
# Irrigation for reducing food insecurity: The case of Niger

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# Irrigation for reducing food insecurity: The case of Niger

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**Abstract**

Effects of irrigation on household food security are examined, in a context of droughts and while controlling for point of crop harvest sales, employing longitudinal household and agriculture data collected by the Living Standards Measurement Study (LSMS) in Niger. Using panel fixed effects, we find that irrigation helped decrease food insecurity by 14 percent, increased food consumption expenditure by 11 percent, and improved dietary diversity, despite droughts. Irrigators had higher cash incomes as they sold a higher share of the harvest and had higher crop revenues; and irrigators had higher consumption of purchased and nutritious food items such as fruits, vegetables, and meat products. These effects were found for irrigators that primarily sold their crop harvest locally to village shops or neighbors as well as those who sold in bulk to regional or national traders. In a context where there is likely under-measurement of irrigation, and policies and projects are focused on developing irrigation in geographies with greater access to formal markets to maximize farmer profits; these results make a case for investing in irrigation in diverse geographies to support reductions in food insecurity.

***Key words***: Irrigation, droughts, point of sales, food security, Niger

***JEL codes***: Q15, Q18, Q13

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## 1. Introduction

This paper examines the effects of irrigation on food security of smallholder agricultural households in Niger, controlling for drought experiences and point of crop harvest sales. This analysis is motivated by an emerging policy discourse in Sub-Saharan Africa of prioritizing irrigation investments in areas that have proximity to regional and national markets, to maximize ‘returns on investment’ (e.g. Initiative pour l’irrigation au Sahel (2iS) 2017; Shah, Namara and Rajan 2020). Irrigation increases production through expanding multi-cropping and dry season cultivation and reducing crop losses; which contribute to food security either by increasing self-consumption or by improving crop sales that generate cash incomes which are then used to purchase food (Adeoti 2008; Bagson and Kuuder 2013; Buisson and Balasubramanya 2019; Burney et al. 2010; Burney and Naylor 2012; de Fraiture and Giordano 2014; Dillon 2008; Gebregziabher and Holden 2011; Giordano and de Fraiture 2014; Lipton et al. 2003; Nakawuka et al. 2018; Pandey et al. 2016; Woodhouse et al. 2017). With more frequent droughts in West Africa, and limited presence of regional and national traders, if irrigation also contributes to food security of smallholder households who experience droughts and sell informally, the policy discourse on investing in irrigation may need to take a broader perspective that includes notions of climate change and social safety nets.

Sub-Saharan Africa is poised to make major investments in small-scale irrigation to address hunger and food insecurity (African Union 2020). The Comprehensive Africa Agriculture Development Program under the African Union’s New Partnership for Africa’s Development (NEPAD) aims to increase irrigated areas (Woodhouse et al. 2017); only 4% of agricultural land was irrigated in Africa in 2013 (Burney et al. 2010). The 2014 Malabo Declaration, and the African Water Facility hosted and administered by the African Development Bank (AWF 2016) aim to increase prosperity and livelihoods in Africa, and expansion of irrigated agriculture was identified as an important strategy (Malabo Montpellier Panel 2018; Wiggins and Lankford 2019).

*Ex ante* feasibility assessments for considering small-scale irrigation projects to expand cultivated areas typically use scenarios of change in crop choice or cropping area[2] to calculate the alternative net present values of net incomes or profits (Balana et al. 2020; Makombe et al. 2017; van der Wijngaart et al. 2019; Xie, You and Takeshima 2017; You et al. 2011; You et al. 2014). Such analyses typically model farmers who sell to national or regional traders (Chazovachii 2012; Magistro et al. 2007; Polak and Yoder 2006; Xie et al. 2017; You et al. 2011; You et al. 2014), often ignoring those who sell informally. *Ex-post* analysis of the effects of irrigation shed light on household welfare effects (food consumption, cash incomes and dietary diversity), but often tend to not consider contexts of drought and points of sales. A common feature of *ex-post* analyses is selection into irrigation[3] (see for example Garbero and Songsermsawas 2018; Tesfaye et al. 2008); most ex post studies involve cross-sectional comparisons between adopters of irrigation and non-adopters. Such studies also often inadequately address study design and sampling issues (Domènech 2015; for examples, see Adeoti 2008; Mangisoni 2008).

This paper takes Niger as a case study, and uses nationally representative and adequately powered World Bank collected Living Standards Measurement Study—Integrated Surveys on Agriculture (LSMS—ISA) panel data for the years 2011 and 2014 that follows ~ 2,200 agricultural households. Panel data estimators are used to identify the effects of

[2] These projections can be based on data collected from a few pilot farmers, which may not be sufficient to cover heterogeneity in farmer conditions.
[3] Such endogeneity can be fairly important; for instance, households with greater education and incomes are more likely to be irrigators (Domènech 2015; Mangisoni 2008); and conditional on adoption, poorer households are likely to earn lower returns (van de Walle 2003).

irrigation on food security of farmers who have experienced droughts[4], while controlling for the point of crop harvest sales (proxy for access to output market). The year of 2012 was a meteorological drought year, allowing us to examine the effects of drought experiences by comparing farmers' outcomes in 2011 and 2014 against access to irrigation. Using panel data allows us to control for time-invariant selection effects into irrigation using a fixed-effects estimator. The potential endogeneity of experiences of droughts is addressed using instrumental variables.

The Government of Niger has exhibited a steady policy to develop irrigated agriculture over the years since 2002, in large part to reduce vulnerabilities to repeated droughts that have threatened food security. More than 270,000 hectare of land is considered suitable for irrigation development across the country, yet only nine percent of it is irrigated, partially (van der Wijngaart et al. 2019). The Initiative 3N (*Les Nigériens Nourrissent Les Nigériens*) aimed to increase contribution of irrigated agriculture to national GDP from 20 percent in 2012 to 30 percent in 2015 (this has not been achieved). More recently, the 2015 *Stratégie de la Petite Irrigation* (SPIN) aimed to harmonize interventions and approaches in expanding small-scale irrigation. Recent irrigation projects—the *Project de Promotion de l'Irrigation Privee* (PIP 2) and the *Projet de Développement des Exportations et des Marchés Agro-Sylvo Pastoraux* (PRODEX)—have expanded irrigation and improved roads around towns and cities in the South-West part of the country which is closer to regional markets. Understanding effects of irrigation for smallholders who experience droughts and who do not sell to national/regional traders is important for development policy in the country.

