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**Drivers of Adoption of Small-Scale Irrigation in Mali and Its Impacts
on Nutrition across Sex of Irrigators**

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Abstract

Irrigation is an important strategy to increase agricultural productivity, improve nutrition security and reduce climate-related risks in rural Africa, but adoption of this technology has been low. Using data from the Living Standards Measurement Study, this paper analyzes the characteristics of irrigation in Mali and its impact on nutrition across sex of irrigators. Results show that gravity irrigation is the most common technology and is practiced by 47 percent of irrigators. The share of women irrigators (3 percent of all plots) is significantly lower than that of men. Econometric results show that the proximity of crop fields to the homestead increases the propensity to use motor pumps while more remote plots are more likely to rely on gravity irrigation. Literacy and income from nonfarm activities increase the propensity to use motorized irrigation technologies. Access to motor pumps, in turn, increases consumption of fruits and vegetables, oils, spices, and cereals for female-headed households. Overall, irrigation increases consumption of nutrient-rich food groups, which significantly improves household nutrition in addition to increasing income. Participation in farmer groups increases the propensity to adopt irrigation. Farmer groups might also be an entry point for capacity building on irrigation; and groups to which women farmers belong should receive information on irrigation. Farmer groups also tend to support market participation, which is important to help address the challenge of economies of scale of small-scale irrigators.

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1. Introduction

Mali, situated in Africa's Sahel region, is exposed to high agricultural production risks due to the unreliable rainfall and other harsh climatic conditions. About 95 percent of agricultural production in Mali is rainfed, putting a high risk on rural communities, the majority of which live below the poverty line (World Bank 2019). High production risks could plunge communities into dire food shortages following drought or dry spells. Farmers in this region have developed several coping strategies for dealing with these conditions (Mortimore and Adams 2001). However, climate change and, recently, insecurity have challenged the traditional coping mechanisms.

In response to the high risks associated with agricultural production, the Malian government has set forth a number of policies and strategies for increasing irrigation. It designed the Master Plan of Rural Development (SDDR1) in 1992, in which irrigation development was one of the strategies for achieving its main objective of increasing rural human development. A second phase (SDDR2) was launched in 2000–2010. In the area of irrigation, SDDR2 particularly aims to exploit the country's large irrigation potential of more than 2 million hectares—located largely in the Niger Delta and the lowland plains in southern and southwestern Mali. The increasing risks related to climate change have made investment in irrigation development more urgent (RdM 2019). To achieve this, the National Rural Infrastructure Program (*Program national d'infrastructures rurales*, or PNIR) was formed. The PNIR has three components: large- and small-scale irrigation, village potable water and sanitation, and rural roads.

Despite these efforts, Mali is using only 34 percent of its irrigation potential (FEWS NET 2019), and as this study shows, only about 5 percent (235,791 hectares) of smallholder farmers practice irrigation and 41 percent of the irrigated area is in Ségou Region—which is part of the large-scale irrigation scheme known as the Office du Niger.

Access to irrigation differs widely depending on the gender of farmers, and that has implications for its impacts on a number of household-level outcomes. The objectives of this study are as follows:

- (i) Analyze the characteristics of irrigation among smallholder farmers in Mali. To achieve this objective, the study will investigate the irrigation technology, source of irrigation water, size of irrigated plots, type of crops irrigated, land tenure, and type of land management practices used. The analysis will be done across the sex of plot owners.
- (ii) Identify the drivers of adoption of irrigation technologies and the impact of irrigation on food and nutrition security.

- (iii) Using the results in (i) and (ii), draw implications for planning future studies on smallholder pathways from irrigation to prosperity, nutrition, and resilience. Particularly, the results will be used to identify gaps that could be filled using household surveys and focus group discussions, which this study plans to implement.

The rest of the paper is organized as follows. The next section discusses the analytical methods and data used in this study. This is followed by a discussion of the results. The last part of the paper draws conclusions based on the results and draws implications for planning future studies on how irrigation may facilitate the pathway to prosperity, nutrition, and resilience.

2. Analytical Methods and Data

We estimate two sets of econometric models—namely, the drivers of adoption of irrigation technologies, for which we use a probit model, and the impact of irrigation on household nutrition, for which we use the Poisson and the negative binomial models.

Drivers of Adoption of Irrigation Technologies

We estimate the drivers of adoption of irrigation technologies using a probit model as follows:

$$Y^* = \Phi - 1(Y) = X\beta + \varepsilon,$$

where Y^* is a latent variable, given by

$$Y = \begin{cases} 0 & \text{if } Y^* \leq 0 \\ 1 & \text{if } Y^* \geq 1 \end{cases};$$

Φ is a normally distributed cumulative statistic with Z-distribution, that is, $\Phi(Z) \in (0,1)$;

X is a vector of covariates of determinants of adoption of irrigation practices; β is a vector of the associated coefficients, $X\beta \sim N(0,1)$; and ε is an error term with normal distribution, that is, $\varepsilon \sim N(0,1)$.

We also estimated linear probability models on dichotomous outcomes where the probit regression model had convergence problems. The problem of nonconvergence was common with the probit regressions involving adoption of different irrigation technologies at the plot level. Thus, for these outcomes we report ordinary least squares (OLS) estimates of the linear probability models, and these estimates are similar to the marginal effects that would obtain from a probit regression if there were convergence (Angrist 2001).

We estimate robust regression models to ensure that we address potential heteroscedasticity.

Impacts of Irrigation on Household Nutrition

To estimate the impact of irrigation on household nutrition, we use household dietary diversity as the outcome indicator. Because this is continuous, we use the linear regression model (OLS), but because it is also continuous and a non-negative count variable, we also use Poisson regression. Because the Poisson model can be sensitive to overdispersion, we also estimated a negative binomial regression that is robust under dispersion. As the results will show later, all our estimates are robust across the three estimators.

To identify irrigation's impact on food and nutrition security, the quantitative impact analysis focuses on the outcome *dietary diversity*. Studies have shown that dietary diversity is highly correlated with dietary quality and quantity (Marshall et al. 2014; Hoddinott and Yohannes 2002). Additionally, dietary diversity is associated with other positive health outcomes including greater birth weight, child anthropometric status, hemoglobin concentration, and reduced hypertension and cardiovascular disease and cancer (Hoddinott and Yohannes 2002; Ruel 2003). The household dietary diversity score (HDDS) is used to analyze dietary diversity. HDDS is the number of food groups that a household consumed in the last seven days. HDDS is based on 12 food groups (1 = cereals; 2 = roots and tubers; 3 = vegetables; 4 = fruits; 5 = meat, poultry, offal; 6 = eggs; 7 = fish and seafood; 8 = pulses, legumes, nuts; 9 = milk and milk products; 10 = oil/fats; 11 = sugar/honey; and 12 = miscellaneous). Each food group receives a score of 1 if consumed, and thus HDDSs range from 0 to 12 (Swindale and Bilinsky 2006).

Table 1 Food group weights

Food group	Weight
Meat and fish	4.0
Milk	4.0
Pulses	3.0
Main staples	2.0
Vegetables	1.0
Fruit	1.0
Sugar	0.5
Oil	0.5
Condiments	0.0

Source: Swindale and Bilinsky 2006.

