
Carrots	0.049	0.215	0.143	0.363
Pepper	0.126	0.332	0.143	0.363
Mango	0.02	0.141	0.143	0.363
Okra	0.038	0.191	0	0
Melon	0.001	0.031	0	0
Turnip	0.043	0.202	0	0

Source: PAPA-farm data (2017)

Table S30: SSI vs. non-SSI

	No irrigation		SSI			LSI		
	Mean	Std. dev.	Mean	Std. dev.	T-stat. (SSI-Noirrig)	Mean	Std. dev.	T-stat. (SSI-LSI)
Household size	7.126684	5.44804	7.249979	1.610259	-3.537512***	6.924158	2.067902	-5.254276***
Household head alphabetization	0.2894812	0.6158418	0.308162	0.1878749	-6.146351***	0.4001589	0.2709354	8.185177***
Gender of household head	0.888348	0-.4276575	0.9147171	0.1136452	-12.0664***	0.9842948	0.0687567	25.74508***
Age of household head	46.30963	20.13371	45.67845	5.712754	5.144815***	50.09626	6.577563	13.52685***
Farm size (hectares)	4.288397	21.14919	2.771179	1.096443	48.61758***	7.26843	9.314948	30.36418***
Location in rainfed agriculture village	0.7280161	0.6042454	0.2166555	0.1676248	126.0739***	0.3242163	0.2588527	9.610295***
Existence of bank	0.0639695	0.3322788	0.0476555	0.0866823	9.240306***	0.0565185	0.1277008	2.977523**
Existence of market	0.3431606	0.6446879	0.3002996	0.1865135	7.381298***	0.3660033	0.2663897	5.420446***
Distance to closest city (km)	33.56	37.93381	35.31295	16.86522	-2.92514**	59.31832	33.09831	14.97793***
Distance to closest road (km)	8.752732	12.7223	10.78123	7.580977	-10.0949***	9.50833	8.444095	-3.905557***
Presence of electricity grid	0.1499719	0.4848338	0.1773228	0.1554082	-5.717876***	0.2187712	0.2286207	4.013337***
Presence of tap water	0.2215555	0.5639315	0.1942589	0.1609775	5.870811***	0.2273399	0.2317733	3.167905**
Contracted credit for the last 12 months	0.1151823	0.4335019	0.1159112	0.130253	-0.1985213	0.1110275	0.1737364	-0.7213619
Uses chemical fertilizer	0.3289264	0.6379779	0.783612	0.1675499	-133.3778***	0.6784757	0.2582887	-9.238455***
Net income from livestock (USD)	23.36162	876.125	18.42969	60.01204	4.449857***	39.35986	122.5639	3.728745***
Existence of livestock income	0.4901418	0.6788234	0.4577277	0.2027166	7.601***	0.4527707	0.2752677	-0.3478771
Off-farm income (USD)	722.9593	10088.7	741.0447	2289.139	-0.6943986	461.8381	1171.251	-8.177855***
Existence of off-farm income	0.6013769	0.6648533	0.4511357	0.2024711	30.78062***	0.508243	0.2764664	5.61518***
Share of off-farm income in total expenditures	0.2774902	1.601498	0.2100251	0.3029315	13.11273***	0.1580664	0.2783585	-6.487621***
Total expenditures (USD)	2549.213	2469.585	2893.698	800.5176	-23.05521***	2784.946	1062.842	-3.513961***
Owns motorized pump	0.0149068	0.1645515	0.2659659	0.1797827	-60.64623***	0.2529629	0.240398	-1.314421
Owns manual pump	0.0283352	0.2253163	0.0980674	0.1210114	-21.24809***	0.096743	0.1634733	-0.15786
Domestic use of solar energy (=1 if yes)	0.2757588	0.6068446	0.3099458	0.1881748	-6.173302***	0.5564256	0.2747376	22.88863***
Total fuel expenses for vehicles (USD)	1.21579	4.283742	1.438174	1.863569	-8.917193***	0.9014426	1.134433	-13.89062***
Share of land under cereals crop	0.8483691	0.3450264	0.7500251	0.127314	35.79906***	0.893614	0.1230109	35.51871***
Share of land under fruits and vegetables	0.0087853	0.0937181	0.1770023	0.1173847	-65.39151***	0.0445182	0.0890708	-46.48127***
Land security	0.0254926	0.2140281	0.0262522	0.0650553	-0.9788118	0.0211252	0.0795235	-4.723208***
Household head has high school diploma	0.0025275	0.068182	0.0032037	0.0229935	-3.012562**	0.0011955	0.0191091	-7.950776***
Commercialization rate	0.1751623	1.573579	0.3317279	0.218578	-38.19925***	0.2486511	0.1655581	-11.94541***
Education of household head	0.1424432	0.4745953	0.1447022	0.143144	-0.8925437	0.1439375	0.1941203	-0.0788529
Durables	0.3450511	0.8763658	0.3591398	0.2642262	-3.03063**	0.3962772	0.3254424	3.541748***
Number of livestock units	17.35985	38.4636	17.10394	10.92691	1.218112	16.15086	14.18268	-2.069592*
Observations	10497		953			170		

Source: Authors based on HSHLS 2018/2019

Labor productivity vs. Wages

Table S31: Average daily earning per activity, period 2013-2022

Country	Agriculture	Manufacturing	Mining, Electricity, Gas & water	Public Admin, community, Social services & others	Trade, transport, accommodation & food, Business and admin services	Laborproductivity rainfed	Labor productivity SSI
Burkina Faso	5.24	6.00	8.95	11.65	7.46		6.63
Mali	3.96	4.03	8.78	6.76	6.31	5.56	9.56
Niger	1.91	4.76	4.78	5.17	8.04	2.60	8.72
Senegal	7.25	7.29	14.73	7.97	9.66	3.02	7.24

Data source: ILO (https://rshiny.ilo.org/dataexplorer56/?lang=en&id=EAR_4MTH_SEX_ECO_CUR_NB_A), Accessed 09.07.2024