[4] The LSMS—ISA in Niger collects data on farmers' experiences of droughts, which are rather frequent in Niger, and these data are used to examine the effect of irrigation when farmers report experiencing droughts.

We find that irrigation helped decrease food insecurity by 12 percent, increase food consumption expenditure by about 9 percent, and improve dietary diversity, in the presence of self-reported experiences of droughts. Irrigators sold more produce and earned greater cash incomes. These effects observed both for farmers who sold their farm products locally in small quantities to neighbors and village shops, and for farmers who sold in bulk to large traders in formal regional markets. Our findings make a case for developing irrigation even when access to formal markets is poor. Irrigation in Niger reduces food insecurity in the presence of weather and climate shocks that small-scale producers are particularly susceptible to. A diversified approach towards developing irrigation will also help the Government of Niger meet its policy goals of increasing irrigated agriculture GDP.

Our paper contributes to the literature on irrigation in a couple of ways. First, the literature does not typically examine the effects of irrigation under conditions of droughts and climate shocks, though scholars have commented on the importance of irrigation to reduce vulnerability to rainfall (Dillon 2008; Lipton et al. 2003; Fox and Rockström 2003). This paper provides an empirical understanding of how irrigation stems losses under extreme climate conditions. Second, the paper highlights the importance of irrigation for reducing farmer vulnerabilities even when access to formal markets is poor, making a case for future work that examines irrigation effects in informal economies (Ricciardi et al. 2020; Ruel, Quisumbing and Balagamwala 2018; Woodhouse et al. 2017).

A limitation of the paper is that irrigation is likely under-measured (Woodhouse et al. 2017). In 2014, the LSMA-ISA in Niger elicited irrigation information only in the dry season, assuming that cultivation in the rainy season is not supplemented with irrigation. In the dry season, information on irrigation was not directly elicited; instead, respondents were asked to choose a primary water source from a list of options. This process of eliciting information on irrigation likely leads to underreporting of irrigated areas and irrigation sources (African

Union 2020). The results in this paper likely provide a conservative estimate of the effects of irrigation.

Section 2 of the paper provides a brief background of Nigerien agriculture, its irrigation goals, policies and progress in increasing irrigation. Section 3 describes the data and Section 4 describes the econometric methods. Section 5 presents results, and Section 6 discusses its implications.

## 2. Background

Niger is a landlocked country in West Africa, and is one of the poorest countries in the world, with a population of ~19.3 million in 2019 (FEWS NET 2019). Its population grew at a rate of 4% between 2011 and 2015, leading to a rapid fall in the ratio of arable land to agricultural workers (Tillie et al. 2016). It has one of the highest population growth rates in the world, at 3.3% in 2019 (Muller and Sayouti 2020). Agriculture contributes about 40% to the country's GDP, and combined with livestock, is also the most important source of livelihood (Muller and Sayouti 2020). Most farms are family farms, less than 2 hectare in size (Tillie et al. 2016). Commonly cultivated staple grains consist of millet, sorghum, and fonio, and these grains are rainfed. Cowpea, cotton, sesame and peanuts are typically cultivated for cash and require some irrigation, while vegetables, also cultivated for cash, require considerable irrigation.

Niger has been prioritizing the development of small-scale irrigation for the last 20 years, since the turn on the millennium. In the 1980s, the country developed surface water lift irrigation schemes in the south of the country along the Niger river to promote rice cultivation (Abernethy et al. 2000; Abernethy and Sally 1999). These schemes fell into disrepair due to high costs of maintenance, and the government has chosen to not invest in revitalizing these schemes, instead promoting small-scale irrigation.

In 2002, the county drafted the Accelerated Development and Poverty Reduction Strategy to halve poverty, and small-scale irrigation was identified as one of the main drivers for poverty reduction. The 2003 Rural Development Strategy which aimed to boost economic growth and food security also prioritized irrigation development to increase agricultural production. The 2005 National Strategy for Development of Irrigation and Collective Runoff waters aimed to increase the share of irrigated agriculture in agricultural GDP. Similarly, the *Project de Promotion de l'Irrigation Privee* (PIP 2), operated between 2003-2008, and the 2009 *Project de Développement des Exportations et des Marchés Agro-Sylvo Pastoraux* (PRODEX), also aimed to expand small-scale irrigation in Niger. These projects strengthened roads around towns and cities in the South-West part of the country, and expanded irrigation in areas where formal markets already existed, through the promotion of subsidized pumps[5] for extracting groundwater (Abric et al. 2011). More recently, the 2012 Initiative 3N (*Les Nigériens Nourrissent Les Nigériens*) and the 2015 *Stratégie de la Petite Irrigation* (SPIN) also aimed to further expand small-scale irrigation.

Formal agricultural markets are underdeveloped in Niger. Markets for grains are relatively more developed; farmers sell to intermediaries in villages, who then sell to wholesalers in local markets (Aker 2008). There is moderate price dispersion for grains, in part due to considerable distance between grain markets, ranging from 8 km to 1,200 km, with the average household around 10 km away from the nearest grain market (Aker 2010; Aker and Ksoll 2016). The majority of farmers use their own grain seeds or purchase them from friends and neighbors (Ndjeunga 2002). Markets for other crops are less well

[5] A 70% subsidy was offered to individuals/households; an 80% subsidy to producer organizations and a 90% subsidy for individuals from vulnerable groups (especially female-headed households).

developed, and sales are likely to take place within villages, especially for perishables such as vegetables (Aker 2008). Due to poor roads[6], and increasing problems of violence and insurgency, informal markets (selling to connections within villages) are likely to be more important than understood (FEWS NET 2019).

Food security is worsening for most households in Niger, based on data collected by the Government of Niger and the World Food Programme between 2008 and 2019. Around 32% of the population was classified as moderately or severely food insecure, with food consumption quantity falling for the majority of households between 2008 and 2017 (FEWS NET 2019). Malnutrition among children is not uncommon, due to lack of access to and knowledge of diversified diets.