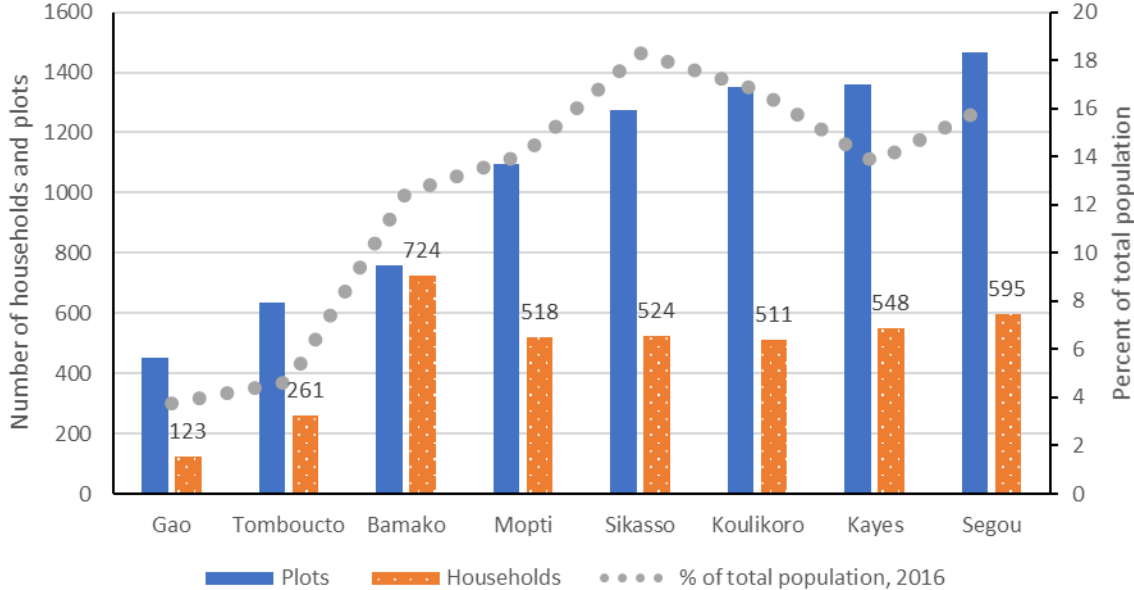
Given that HDDS is a count variable and most likely skewed (that is, some households have a lower or higher HDDS), the Poisson distribution captures well such a pattern. Typically, the mean and variance of the Poisson distribution are equal, that is, $\bar{y} = var(y)$. But there is the potential of overdispersion—that is, when $var(y) > \bar{y}$ —in which case, the negative binomial distribution is appropriate for estimation of

the model. When the dispersion parameter nears zero, the negative model distribution is equivalent to the Poisson distribution. The negative binomial distribution approaches the Poisson distribution. We estimate both the Poisson and negative binomial models to check robustness of the results.

Data

We use 2017 data from the Living Standards Measurement Study–Integrated Surveys on Agriculture (LSMS-ISA). The LSMS-ISA is a nationally representative dataset that covered 3,804 households, including rural and urban residents. A total of 8,390 plots were reported by the sampled households, and this strengthens our plot-level analysis. We particularly use the section that reports irrigation. Figure 1 shows the data distribution across Mali’s regions. As expected, the sample size per region is proportional to the population. However, Ségou seems to be given relatively higher weight and Kayes lower weight than the corresponding population.

Figure 1 LSMS-ISA sample size by region and corresponding human population



Source: Sample size is computed from LSMS-ISA 2017 raw data; population by region is from INSTAT (2016).

3. Results

Adoption of Irrigation Technologies across Regions

Tomboucto has the highest irrigation adoption rate (Table 2 and Figure 2). The high aridity index in the region makes rainfed agriculture almost impossible to practice in most parts of the region. Motor pump irrigation is the most common technology used in Tomboucto. At the same time, irrigation in

Tomboctou is concentrated along the Niger River and is nonexistent in the Sahara Desert (Figure 2). At the national level, gravity irrigation is the most common technology (Figure 3). Established in 1932, the Office du Niger is the largest irrigation scheme in West Africa, and it accounts for the largest share of gravity irrigation (World Bank 2017). The Office du Niger irrigation scheme is mainly in Ségou Region (Djiré, Keita, and Diawara 2012). Irrigation using motor pumps is used by the largest share (57 percent) of irrigators in Mopti, where gravity irrigation is practiced on 41 percent of the plots. Bucket irrigation is the major technology in Sikasso, where 83 percent of irrigators use it (Figure 4). Bucket irrigation is labor intensive and implies a smaller irrigated area for the farmers using it. Accordingly, Sikasso irrigators report the third smallest irrigated area while Tomboctou irrigators report the largest area (Table 2). Figure 3 confirms that bucket irrigators have the smallest irrigated area while those using gravity irrigation report the largest area.

Table 2 Irrigation technology adoption rates across regions

Region (sample size)	Irrigated plots		Irrigation technology			
	Irrigated area (hectares)	Percent of plots	Motor pump	Gravity	Bucket	Other
			Percent			
Kayes (<i>n</i> = 1,518)	1.45	0.4	0	0	0	100
Koulikoro (<i>n</i> = 1,774)	0.39	0.17	0	100	0	0
Sikasso (<i>n</i> = 2,285)	0.47	0.79	0	6	83	11
Ségou (<i>n</i> = 2,233)	1.87	7.12	3	86	3	6
Mopti (<i>n</i> = 1,392)	1.20	4.67	57	41	0	3
Tombouctou (<i>n</i> = 272)	3.28	38.24	95	5	0	0
Gao (<i>n</i> = 169)	0.29	4.73	25	25	0	50
Bamako (<i>n</i> = 15)	0	0	0	0	0	0
National	2.08	3.76	39	47	6	6

Source: Computed from LSMS-ISA 2017 raw data.