Droughts are common in Niger, and it has the most recorded drought events for West Africa in recent years (van der Wijngaart et al. 2019). The years of 2001, 2005, 2010 and 2012 were drought years, where rainfall was significantly lower than historical levels (Ado, Savadogo and Abdoul-Azize 2019; FEWS NET 2019). Frequent droughts have changed agricultural practices in the country. Historically, settled agriculture used to be practiced by *Hausa* and *Djerma* communities in the rainfed semi-arid zone in the south of the country, while livestock tending was common among transhumance practicing *Fula* (*Pheul*) and *Tuareg* (Tamachek) communities. Based on cooperative relationships between the two groups, agro-pastoralists would take their herds and those of settled cultivators out north during the wet season and return in the dry season to graze on crop stubble on farms; manure from livestock would improve soil fertility on farms (Phillips 2007). Due to a fall in land per capita (as a result of population growth) and repeated droughts, both settled cultivators and agro-pastoralists have diversified livelihoods, with *Fula* communities also cultivating and

[6] Only 8% of roads are paved (Aker and Ksoll 2016).

irrigating in the dry season; and *Hausa* and *Djerma* communities increasing their ownership of livestock (FEWS NET 2019).

## 3. Data

The data come from two periods of longitudinal surveys in Niger. The first survey was conducted in 2011 and the second survey was conducted in 2014. Both surveys were conducted by the national statistical agency – *Institut National de la Statistique du Niger (INS-Niger)* – with technical and logistical help from the World Bank group as part of the Living Standard Measurement Study – Integrated Survey in Agriculture (LSMS-ISA). In 2011, the full sample consisted of 3,968 households of which 3,457 were successfully tracked in 2014 survey.[7] Both surveys are nationally representative and include comprehensive modules on household demographics, individual characteristics, agriculture, livestock, food security, consumption expenditure, shocks etc. Households that owned or cultivated agricultural land or owned or kept livestock in the 12 months preceding the survey were considered agricultural households; there were 2,339 agricultural households in 2011 and 2,180 such households in 2014. The analyses in this paper is based on the agricultural household sample.

In each year, data were collected in two separate visits by INS-Niger. In 2011, the first visit was conducted during July-September 2011 and the second visit during November 2011-January 2012. For the 2014 survey, the first visit was during September-November 2014 and the second visit during January-March 2015. In the first visit, the household module collected data on household demographics, income, housing characteristics, asset ownership, and shocks; the agriculture module collected information about plots, crops, inputs, irrigation, labor etc. for the post-planting period. In the second visit, the household module collected

[7] The 2014 survey consisted of 3,617 households including 160 split-off households

data on food and non-food consumption (both consumption frequency and expenditure), food security, and other information; the agriculture module collected data on post-harvest details (crop harvest, sales, and revenues) and livestock keeping.

### *3.1. Variables of interest*

The key variables of interest for this paper are irrigation, drought, and point of crop sales. In both survey years, irrigation information was collected for dry season only and access to irrigation was elicited by asking about the source of water for irrigation for each of the plots the household cultivated in dry season. Farmers were provided with five options (waterway (river, lake etc.), well, drilling, dam, and rainwater) and asked to name the primary source of water they had used to irrigate the plot. Source of irrigation water consisted both surface water sources (lake, river, dam) and groundwater sources (well, drilling). If the primary source of irrigation for a plot was rainwater, then such plots are considered rainfed for this analysis. Households that cultivated at least one irrigated plot are considered irrigated households even when they cultivated other plots that were rainfed.

The LSMS-ISA elicited farmers' drought experience through a detailed module pertaining to shocks. Respondents were provided with a list of 19 types of shocks and asked whether the household had been negatively affected by any of these shocks in the last 12 months. Drought was the most commonly reported shock that had negatively affected households. Households are considered to have experienced droughts if the respondent perceived (and thus reported) that the household had been negatively affected by drought in the last 12 months preceding the survey. If the respondent reported the household was negatively affected by drought, then they were asked to report if they had faced any losses in incomes, crops, assets and food items due to droughts.

Market access in the LSMS-ISA was elicited by asking the primary point of crop harvest sales (where farmers sold their products, primarily). Options for the point of sales included: 1) the state, 2) national traders, 3) foreign traders, 4) local shops, 5) local co-operatives, 6) neighbor or other farmers, and 7) relatives. Farmers were categorized into two groups based on where they sold their products, primarily. Those selling to the state, national traders, foreign traders and local cooperatives are considered connected to national/regional traders (formal markets). Those selling to local shops, neighbors, or relatives are considered to have access to local/informal markets.

### *3.2. Outcome variables*

In the LSMS-ISA, household food insecurity was elicited differently in different survey years. In 2011, the survey assessed household food insecurity using two binary choice questions, one for the last seven days and the other for the last 12 months. A household was considered food insecure in 2011 if the respondent reported that their household members were worried about having enough to eat in the last seven days or there was a time in the last 12 months when the household did not have sufficient food to eat. In 2014, however, household food insecurity was assessed by using FAO's food insecurity experience scale (FIES)[8]. As the food insecurity indicator in 2014 was not a binary indicator, we converted the FIES scores to a binary indicator to make it comparable with 2011 food insecurity status. FIES scores range between one and eight, one being severely food insecure and eight being no food insecure. For this analysis, households with FIES scores between one and five are considered to be food insecure.

Information on food consumption in the last 24 hours was collected for 60 different food items. We grouped together individual food items into 13 different food groups and

[8] See Cafiero et al. (2018) and Ballard et al. (2013) for details on the food insecurity experience scale (FIES).

calculated the household dietary diversity score as the sum of the number of food groups consumed in the last 24 hours, out of the 13 food groups, using FAO's approach to calculate the dietary diversity score (Kennedy, Ballard and Dop 2011). Since the household dietary diversity score combines staples and nutritious food items, we also used the frequency of consumption of key food items to complement the dietary diversity score—the number of days the household consumed cereals, vegetables, fruits, and meat/fish in the last seven days

The LSMS-ISA elicited expenditure on home-produced food items for the last seven days, but expenditure on purchased food items was recorded for the last 30 days. Expenditure on non-food items was recorded for the last 12 months. Consumption expenditure values collected for different time periods were converted to annual expenditure values by using appropriate multipliers. In this analysis, food expenditure is disaggregated into the value of home-produced food items and the value of purchased food items. Each of these expenditure variables are assessed at West-African Franc per-capita per year and deflated with regional price indexes to convert to real expenditure values.

We used additional variables to unpack the potential pathway for effects of irrigation on food security indicators. First, we assessed the effects of irrigation on crop diversification, share of crop harvest sold, and crop revenue. Crop diversification is defined as the number of crops cultivated in the dry season; the share of crop harvest sold is the percentage of dry season crop harvest sold; and crop revenue is the total revenue from all the crops grown in the dry season. Since the LSMS-ISA elicited irrigation status for the dry season alone, rainy season crop production information (though available in the data) was not included in the analysis. We also assessed the effects of irrigation on the probability of economic or food loss from drought and the probability of using different drought coping strategies, to understand whether irrigation stems losses from drought and reduces the need for using coping strategies such as distress sales etc.

## 4. Econometric methods

### *4.1. Panel fixed effects*

We use a fixed effects estimator to estimate the effects of irrigation on consumption expenditure, food security, and dietary diversity, controlling for the experience of drought and point of sales (market access). Let $Y_{it}$ indicate the outcome variable for household *i* in year *t*, $I_{it}$ indicate access to irrigation, $R_{it}$ indicate regional sales of farm produce, $L_{it}$ indicate local/informal sales, $S_{it}$ indicate the perception of drought, *X* indicate the vector of control covariates, and $\varepsilon_{it}$ indicate the idiosyncratic error term. The effects of irrigation on outcome *Y* is estimated using equation 1:

$$Y_{it} = \alpha + \beta I_{it} + \gamma_1 R_{it} + \gamma_2 L_{it} + \delta S_{it} + \Theta X + \mu_i + \varepsilon_{it} \qquad (1)$$

In equation 1, $\beta$ is the effect of irrigation on outcome *Y*, $\gamma_1$ is the effects of selling to regional traders, $\gamma_2$ indicates the effects of selling locally/informally, $\delta$ is the effect of drought, $\Theta$ is the vector of coefficient estimates on control covariates *X*, and $\mu_i$ is the household fixed effects. Estimating equation 1 with the fixed effect estimator would identify the effects of irrigation ($\beta$) if the outcome variables (or the idiosyncratic error term) is uncorrelated with explanatory variables and the unobserved time constant errors (strict exogeneity) i.e.

$$E[\varepsilon_{it} | I_{it}, R_{it}, L_{it}, S_{it}, X, \mu_i] = 0.$$

Access to irrigation is likely correlated with both time-invariant characteristics such as, ethnicity, gender, socio-cultural identity and time-variant characteristics such as income level, land holding size, social capital etc. The fixed effects estimator control for time-invariant unobserved heterogeneity; and Equation 1 controls for observed time-variant variables; but unobserved heterogeneity due to time-varying variables remains a concern. Since assessing the source of endogeneity of irrigation is challenging, our analysis does not attempt to estimate the causal effects of irrigation.

Information about crop cultivation in dry season was not available for 2014 survey; equation 1 cannot be used to estimate the effects of irrigation on crop diversification, sales, and revenue. We estimate these effects instead by using a OLS estimator. We control for regional dummies to remove the potential regional differences in crop production and access to irrigation. In equation 1, the regional effects are embedded in the fixed effects.

*4.2. Control function approach*

Equation 1 works best for outcome variables that are continuous. In this analysis, a few outcome variables are not continuous. We use the control function approach (also known as Chamberlin-Mundlak approach) to estimate the effects or irrigation on these variables. By design, this approach allows the unobserved fixed effects ($\mu_i$) to be correlated with other explanatory variables. Let $X_1$ be the vector of explanatory variables including irrigation *(I)*, point of sales, drought *(S)*, and other regressors *(X)*. Let $\overline{X_1}$ be the vector of time-constant means of each element of $X_1$. Equation 2 demonstrates the control function approach:

$$E(Y_{it}|X_1, \overline{X_1}) = \exp(\beta I_{it} + \gamma_1 R_{it} + \gamma_2 L_{it} + \delta S_{it} + \Theta X + \Pi \overline{X_1}) \quad (2)$$

Estimating equation 2 by Quasi-Maximum Likelihood Estimation (QMLE) yields consistent estimates of the coefficients of interest. We use equation 2 to estimate the effects of irrigation on the frequency of consumption of specific food items using a pooled poisson estimator (as consumption frequency follows a poisson distribution).

## 5. Results and discussion

We provide descriptive results pertaining to key variables used in the analysis, along with t-tests of the differences in key outcome variables between irrigated and non-irrigated households. Econometric results on effects of access to irrigation on food security indicators are then presented.

### *5.1. Descriptive results*

Table 1 presents probability weighted summary statistics of explanatory variables for both survey years and therefore is representative of farming households in Niger. Access to irrigation decreased over time, from 10.5% in 2011 to only 2.7% in 2014. Share of irrigated area per household also decreased over time from 2.5 % in 2011 to 0.9 % in 2014.[9] Share of respondents reporting drought was statistically significantly greater in 2014 (with 30% of farmers reporting drought) than in 2011 but the difference was only 2%.

In 2011, about 7 % farmers sold to regional or national traders and more than 30% of farmers sold locally (16% to local shops, 14% to neighbors, relatives). Share of farmers selling to local shops increased to 27% % in 2014, but the share of farmers selling to neighbors or relatives decreased to 11%.

--Table 1 here--

Table 1 also presents summary statistics for control covariates – household demographics, agricultural variables, and housing quality. Most households were male

[9] The decrease in irrigation coverage might have been a result of severe meteorological drought in 2012 which would have forced small-scale farmers out of dry season cultivation in 2014. Since information about dry season cultivation was not collected in 2014, this claim cannot be validated in our data.

headed but the share of female households increased over time from 8% in 2011 to 12% in 2014. The average household size was between 6 and 7 individuals with about four children (0 to 15 years), two youth (15 to 34 years) and one adult (35 to 64 years) indicating a rather young population. In 2011, more than 64% of households belonged to traditionally farming communities (*Hausa* or *Zarma* ethnic groups) and 12% belonged to traditional pastoralist groups (*Tuareg* and *Fulani* tribes). In 2014, share of farming communities increased to 69% but the share of pastoralist groups declined to 8%.