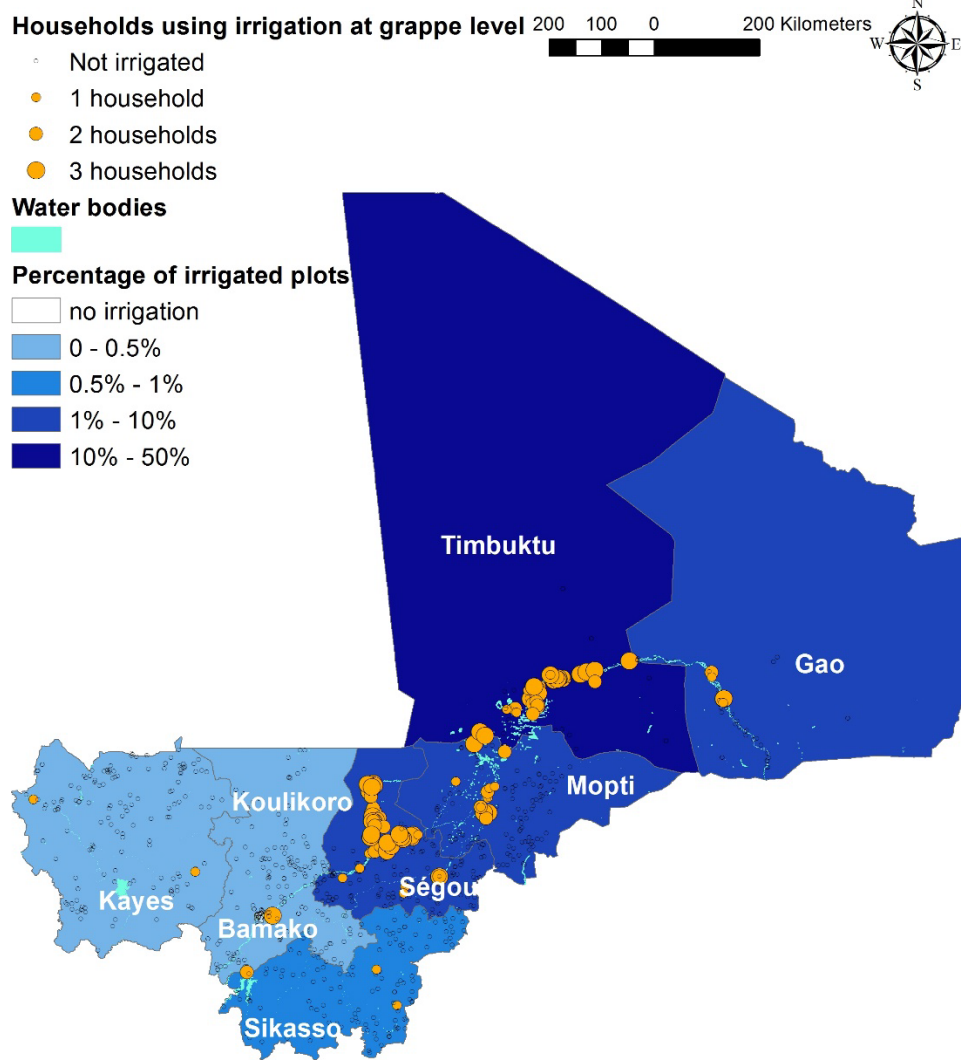
Note: Henceforth, Bamako will not be reported in the tables that follow because no farmer reported to have practiced irrigation.

Figure 2 confirms the concentration of irrigation along the Niger River. In Molasso village (Sikasso)—which the authors visited—bucket irrigation (Figure 5) is the most common technology for all three cropping cycles. The project operating in Molasso—I PRO IRRIGAR—constructs micro-dams (barrage), and the project has constructed a total of 50. There is limited promotion of solar pumps in Molasso and other I PRO IRRIGAR project villages because the project’s major objective is to improve traditional technologies that farmers use rather than introduce a brand-new technology. In this case, I PRO IRRIGAR

improved the bucket method of irrigation by reducing the depth of the water table and making water available in the dry season.

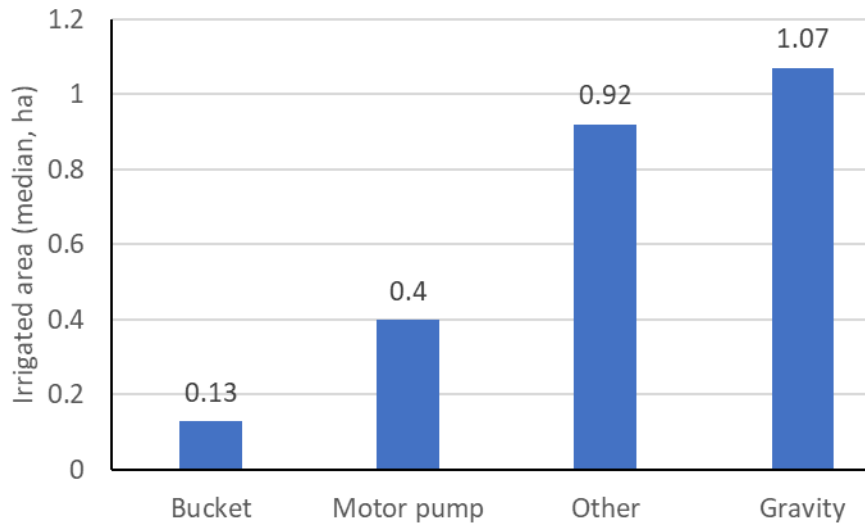
A problem of bucket irrigation is loss of space. Farmers make a line of shallow wells along the rows of irrigated crops (Figure 5) to minimize the distance of hauling water. There is a need to compute the loss of area due to digging holes for bucket irrigation and to compare that against the motor pumps. The LSMS-ISA data did not capture the area lost to this practice.

Figure 2 Location of irrigated plots per sampling cluster (grappe)



Source: Designed using LSMS-ISA 2017 data.

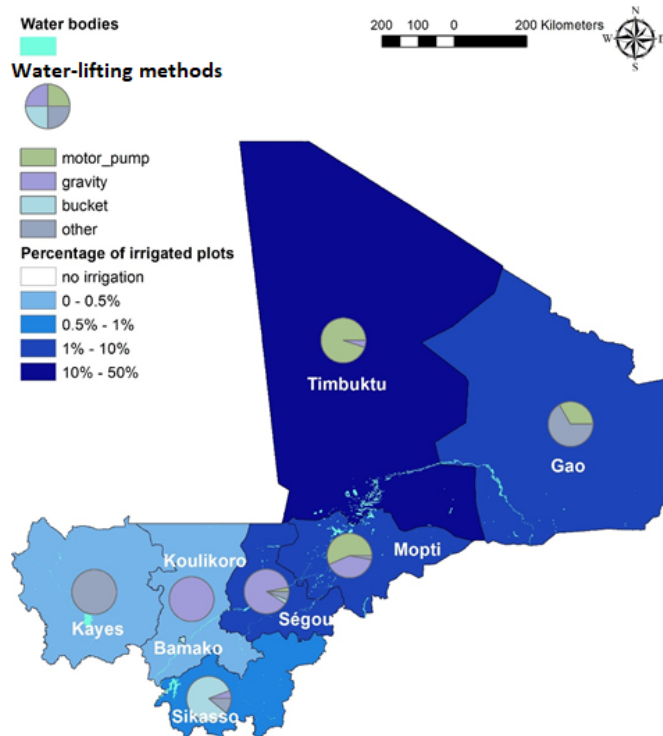
Figure 3 Irrigated area by type of technology used



Source: Computed from LSMS-ISA 2017 raw data.

Note: “Other” includes pedal, solar, and other types of pumps.

Figure 4 Incidence of water-lifting technologies and irrigation adoption by region



Source: Designed using LSMS-ISA 2017 raw data.

Figure 5 Bucket irrigation in Sikasso



Photo credit: Ephraim Nkonya.

Characteristics of Plots across Gender

As expected, the share of women irrigators (3 percent of all plots) is significantly lower than that of men (5 percent) (Table 3). However, the source of irrigation water is comparable across sex, except that women are more likely to use lake water than men. Adoption of irrigation technologies also differs by sex, with men being more likely to use motor pumps than women. However, the use of gravity irrigation is comparable across sex of irrigators. This is largely due to the predominance of that irrigation method in Office du Niger farmers. Consistent with the literature, land area owned by women is significantly smaller than men's. Surprisingly, however, the irrigated area is comparable across sex.