In 2011, more than 87% of farming households owned some land and the average land size was 4.6 hectare[10]. About 24% of households reported soil erosion on at least one of their cultivated plots in 2011, which increased to 36% in 2014.[11] Access to agricultural credit was low; only 6% of farming households reported using credit in 2011 and the share decreased further to 1% in 2014. Access to agricultural extension increased over time from 13% in 2011 to 25% in 2014. Livestock keeping was common (including among the farming households); more than 78% households kept some animals in 2011, but the share decreased to 73% in 2014. [12]

Table 2 presents summary statistics on outcome variables. Food insecurity was high during both years; 47% of household in 2011 and 57% in 2014. While food insecurity numbers are not directly comparable across years due to the differences in the survey instrument, they show rather widespread food insecurity (which likely increased due to a meteorological drought).

--Table 2 here--

[10] However, land ownership should not be understood as possession of land title or user right certificate because land allocation is still managed by traditional authorities and most farmers cultivate the land they are given by the *Chef de Canton*.

[11] Soil erosion is one of the major problems in Nigerien agriculture (World Bank 2000; Moussa et al. 2016; Tillie, Louhichi and Gomez-Y-Paloma 2018).

[12] In the data, 15% farmers reported selling livestock to cope with negative effects of drought.

In terms of household dietary diversity, household consumed food items that belong to nine different food groups out of the 13 groups. Disaggregating the food groups and examining consumption pattern of some key food items shows that cereals were consumed every day but the frequency of consumption of vegetables, fruits, and meat or fish was less common. Vegetables were consumed about three days a week, fruits were consumed just over a day per week and meat or fish was consumed between one and two days a week. Vegetables were consumed slightly more frequently in 2014 than in 2011, but both fruits and meat/fish were consumed less frequently in 2014.

On average, per-capita consumption expenditure was about US $ 34 per month in 2011 and US $ 31 per month in 2014. Food expenditures were the primary consumption expenditure, about US $ 24 per-capita per month. Value of consumption expenditures decreased over time and the difference was statistically significant. Breaking down food expenditures into the values of purchased food items and home produced food items, purchased food expenditure was the primary expenditure category with about US $ 17 per-capita per month. Comparing the values of consumption between 2011 and 2014, all but home-produced food consumption decreased over time.

### *5.2. Econometric results*

Tables 3, 4, and 5 present the effects of irrigation on food security indicators. Tables 6 and 7 explore potential pathway for the effects of irrigation. Control variables are included in each of the regressions but they are omitted from result tables for brevity. Full results including the coefficient estimates on control variables are available upon request.

#### *Effects on household food security*

Table 3 present the effects of irrigation on food security indicators. The first two columns show the effects on household food insecurity experience with and without controlling for point of crop harvest sales. Access to irrigation reduced food insecurity by 11%. When the point of sales was controlled for, irrigation had greater effects with a 14% reduction on food insecurity. Irrigators who sold to regional or national traders saw a further 5% reduction in food insecurity, but the effect was not statistically significant. While self-reported experience of drought was associated with 18% increase in food insecurity, access to irrigation reduced the effects of drought on food insecurity to 0.3%.

--Table 3 here—

Irrigation also enhanced food security by increasing household dietary diversity. On average, irrigators consumed 0.38 more food groups than non-irrigators. When point of sale was controlled for, irrigators who sold locally experienced an improvement in dietary diversity (consumption of 0.75 more food groups) as did irrigators who sold to national/regional traders (0.64 more food groups), though the latter was not significant statistically. Since one food group contains several food items, increase in dietary diversity by less than one food group can have large practical effects. We unpacked the dietary diversity score and assessed the effects of irrigation on consumption of a few major food items (Table 4).

*Effects on frequency of consumption*

Results in Table 4 show that irrigation's effect on dietary diversity were practically significant in that the frequency of consumption of nutritious food items was higher for irrigators than non-irrigators. Specifically, in the last seven days preceding the survey, irrigators consumed vegetables, fruits, and meat significantly more often than non-irrigators. Irrigators consumed cereals less often than non-irrigators, but the effect was not statistically significant. The point of crop harvest sales was positively associated with food consumption frequency, but the effects of the point of sale on consumption frequency disappeared for irrigators. Farmer's self-reported drought significantly reduced the frequency of consumption of fruits, vegetables, and meat products, but it increased the consumption of cereals. The adverse effects of drought on nutritious food item consumption was abated by irrigation indicating the importance of irrigation for food security in the event of drought.

--Table 4 here—

*Effects on food consumption expenditure*

Table 5 examines per-capita consumption expenditure as an indicator for household food security. Food expenditure was disaggregated into the value of purchased food items and the value of home-produced food items. Results show that, without controlling for the point of crop sales, irrigation increased total consumption expenditures by 7.2%. Controlling for the effects of point of sales, irrigators selling locally to local shops or villagers saw an increase in consumption expenditure of 17.8%, and those selling in bulk to regional/national traders experienced an increase of 6.7%. A similar pattern was observed for food consumption expenditure; on average irrigators experienced a 12% increase in food consumption expenditure. Controlling for the point of sales, irrigators selling locally saw a greater increase in food expenditure (25%) than those selling to regional/national traders (11%).[13]

--Table 5 here—

Food expenditure was disaggregated into the value of purchased food items (columns 5, 6 of Table 5) and the value of home produced food items (columns 7, 8 of Table 5). Irrigation's effects were estimated on each of these with and without controlling for point of sales. Results show that the increase in food expenditure among irrigating households was primarily driven by significant increase in value of purchased food items. Specifically, access to irrigation increased the value of purchased food items by 13%. Irrigators who sold crop harvest locally saw a 26 % increase in the value of purchased food items and those who sold to regional traders saw a 13% increase. Conversely, the effect of irrigation on the value of home-produced food items was negative; irrigators saw 11% reduction in the value of home-produced food items, albeit the change was not statistically significant.

*Potential pathways*

We also explored potential pathways through which irrigation might have enhanced household food security. First, we assessed how access to irrigation affects crop diversification, sales, and revenue in dry season (Table 6). In addition, we tested whether access to irrigation enhanced food security by reducing the probability of economic or food

[13] The finding that irrigation's effects on consumption expenditure was greater for farmers selling locally than those selling to traders does not mean that regional sales offer smaller margin. Irrigators who sold to regional traders had higher level of consumption expenditure to start with, so even a larger absolute increase in consumption expenditure can be a small percentage increase. Also, the sampling strategy of the LSMS-ISA does not allow a direct comparison between irrigators who sold locally and irrigations who sold to traders.

loss from drought (Table 7); this was estimated by dropping the indicator for drought from the estimating equation since the dependent variable is conditional on drought being experienced by the respondent.

--Table 6 here--

Results in Table 6 show that, in dry season, irrigators cultivated about two more crops than non-irrigators who mostly cultivated staple crops in the rainy season. Irrigation increased the number of crops cultivated, primarily by allowing cultivation in the dry season. Results in the second column show that irrigators were able to sell more than two-third of the crop harvest in dry season. For irrigators, cultivation of two more crops and the increase in crop harvest sales resulted into a significant increase in crop revenue. Compared to non-irrigators, irrigators saw an 806% increase in crop revenue in the dry season. This finding is consistent with the existing body of evidence that access to irrigation provides the opportunity to cultivate cash crops, which, when sold, provide additional cash incomes. These findings indicate that additional cash income from irrigated crop sales enabled Nigerien farmers to improve food security and dietary diversity by consuming more of nutritious purchased food items. For poor and vulnerable households, additional incomes allow buying more and more diverse food items, hence improving their food security and dietary diversity.

--Table 7 here--

Table 7 presents effects of irrigation on the probability of economic or food losses from drought and strategies used to cope with the losses. Irrigators were 16% less likely to lose income, 21% less likely to lose assets, and 17% less likely to lose food items due to drought than non-irrigators. Crop harvest sales also reduced the probability of loss from drought, but the point of sales did not matter much for irrigators. There was no statistical difference for the probability of loss from drought between irrigators who primarily sold crop harvest to regional traders and those who sold locally. The last two columns in Table 7 present the effects of irrigation on the use of different coping strategies in the event of loss from drought. Irrigators were 19% less likely to use savings and 7.4% more likely to 'do nothing' in coping with drought than non-irrigators, though the latter is not statistically significant. Results indicate that, in addition to the direct effects through increase in crop diversification and crop revenue, irrigation helped enhance household food security by reducing economic- and food losses and by reducing householder's dependency on savings.

### *5.3. Robustness checks*

Various robustness checks were used to validate the main findings. First, we used an instrumental variable (IV) estimator to estimate the effects of irrigation on food security indicators, controlling for the point of sale and the experience of drought. We also ran placebo regressions to demonstrate that a randomly generated 'false' irrigation variable did not affect food security indicators. Finally, we used a p-value correction method to address the issue of multiple hypothesis testing by adjusting the p-values for the number of null hypotheses tested.

*Instrumental variable (IV) method*

In equation 1, farmers' perception of drought is ($S_{it}$) is likely correlated with the idiosyncratic error. It is reasonable to assume that the same meteorological drought can impact farmers with different socio-economic status in different ways. Unobservable characteristics that influence different farmers' perception of drought can also affect their food security and dietary diversity status. As the perception of drought is likely determined by unobserved variables that also influence both $\mu_i$ and $\varepsilon_{it}$, the identifying assumption is perhaps violated. While we have no way to test whether $\mu_i$ is correlated with $\varepsilon_{it}$, it would be reasonable to find a set of instrumental variables (IVs) – observables that are correlated with the perception of drought but not correlated with $\varepsilon_{it}$ – and use them to control for unobserved heterogeneity.

We instrumented perceived drought with two variables that are orthogonal to the outcome variables but are correlated with the perception of drought. These variables include 1) distance to the primary source of drinking water in dry season, 2) share of agricultural plots with slope. These variables are valid instruments for the perception of drought, both conceptually and econometrically. The distance to the primary drinking water source increases in the dry season and farmers' perception of drought is largely shaped by the distance they need to travel to fetch drinking water. Existing evidence from other countries shows that drought can increase the distance to drinking water source (Bonsor, MacDonald and Calow 2010). In our data, the perception of drought was positively correlated with the distance to drinking water source (Table A1 in appendix). Farmers who own higher share of sloped land are more likely to perceive drought; a sloped land has lower water holding capacity than a flat land. An increase in the share of plots with slope can increase the perception of drought but is less likely to directly affect food security indicators.[14]

[14] Farmers' perception on the timing of the arrival of rainfall in the survey year could be a potential instrument for drought, Results in Table A1 show that the perception of rainfall arrival is significantly correlated with food insecurity but not correlated with other outcome variables. Hence, we do not use this variable as an instrument in the food insecurity regression.

Appendix Table A2 presents IV results for four major outcome variables – food insecurity, dietary diversity score, total consumption expenditure, and food expenditure. Results are qualitatively similar with the main findings in Table 3 and Table 5. Even after removing potential endogeneity of the perception of drought, effects of irrigation on food security indicators persist. We also conducted various IV validity tests, and the findings presented in the bottom part of Table A2 suggest that the instruments were valid.

*Placebo tests*

Placebo tests were carried out by regressing food security indicators on a randomly created 'false' irrigation variable along with other control variables including point of sales and self-reported drought. A 'false' access to irrigation was created by assigning irrigation status to some households and not to others, randomly. In the data generation process, the arithmetic mean for the randomly created 'false' irrigation was set equal to the mean of the true irrigation variable in the data. Placebo test results are presented in Table A3 in the appendix, showing that the 'false' access to irrigation did not have significant effects on any of the outcome variables.

*Multiple testing*

We corrected for multiple hypothesis testing by using Anderson-BKY adjusted p-values (also known as sharpened q-values), adjusted for the potential false discovery rate due to multiple hypotheses testing (Anderson 2008; Benjamini, Krieger and Yekutieli 2006). Results in Table A4 suggest that the analyses did not suffer from multiple testing; out of the 18 hypotheses tested, original p-values were greater than 0.1 for five hypotheses, but the Anderson-BKY adjusted p-values were greater than 0.1 in two cases only. After adjusting for multiple testing, three hypotheses that we failed to reject initially were rejected at 10% level of significance.