Year of acquisition and distance of irrigated and any plot to home are comparable across sex of irrigator. Men's adoption rate of soil and water conservation (SWC) structures is significantly higher than that of women. This is expected given women's limited resource endowments and access to agricultural advisory services. Generally, there is no significant difference across gender in terms of soil type, plot slope, or method of land acquisition (Table 3). It is surprising that women are as likely as men to inherit land and to receive it from a village chief. The results are consistent with those of Nkonya et al. (forthcoming), who found that female farmers in Uganda were as likely as men to inherit land. However, men are more likely than women to acquire land from farmer groups.

Men are more likely than women to have title deed to their plot. However, even though the differences are significant at $p = 0.01$, the absolute difference is quite small—suggesting that the land tenure system in Mali is well balanced across sex of landowner.

Men are more likely than women to grow cereals (millet, sorghum, and rice) (Table 3). Given that those three crops account for the largest cropped area in Mali (FAOSTAT), this reflects the large share of household farms under men's ownership. Women are more likely than men to grow groundnuts. Interestingly, there is no difference between the shares of men and women growing horticultural crops.

Table 3 Characteristics of men and women irrigator plots

	Men's plots (n = 5,013)	Women's plots (n = 4,482)	p-value
Percent of irrigated plots	5	3	0.000***
Source of irrigation water (percent reporting source):			
• River	57	50	0.099*
• Dam or water reservoirs	36	34	0.709
• Groundwater	5	7	0.566
• Lake or pond	1	7	0.006***
• Other	1	3	0.096*
Irrigation water-lifting methods (percent reporting method):			
• Motor pump	42	33	0.047**
• Gravity	46	49	0.674
• Bucket	5	7	0.449
• Other	5	9	0.076*
Plot size (hectares):			
• Farm size	3.4	2.9	0.009***
• Irrigated area	2.5	2.2	0.788
Plot distance (kilometers) from:			
• Any plot to homestead	3.1	2.9	0.233
• Irrigated plot to homestead	3.9	2.9	0.082*
Years owning the plot	18.6	18.6	0.344
Years owning the irrigated plot	14.5	16.2	0.320
Soil erosion control structures (percent reporting):			
• Any soil erosion control structure	5.3	3.9	0.001***
• Half moon	1.0	0.7	0.072*
• Agroforestry	0.8	0.5	0.077*
• Stone walls	2.0	1.1	0.002**
• Stone rows	1.7	1.2	0.036**
• Other structures	0.6	0.3	0.015
Soil type conditions (percent reporting soil type):			
• Sandy	49.7	50.2	0.679
• Clay	39.9	38.9	0.314
• Red	5.4	5.4	0.994
• Other type	4.7	5.3	0.189

	Men's plots (n = 5,013)	Women's plots (n = 4,482)	p-value
Plot slope (percent reporting slope type):			
• Flat	66.9	66.5	0.686
• Plateau	14.5	15.1	0.385
• Lowlands	5.8	5.2	0.250
• Gentle slope	11.3	11.7	0.557
• Steep slope	0.9	0.8	0.650
• Valley	0.4	0.4	0.978
Plot acquisition (percent reporting acquisition methods):			
• Inherited from household head	55.7	56.8	0.264
• Customary chief	21.2	20.9	0.781
• Given by household member	11.7	12.7	0.074*
• From non-household member	3.5	3.1	0.271
• From agricultural group	1.7	1.0	0.006***
• Administrative authority	1.5	1.2	0.089*
• From company or firm	0.1	0.1	0.744
Plot tenure (percent reporting tenure type):			
• Title deed	4.5	3.3	0.003***
• No title deed	86.5	88.4	0.004***
• Loaned	5.6	5.3	0.500
• Rented	0.9	0.8	0.794
• Purchased	0.2	0.2	0.748
• Other type	0.4	0.2	0.029
Crop choice (percent reporting crop):			
• Millet	24.3	20.3	0.000***
• Sorghum	18.1	16.7	0.034**
• Rice	14.9	11.1	0.000***
• Maize	15.3	15.1	0.843
• Fonio	1.6	2.2	0.028**
• Groundnuts	14.7	21.3	0.000**
• Cotton	2.1	2.6	0.061*
• Horticultural crops	1.2	1.4	0.316
Irrigated crops			
• Millet	0.0	4.1	0.002***
• Sorghum	0.0	0.8	0.083*
• Rice	93.5	83.4	0.003***
• Maize	0.4	1.6	0.236
• Fonio	0.0	0.0	-
• Groundnuts	0.8	4.1	0.018**
• Cotton	0.0	0.0	-
• Horticultural crops	1.6	0.8	0.500

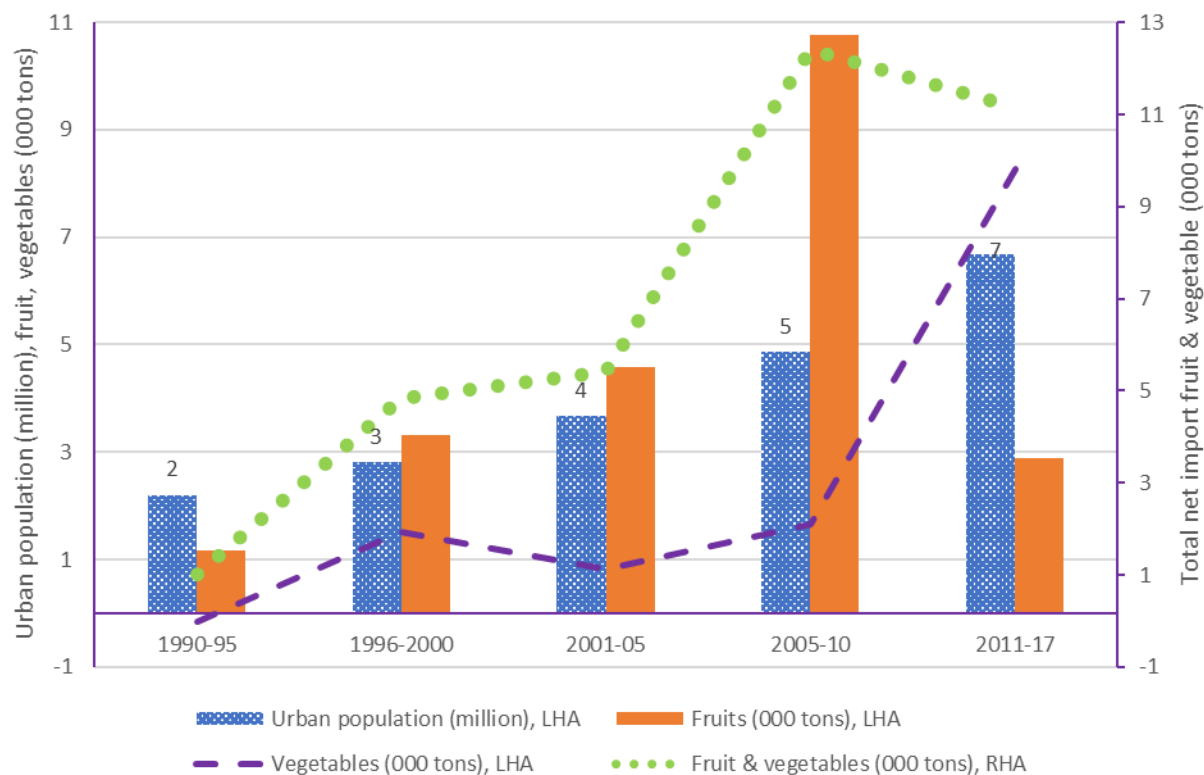
Source: Computed from LSMS-ISA 2017 raw data.