## 6. Conclusion

This analysis investigated the effects of irrigation on household food insecurity experience, household dietary diversity, food consumption expenditure, and food consumption frequency, in the context of droughts and controlling for point of crop harvest sales. Results showed that, in Niger, irrigation reduced food insecurity and improved dietary diversity through increase in consumption of nutritious food items (fruits, vegetables, meat and fish) that were purchased. Analysis of the potential pathway for irrigation's positive effects revealed that irrigators were able to purchase additional food items by using cash income generated by higher sales of irrigated crop harvest. These findings persisted even after controlling for the point of crop harvest sales and farmers' perception of drought. Grouping the point of sales into sales to national/regional traders and sales to local shops or villagers, results showed irrigation improved food security both for farmers who sold informally and for those who sold to traders.

Results in this analysis have important policy implications. First, access to irrigation can work as a social safety net for small-scale producers by providing some cash in hand and little more food on the plate, even when they experience drought. Second, results suggest that irrigation also helps small-scale farmers who are not connected to national/regional traders through formal markets; in Niger, irrigation's positive effects were mediated through increased crop sales and crop revenue, and the increase in crop revenue was higher for farmers selling locally to small shops and villagers than farmers who sold in bulk to regional traders.

Taken together, results suggest that expansion of small-scale irrigation in areas with existing access to formal/regional markets likely misses an important opportunity to achieve Niger's poverty reduction and food security goals. In fact, irrigation investments that prioritize geographies where farmers are already connected to national/regional traders (or markets) may not reach small-scale farmers who are likely more vulnerable and in need of public support for irrigation development (so that private investments also become more feasible).

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## Tables

**Table 1. Summary statistics of explanatory variables**

| **Variables** (all variables are binary, unless otherwise noted | **2011** | **2014** | **Difference** |
|---|---|---|---|
| | *1* | *2* | *3* |
| *Key variables* | | | |
| Access to irrigation | 0.105 | 0.027 | -0.078*** |
| | (0.306) | (0.161) | |
| Share of irrigated area | 0.025 | 0.009 | -0.015*** |
| | (0.127) | (0.091) | |
| Drought | 0.283 | 0.301 | 0.014** |
| | (0.450) | (0.459) | |
| *Point of sale* | | | |
| Regional/national traders | 0.076 | 0.064 | -0.012 |
| | (0.265) | (0.244) | |
| Local shops | 0.159 | 0.269 | 0.110*** |
| | (0.366) | (0.444) | |
| Neighbors, relatives | 0.144 | 0.107 | -0.036*** |
| | (0.351) | (0.310) | |
| *Household demographics* | | | |
| Head: Age (years) | 44.50 | 46.73 | 2.24*** |
| | (14.62) | (14.14) | |
| Female headed | 0.077 | 0.12 | 0.041*** |
| | (0.27) | (0.32) | |
| Number of children | 3.66 | 3.81 | 0.15 |
| | (2.55) | (2.49) | |
| Number of youth | 1.76 | 1.55 | -0.21*** |
| | (1.28) | (1.16) | |
| Number of adult | 1.17 | 1.25 | 0.082** |
| | (0.96) | (0.96) | |
| Houssa/Zarma household | 0.64 | 0.69 | 0.059*** |
| | (0.48) | (0.46) | |
| Tuareg/Fulani household | 0.12 | 0.084 | -0.036*** |
| | (0.32) | (0.28) | |
| *Agricultural variables* | | | |
| Land size (Ha) | 4.67 | 4.08 | -0.59*** |
| | (5.39) | (4.40) | |
| Soil erosion | 0.24 | 0.36 | 0.12*** |
| | (0.43) | (0.48) | |
| Used improved seed | 0.024 | 0.061 | 0.038*** |
| | (0.15) | (0.24) | |
| Used organic fertilizer | 0.54 | 0.60 | 0.058*** |
| | (0.49) | (0.49) | |
| Used pesticides | 0.078 | 0.103 | 0.025** |

| | | | |
|---|---|---|---|
| | (0.27) | (0.30) | |
| Used outside labor | 0.076 | 0.22 | 0.14*** |
| | (0.26) | (0.41) | |
| Agricultural credit | 0.062 | 0.007 | -0.055*** |
| | (0.24) | (0.084) | |
| Agricultural extension | 0.13 | 0.25 | 0.12*** |
| | (0.34) | (0.43) | |
| Livestock household | 0.78 | 0.73 | -0.055*** |
| | (0.41) | (0.44) | |
| *Housing quality* | | | |
| Home ownership | 0.95 | 0.96 | 0.006 |
| | (0.22) | (0.20) | |
| Improved roof | 0.059 | 0.063 | 0.004 |
| | (0.24) | (0.24) | |
| Improved floor | 0.057 | 0.064 | 0.007 |
| | (0.23) | (0.25) | |
| Improved wall | 0.022 | 0.036 | 0.014** |
| | (0.15) | (0.19) | |
| Connected to public water network | 0.019 | 0.019 | 0.0005 |
| | (0.138) | (0.140) | |
| **Number of households** | **2339** | **2168** | |

*Notes:* Point estimates are weighted means. Standard deviations are in parentheses. Significance stars in the last column indicate the level of significance for the null hypothesis that the mean difference is equal to zero. Level of significance * <0.1, ** <0.05, *** <0.01

**Table 2. Summary statistics of outcome variables**

| Variables | 2011 | 2014 | Difference |
|---|---|---|---|
| *Food insecurity and dietary diversity* | *1* | *2* | *3* |
| Food insecurity (1=yes, 0=no) | 0.472 | 0.571 | 0.099*** |
| | (0.499) | (0.495) | |
| Household dietary diversity | 9.44 | 9.26 | -0.17** |
| | (1.89) | (1.77) | |
| *Number of days [food] was consumed last week* | | | |
| 1. Cereals | 6.4 | 6.8 | 0.39*** |
| | (1.35) | (0.82) | |
| 2. Vegetables | 2.6 | 3.5 | 0.85*** |
| | (2.63) | (2.69) | |
| 3. Fruits | 1.3 | 0.9 | -0.44*** |
| | (2.12) | (1.67) | |
| 4. Meat/Fish | 1.5 | 1.4 | -0.09 |
| | (1.80) | (1.74) | |
| *Consumption expenditure (USD, monthly/person)* | | | |
| Total expenditure | 34.01 | 30.87 | -3.13*** |
| | (19.73) | (20.73) | |
| Food expenditure | 23.91 | 21.82 | -2.08*** |
| | (12.93) | (15.21) | |
| 1. Value of purchased food | 17.44 | 14.70 | -2.73*** |
| | (11.83) | (12.07) | |
| 2. Value of home produced food | 5.07 | 6.28 | 1.21*** |
| | (4.59) | (7.12) | |
| *Crops sales and diversification in **dry season*** | | | |
| Crop revenue (USD) | 44.55 | - | - |
| | (341.1) | | |
| Share of harvest sold | 0.062 | - | - |
| | (0.22) | | |
| Number of crops cultivated | 0.21 | - | - |
| | (0.81) | | |
| **Number of households** | **2,339** | **2,168** | |