The results could suffer from a small sample problem since the absolute share (1.6 percent) of men growing horticultural crops—a cash crop—is twice the share reported by women. The limited production of horticultural crops is a concern given their growing demand; rapid urbanization and a growing middle-income population both are increasing demand for horticultural crops. The Malian urban population increased from only two million in 1990–1995 to seven million in 2011–2017—a threefold increase. During the same period, net imports of fresh fruits and vegetables grew from 1 to 11 tons—a tenfold increase (Figure 6). Net imports of fresh vegetables increased the most throughout—underscoring an untapped demand that smallholder farmers could exploit using irrigation.

Comparison of the same characteristics across irrigation and rainfed plots offers interesting insights. Irrigated plots are significantly farther away from the homestead than rainfed plots (Table 4). This could be due to the need for irrigators to acquire a plot closer to water sources rather than the homestead. For example, irrigators who use a river as the source of irrigation water need to buy or rent a plot closer to the river rather than closer to their homestead. Irrigated plots were acquired more recently than rainfed crop plots. With no exception, the adoption rates of SWC structures and improved rice seed as well as hired labor investment for irrigated plots were significantly higher on irrigated plots than on rainfed plots. As expected, irrigated plots are more clayey and less sandy than rainfed plots. Similarly, irrigated plots are more likely to be in the lowlands and valley bottoms than on plateaus. This suggests that farmers are well aware of the irrigation suitability characteristics and they invest more on irrigated plots to enhance their returns. Similarly, owners of irrigated plots are more likely to have land title than those owning rainfed plots. Irrigators also are more likely to rent a plot than rainfed farmers. This suggests that land markets could enhance access to irrigation, especially for women, youth, and vulnerable groups—at least in the short term.

Irrigated plots are more likely to be acquired from a farmer group or allocated by a government official. This is largely due to the Office du Niger method of land allocation and the corresponding irrigator groups used in the allocation process. Regarding crop choice, all crops, including horticultural crops, are likely to be planted on rainfed plots—all due to the low adoption of irrigation (Table 2).

Figure 6 Trends in urban population and net imports of fresh fruits and vegetables in Mali, 1990–2017



Notes: LHA=Left-hand axis, RHA=Right-hand axis

Source: Computed from FAOSTAT raw data—available at <http://www.fao.org/faostat/en/#data/>.

Table 4 Characteristics of irrigated and rainfed plots

	Rainfed	Irrigated	p-value
Plot size (hectares)	3.1	2.4	0.252
Plot distance from homestead (kilometers)	3.0	3.6	0.018**
Years owning the plot	18.5	15.2	0.001***
Soil and water control structures (percent reporting):			
• Half moon	0.7	3.3	0.000***
• Agroforestry	0.5	3.3	0.000***
• Stone walls	0.8	20.9	0.000***
• Stone rows	1.4	2.8	0.036**
• Other structures	0.4	4.1	0.000***
Soil type conditions (percent reporting):			
• Sandy	51.1	10.6	0.000***
• Clay	37.9	79.5	0.000***
• Red soil	5.4	5.8	0.706
• Other soil type	5.2	3.9	0.298

	Rainfed	Irrigated	<i>p</i> -value
Plot slope conditions (percent reporting):			
• Flat	66.7	67.9	0.632
• Plateau	15.2	6.2	0.000***
• Lowlands	5.2	14.7	0.000***
• Gentle slope	11.7	3.9	0.000***
• Steep slope	0.8	2.8	0.000***
• Valley	0.3	4.2	0.000***
Plot acquisition (percent reporting):			
• Inherited	57.4	20.3	0.00***
• Allocated by customary chief	21.6	13.1	0.000***
• Given by family member	12.4	6.5	0.001***
• Given by non-family member	3.3	3.1	0.835
• Acquired from agricultural group	0.4	23.4	0.000***
• Allocated by government official	0.4	25.5	0.000***
• Acquired from company or firm	0.1	0.8	0.001***
Plot tenure (percent reporting):			
• Title deed	3.7	11.0	0.000***
• No title deed	88.5	60.6	0.000***
• Loaned	5.3	8.8	0.005***
• Rented	0.4	12.9	0.000***
• Other land tenure	0.1	3.8	0.000***
Input use:			
• Hired labor costs paid (CFA)	3,482	12,860	0.000***
• Uses improved rice seeds (percent)	11.8	70.7	0.000***
Crop choices (percent reporting):			
• Millet (<i>n</i> = 2,127)	99.8	0.2	0.000***
• Sorghum (<i>n</i> = 1,648)	99.9	0.1	0.000***
• Rice (<i>n</i> = 1,247)	74.3	25.7	0.000***
• Maize (<i>n</i> = 1,432)	99.8	0.2	0.000***
• Fonio (<i>n</i> = 188)	100	0.0	0.007***
• Groundnuts (<i>n</i> = 1,684)	99.6	0.4	0.000***
• Cotton (<i>n</i> = 241)	100	0.0	-
• Cabbage (<i>n</i> = 3)	66.7	33.3	-
• Pepper (<i>n</i> = 6)	66.7	33.3	-

Source: Computed from LSMS-ISA 2017 raw data.

Note: CFA = CFA franc.

The source of irrigation water differs significantly across regions (Figure 7). In Mopti, Tomboctou, and Gao, river water is the major source (Table 5). These regions are on the Niger watershed and some are part of the Office du Niger (Figure 7). Dams are the major source of irrigation water in Ségou. Sikasso stands out by having groundwater as its major source of irrigation. Lakes and ponds are the major

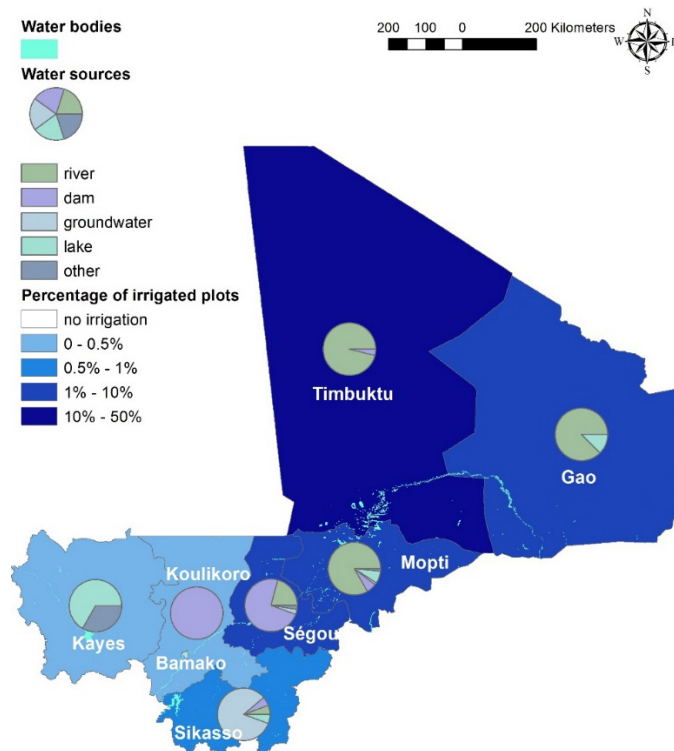
source of irrigation in Kayes. At the national level, rivers are the most important source of irrigation—all due to the Office du Niger and abstraction from the Niger River done in other areas.

Table 5 Source of irrigation water

Region	Rivers	Dams	Groundwater	Lakes and ponds	Other
Percent					
Kayes	0.0	0.0	0.0	66.7	33.3
Koulikoro	0	0.33	0	0	0
Sikasso	5.6	5.6	83.3	5.6	0.0
Ségou	20.8	73.6	3.1	0.0	2.5
Mopti	84.6	6.2	1.5	7.7	1.5
Tombouctou	96.2	3.8	0.0	0.0	0.0
Gao	87.5	0.0	0.0	12.5	0.0
National	54.0	35.5	5.8	3.0	1.9

Source: Computed from LSMS-ISA 2017 raw data.

Figure 7 Source of irrigation water across regions



Source: Designed using LSMS-ISA 2017 raw data.

Econometric Results

Drivers of Adoption of Irrigation Technologies

Water sources are important drivers of irrigation technologies. Farmers with access to groundwater or lake or pond water are more likely to use motor pumps and less likely to use dams or reservoirs (Table 6). Access to dams or water reservoirs increases the likelihood of using gravity or bucket irrigation. The results suggest that farmers decide to buy the appropriate equipment to lift water from the nearest source available.

Regarding method of land acquisition, having acquired land by inheritance or through a family member reduces the probability of using a motor pump (Table 6). However, acquiring land through the government or through agricultural groups increases the propensity to use motor pumps and gravity irrigation. Bucket irrigation is not affected significantly by method of land acquisition, and this could be due to its short-term nature, which does not depend on land rights. Land tenure does not have a significant effect on adoption of any of the three irrigation technologies. This could be due to limited variability of land tenure as about 90 percent of irrigators do not have land title (Table 3). Plot area is inversely related to motor pump adoption. This is due to the limited capacity of motor pumps to irrigate a big area. For example, Takeshima (2016) estimates a 2-horsepower pump could irrigate only 1 to 2 hectares if used continuously for 12 hours at 50 percent efficiency. Sex of plot owner does not have an impact on choice of irrigation technology. This is due to the water availability's impact on the irrigation technology choice. For example, farmers in the Office du Niger use gravity irrigation regardless of their sex.

Compared to sandy soils, both clayey and red soils are more likely to be irrigated using motor pumps and gravity. As discussed earlier, farmers determine the irrigation suitability of their plots before they invest in technologies. Accordingly, plots with higher irrigation suitability are more likely to be irrigated using gravity than those with lower suitability (Table 6). Surprisingly however, plots with medium irrigation suitability are less likely to be irrigated using motor pumps than those with low irrigation suitability. This could be due to poor data on groundwater, which could have compromised its effect—as it is the major water source for pump irrigation.

Investment in SWC structures does not significantly affect choice of irrigation technologies. Only stone walls significantly affect the choice of motor pumps. As shown in Table 3, farmers invest more in SWC structures for irrigated plots than for rainfed plots. Such investment is done regardless of the irrigation technology—the result of which is its nonsignificant effect on technology choice.

Proximity to home increases the propensity to use motor pumps. This could be due to the aspects of portability of pumps, which gives an advantage for plots closer to home. Distance from home increases the propensity to use gravity irrigation. This is due to the renting of irrigation plots in the Office du Niger, which tend to be distant from homesteads. The Office du Niger irrigation scheme does not allow irrigators to settle in its area. Distance from home does not have a significant impact on choice of bucket or gravity irrigation.

Table 6 Determinants of choice of irrigation technology (marginal probabilities)

Variable	Motor water pump		Gravity		Bucket	
	OLS	Robust OLS	OLS	Robust	OLS	Robust OLS
Water source: (cf. river)						
• Dam or reservoir	-0.280***	-0.280***	0.689***	0.689***	0.008***	0.008
• Groundwater	0.048**	0.048	-0.023*	-0.023	0.936***	0.936***
• Lake/pond	0.301***	0.301***	-0.029	-0.029*	0.00024	0.001
• Other sources	-0.077	-0.077**	0.667***	0.667***	0.019***	0.019
Plot Acquisition: (cf. acquired from customary chief)						
• Inheritance	-0.008***	-0.008***	0.001	0.001	0.001	0.001
• Family member	-0.013***	-0.013***	0	0	0.001	0.001
• Non-family member	-0.010*	-0.010*	0	0	-0.001	-0.001
• Agricultural group	0.444***	0.444***	0.043***	0.043*	-0.001	-0.001
• Government	0.072***	0.072**	0.332***	0.332***	-0.019***	-0.019
• Other acquisition	0.024	0.024	0.030***	0.03	-0.001	-0.001
Land tenure: (cf. title deed), sex of owner and land area						
• No title deed	-0.004	-0.004	-0.006*	-0.006	-0.001	-0.001
• Loaned	-0.004	-0.004	-0.001	-0.001	-0.001	-0.001
• Other Tenure	0.011	0.011	0.023***	0.023*	0.001	0.001
Ln(plot area, ha)	-0.002***	-0.002***	0	0	-0.001	-0.001
Female-owned (cf. man)	-0.001	-0.001	0	0	0.001	0.001
Soil type (reference group: sandy soil)						
• Clayey	0.015***	0.015***	0.004***	0.004***	-0.001	-0.001
• Red	0.005	0.005*	0.008***	0.008**	0.002***	0.002
• Other type	0.005	0.005*	0	0	-0.001	-0.001
Soil and water conservation (SWC) structures (cf. no SWC)						
• Half moons	0.003	0.003	-0.007	-0.007	0.001	0.001
• Agroforestry	-0.014	-0.014*	-0.005	-0.005	-0.001	-0.001
• Stone walls	0.077***	0.077***	-0.002	-0.002	0.001	0.001
• Stone rows	-0.005	-0.005	-0.003	-0.003	0.001	0.001
• Other SWC	-0.015	-0.015	0.020*	0.02	0.001	0.001
Irrigation suitability index (S) (cf. low suitability, S ≤ 20)						
• Medium (20 < S ≤ 30)	-0.005**	-0.005***	0.003*	0.003***	0.000	0.000
• High (S ≥ 30)	0.000	0.000	0.009***	0.009***	-0.000	-0.000
Market access						
• Ln(distance from home, km)	-0.003**	-0.003**	0.003***	0.003*	-0.001**	-0.001
• Ln(distance to market, km)	0.003**	0.003*	-0.001	-0.001*	0.001**	0.001
• Ln(distance to market, km)	0.007***	0.007***	0.002**	0.002**	0.001	0.002
• Cooperative	0.007***	0.007***	0.006***	0.006***	0.001**	0.001
• Microfinance	-0.005*	-0.005**	0	0	-0.001	-0.001

Household factors (of household head):						
• Ln(age)	-0.001	-0.001	-0.009***	0.009***	0.001	0.001
• Ln(family size)	-0.001	-0.001	0.001	0.001	-0.001	-0.001
• FHH (cf. MHH) ^a	-0.015*	-0.015*	-0.002	-0.002	-0.001	-0.001
• Literate (cf. illiterate)	0.006***	0.006**	-0.001	-0.001	0.001	0.001
• Nonfarm Income	0.115***	0.115**	-0.027	-0.027	0.021***	0.021
• Ln(nonfarm income, CFA)	-0.010***	-0.010**	0.003	0.003	-0.002***	-0.002
• Received remittances	-0.001	-0.001	0.003**	0.003**	0.001	0.0001
Agroclimatic zone: (cf. Sudano-Guinean)						
• Sudanian	0.002	0.002	0.005***	0.005***	0.0001	0.001
• Sahelian	0.020***	0.020***	0.011***	0.011***	-0.00041	-0.001
• Sahara	0.278***	0.278***	0.008*	0.008	0.00046	0.005
Constant	-0.019	-0.019	0.023**	0.023*	-0.00132	-0.001
Prob > F	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
R ²	0.416	0.416	0.382	0.382	0.999	0.999

Note: OLS = ordinary least squares; FHH = female-headed household; MHH = male-headed household; CFA = CFA franc.

Source: Computed using LSMS-ISA 2014

Surprisingly, younger farmers are more likely to use gravity irrigation than older farmers. Older farmers were expected to be more likely to use gravity irrigation since irrigation areas were allocated long time ago when the irrigation scheme was established. However, the rapid expansion of the Office du Niger could be the reason for these results, as it is possible that younger farmers are given priority in land allocation. Literate farmers are more likely to use motor pump irrigation than illiterate farmers. Similarly, income from nonfarm activities increases the propensity to use motor pumps. This is expected given that nonfarm activities increase the farmers' purchasing power. Similarly, nonfarm income reduces the propensity to use bucket irrigation but has an insignificant impact on gravity irrigation.

The Sudanian zone—wherein the Office du Niger is located—is strongly associated with gravity irrigation. Farmers in the Sahelian and Saharan zones are more likely to use motor pumps than those in the Sudano-Guinean zone. The results are supported by the maps showing the incidence of irrigation technology.

Impact of Irrigation on Nutrition across Gender

There is no significant impact of female household headship or type of irrigation technology on household dietary diversity (HDD) (Table 7). Only FHH x motor pump has a weak effect (significant at $p = 0.10$) on HDD. We expect the interaction term to be significant if the effect of irrigation technology depends on household headship, but this is not the case—suggesting that the two covariates do not have significant interaction. Accordingly, female household headship also does not significantly affect HDD in all the models. However, motor pump irrigation and gravity irrigation both significantly increase HDD, and the results are robust across the three models used.

As expected, access to microfinance institutions and proximity to roads both increase HDD. Similarly, literacy increases HDD. The results are consistent with those of other studies (e.g., Kuchenbecker et al. 2017; Smith and Haddad 2015; Gissing et al. 2017) and confirm the importance of rural services in improving household nutrition. As expected, receiving remittances increases HDD. This underscores the importance of a household having a safety net of relatives and friends who support it during difficult times. As expected, the Sudano-Guinea zone has higher HDD scores than the rest of the zones. The humid zone allows households to grow horticultural crops and other plants that enhance HDD.

Table 7 Impact of small-scale irrigation on household dietary diversity across sex of household head

	OLS	Poisson	Negative binomial
Irrigation technology and women interaction effects (cf. bucket irrigation):			
• FHH x motor pump	-0.065*	-0.119*	-0.119*
• FHH x gravity	-0.001	0.000	0.000
• FHH x other technology	0.107*	0.166	0.166
Type of irrigation technology:			
• Motor pump	0.050**	0.091**	0.091**
• Gravity	0.029*	0.049*	0.049*
• Bucket	-0.008	-0.013	-0.013
• Other technology	0.013	0.022	0.022
Access to rural services			
• Cooperative	0.002	0.003	0.003
• Microfinance institution	0.030***	0.053***	0.053***
• Ln(distance to market, km)	-0.015***	-0.028***	-0.028***
Irrigation suitability index (S) (cf. low suitability, S ≤ 20)			
• Medium (20 < S ≤ 30)	-0.01	-0.019	-0.019
• High (S ≥ 30)	0.014	0.025	0.025
Household factors			
• FHH (cf. MHH)	0.011	0.018	0.018
• Literate household head (cf. illiterate)	0.021**	0.037**	0.037**
• Ln(age of household head)	0.004	0.007	0.007
• N(family size)	-0.001	-0.001	-0.001
• Ln(Farm size)	0.003	0.005	0.005
Physical and financial capital endowment			
• Nonfarm	-0.122	-0.203	-0.203
• Received remittances	0.027***	0.049***	0.049***
Agroclimatic zones: (cf. Sudano-Guinean)			
• Sudanian	0.005	0.008	0.008
• Sahelian	-0.060**	-0.113**	-0.113**
• Sahara	-0.558***	-0.585***	-0.585***
R ²	0.025	-	-
Pseudo R ²	-	0.001	0.001
Prob > F	0.000***	-	-
Prob > χ^2	-	0.000***	0.000***

Note: OLS = ordinary least squares; FHH = female-headed household; MHH = male-headed household.

Source: Computed from LSMS-ISA 2017 raw data.

We analyze the effect of irrigation technologies on consumption of specific food groups. As expected and consistent with Passarelli et al. (2018), use of motor pumps increases consumption of fruits and vegetables, oils, spices, and cereals for female-headed households (Table 8). However, consumption of

roots and tubers and legumes is reduced by use of motor pumps for female-headed households. Gravity irrigation increases consumption of cereals (probably rice, which is common in the Office du Niger), oils, and spices. Surprisingly, gravity irrigation does not increase consumption of fruits and vegetables for female-headed households—an aspect that shows the limited dry season irrigation in the Office du Niger scheme. Except for fruits, other irrigation technologies increase consumption of all crops included. Overall irrigation increases consumption of nutrient-rich food groups, and this significantly increases household nutrition in addition to increasing income.

Considering irrigation alone without interaction, motor pump use increases consumption of cereals and spices while gravity irrigation increases only consumption of spices. Interestingly, bucket irrigation increases consumption of cereals, oils, and spices, but has no effect on intake of vegetables. The impact of bucket irrigation on cereals is likely due to its extensive use in Sikasso for irrigating rice—a staple subsistence consumption crop in the region.

Access to cooperatives and access to microfinance institutions each increase consumption of vegetables. Similarly, proximity to markets increases consumption of legumes, vegetables, and fruits. The results underscore the role played by rural services in increasing intake of nutrient-dense foods and by farmer groups in enhancing collective production and marketing.

Compared with the lowest irrigation suitability, the highest irrigation suitability ($S > 30$) increases consumption of cereals, fruits, oils, and spices. Areas with the lowest irrigation suitability are likely to be planted with roots and vegetables—which are drought tolerant and capable of performing relatively well under poor soil fertility (Scott et al. 2000). Likewise, legumes are planted in poor soils and can survive under poor rainfall due to their deep roots that exploit water from deeper soil moisture.

Table 8 Do small-scale irrigation technologies benefit women on nutrition outcomes?

	Food group consumed (marginal probability)						
	Cereals	Roots and tubers	Legumes	Vegetables	Fruits	Oils	Spices
Irrigation technology and women interaction effects (cf. bucket):							
FHH x motor pump	0.024***	-0.280***	-0.716***	0.355***	0.684***	0.201***	0.071***
FHH x gravity	0.024***	0.393*	-0.386*	-0.161	-0.051	0.201***	0.071***
FHH x other technology	0.024***	0.720***	0.284***	0.355***	-0.316***	0.201***	0.071***
Type of irrigation technology:							
Motor pump	0.024***	0.029	0.084*	-0.007	0.097	0.084*	0.058***
Gravity	0.006	0.084*	-0.086*	0.090*	0.080*	0.064*	0.043**
Bucket	0.024***	-0.043	-0.228	-0.111	-0.083	0.201***	0.071***
Other technology	-0.048	0.067	0.012	0.132	0.042	-0.025	-0.077
Access to rural services							
Cooperative	0.006	0	-0.027	0.059***	-0.001	-0.025	0.005
Microfinance	0.013*	0.039	0.049*	0.119***	0.03	0.002	0.02
Ln(distance to market, km)	-0.008*	-0.003	-0.036***	-0.04***	-0.033***	-0.016*	-0.012**
Irrigation suitability index (cf. $S \leq 20$)							
• Medium ($20 < S \leq 30$)	-0.001	-0.053**	-0.061**	-0.046*	-0.031	0.073***	0.007
• High ($S \geq 30$)	0.020***	-0.053**	-0.072***	0.002	0.071***	0.051***	0.055***
Household factors							
Nonfarm	0.036***	-0.291***	-0.198	0.063	-0.137	-0.652***	0.081**
FHH	-0.009**	0.075**	0.014	-0.001	0.015	0.050*	-0.017
Literate household head (cf. illiterate)	0.003	0.03	0.002	0.050**	0.056**	0.052***	0.016
Ln(age of household head)	0.002	0.034	-0.014	0.007	0.031	-0.006	-0.016

Food group consumed (marginal probability)							
	Cereals	Roots and tubers	Legumes	Vegetables	Fruits	Oils	Spices
Physical and financial capital endowment							
Ln(farm size, ha)	0.005	0.009	0.007	0.01	0.013	-0.025***	0.006
Ln(family size)	-0.010*	-0.026	-0.001	0.014	0.025	-0.008	-0.011
Received remittances	0.010*	0.013	0.052***	0.070***	0.015	0.071***	0.021*
Agroclimatic zones: reference group (cf. Sudano-Guinean)							
• Sudanian	0.015**	0.038*	0.058**	0.159***	-0.022	0.032*	0.001
• Sahelian	0.008	0.064**	-0.119***	0.104***	0.048*	0.095***	0.008
• Sahara	-0.04	-0.068	-0.357***	0.200***	-0.024	0.095***	-0.083*
Pseudo R ²	0.064	0.017	0.049	0.04	0.015	0.039	0.032
Prob > χ^2	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Log pseudo likelihood	-228.76	-1339.05	-1313.17	-1428.11	-1421.34	-1081.06	-543.18

Note: FHH = female-headed household.

Source: Computed from LSMS-ISA 2017 raw data.

4. Conclusions and Implications for Future Research

The results of this study show that use of motor pumps increases consumption of fruits and vegetables, oils, and spices for both female-headed and male-headed households. Additionally, motor pump irrigation increases consumption of cereals for female-headed households. The results confirm the role played by small-scale irrigation in improving food and nutrition security. Gravity irrigation, on the other hand, increases consumption of cereals—largely due to the Office du Niger irrigation scheme—in which rice production is the predominant crop. The Office du Niger has been promoting rice-horticulture rotation, which increases the use of organic and inorganic inputs on rice plots because farmers tend to apply organic inputs on horticultural crops and fertilizer on rice. Results of this study show this effort has not paid off yet. There is a need to more aggressively promote dry season horticultural production in the Office du Niger, which in turn will significantly improve farmers' nutrition security. The long history of promoting rice-horticulture rotation serves as an entry point for promoting small-scale irrigation and nutrition enhancement in the largest irrigation scheme in West Africa.

Despite its multiple advantages, access to irrigation water and technologies in Mali is quite low, especially for women. Overall, only 4 percent of plots are irrigated; of those, 5 percent of men's and 3 percent of women's plots are irrigated. The government's food security policies and strategies have prioritized irrigation, yet adoption remains quite low and is mainly concentrated in the Office du Niger, despite other large areas that are suitable for irrigation but not yet developed or utilized.

Our study shows that the major policy-relevant drivers of adoption of motor pump irrigation include nonfarm income, participation in farmer groups, primary education (as compared to no formal education), and market access. The results underscore the importance of nonfarm income in increasing smallholders' income for investing in irrigation. This underscores the need to design strategies for increasing entrepreneurship and access to credit, both of which increase the propensity to be engaged in nonfarm activities. Promoting education, especially for girls, has multiplier effects. Only 27 percent of female adults (15 years or older) are literate in Mali, versus 50 percent of men (UNESCO 2019). This means emphasis on education needs to be directed toward women.

Our study shows that participation in farmer groups increases the propensity to adopt irrigation. This is important given that farmer groups both increase smallholder farmer market participation and address the challenge of economies of scale such farmers face. Economies of scale are a particularly serious problem for horticultural crops, which are grown on small pieces of land and in specific seasons. These challenges are even more serious for smallholder female and youth farmers who are less resource-

endowed and have lower access to various services. Since 1990, net imports of fruits and vegetables in Mali have increased more than tenfold—underlining their growing demand driven by urbanization and growth of the middle-income group population.

With regard to type of irrigation technology, the predominance of bucket irrigation in Sikasso is puzzling—even among male farmers who usually grow crops for market and are thus able to buy motor pumps. There is a need to calculate the labor intensity and returns on investment in irrigation technology and infrastructure to determine the technology with the highest returns. However, the LSMS survey did not collect data on costs of irrigation and labor input. Our future planned study will collect such data. Similarly, irrigation could increase availability of potable water and improve general hygiene and sanitation. Such data were not collected by the LSMS. Our survey will collect those data to determine the impact of smallholder irrigation on hygiene, sanitation, and nutrition.

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