*Notes:* Point estimates are weighted means. Standard deviations are in parentheses. Significance stars in the last column indicate the level of significance for the null hypothesis that the mean difference is equal to zero. Level of significance * <0.1, ** <0.05, *** <0.01

**Table 3. Effects of irrigation on food security and dietary diversity**

| | Food insecurity | | Dietary diversity | |
|---|---|---|---|---|
| | *1* | *2* | *3* | *4* |
| Irrigation | -0.11** | -0.14** | 0.38** | 0.28 |
| | (0.051) | (0.055) | (0.17) | (0.18) |
| Sold to regional/national traders | - | 0.095* | - | 0.21 |
| | | (0.049) | | (0.16) |
| Regional sales x irrigation | - | -0.047 | - | 0.38 |
| | | (0.11) | | (0.35) |
| Sold to local shops, neighbors | - | -0.040 | - | 0.054 |
| | | (0.029) | | (0.097) |
| Local sales x irrigation | - | 0.15 | - | 0.47* |
| | | (0.090) | | (0.25) |
| Drought | 0.18*** | 0.17*** | -0.031 | -0.030 |
| | (0.025) | (0.025) | (0.088) | (0.088) |
| Drought x irrigation | 0.015 | 0.0029 | 0.27 | 0.17 |
| | (0.081) | (0.081) | (0.25) | (0.25) |
| Controls | Yes | Yes | Yes | Yes |
| Constant | 0.66*** | 0.67*** | 8.42*** | 8.41*** |
| | (0.11) | (0.11) | (0.37) | (0.37) |
| **Observations** | **4,507** | **4,507** | **4,507** | **4,507** |

*Notes*: Results come from the panel fixed effects estimator. Standard errors are in parentheses. Level of significance * $p < .10$, ** $p < .05$, *** $p < .01$. Control covariates include household demographics, agricultural variables, and housing characteristics. Summary of control variables is presented in Table 1.

**Table 4. Effects of irrigation on food consumption frequency**

| | Days consumed [food] in the last week | | | |
|---|---|---|---|---|
| | Cereals | Vegetables | Fruits | Meat |
| | *1* | *2* | *3* | *4* |
| Irrigation | -0.0056 | 0.098$^{*}$ | 0.34$^{***}$ | 0.31$^{***}$ |
| | (0.012) | (0.052) | (0.12) | (0.072) |
| Sold to regional/national traders | 0.028$^{***}$ | 0.14$^{***}$ | 0.35$^{***}$ | 0.035 |
| | (0.0093) | (0.053) | (0.096) | (0.073) |
| Regional sales x irrigation | -0.0048 | 0.12 | 0.042 | -0.027 |
| | (0.016) | (0.10) | (0.20) | (0.15) |
| Sold to local shops, neighbors | 0.016$^{***}$ | 0.12$^{***}$ | 0.061 | 0.068 |
| | (0.0060) | (0.033) | (0.066) | (0.043) |
| Local sales x irrigation | -0.013 | 0.094 | -0.23 | -0.047 |
| | (0.017) | (0.080) | (0.21) | (0.12) |
| Drought | 0.017$^{***}$ | -0.10$^{***}$ | -0.33$^{***}$ | -0.21$^{***}$ |
| | (0.0053) | (0.032) | (0.065) | (0.044) |
| Irrigation x drought | -0.078$^{***}$ | 0.069 | -0.097 | 0.18$^{*}$ |
| | (0.021) | (0.078) | (0.19) | (0.11) |
| Controls | Yes | Yes | Yes | Yes |
| Constant | 1.89$^{***}$ | 0.79$^{***}$ | -0.29 | 0.29$^{*}$ |
| | (0.022) | (0.11) | (0.23) | (0.16) |
| **Observations** | **4,507** | **4,506** | **4,506** | **4,507** |

*Notes*: Results come from the panel fixed effects estimator. Standard errors are in parentheses. Level of significance $^{*}$ $p < .10$, $^{**}$ $p < .05$, $^{***}$ $p < .01$. Control covariates include household demographics, agricultural variables, and housing characteristics.

**Table 5. Effects of irrigation on consumption expenditure**

| | Total consumption expenditure | | Food expenditure | | Value of purchased food | | Value of home produced food | |
|---|---|---|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| Irrigation | 0.072* | 0.058 | 0.12*** | 0.11*** | 0.13*** | 0.13** | -0.12 | -0.11 |
| | (0.037) | (0.039) | (0.039) | (0.041) | (0.048) | (0.052) | (0.083) | (0.093) |
| Sold to regional/national traders | - | 0.15*** | - | 0.18*** | - | 0.20*** | - | 0.16** |
| | | (0.035) | | (0.039) | | (0.055) | | (0.063) |
| Regional sales x irrigation | - | 0.0087 | - | -0.050 | - | -0.13 | - | 0.15 |
| | | (0.069) | | (0.076) | | (0.088) | | (0.18) |
| Sold to local shops, neighbors | - | 0.046** | - | 0.044* | - | 0.035 | - | 0.14*** |
| | | (0.023) | | (0.025) | | (0.031) | | (0.040) |
| Local sales x irrigation | - | 0.12** | - | 0.14** | - | 0.13* | - | -0.0088 |
| | | (0.059) | | (0.067) | | (0.069) | | (0.14) |
| Drought | 0.0025 | 0.0034 | 0.012 | 0.013 | 0.035 | 0.035 | -0.024 | -0.019 |
| | (0.020) | (0.020) | (0.022) | (0.022) | (0.028) | (0.028) | (0.041) | (0.041) |
| Drought x irrigation | -0.0068 | -0.038 | -0.035 | -0.067 | 0.031 | 0.0055 | 0.10 | 0.062 |
| | (0.058) | (0.057) | (0.064) | (0.064) | (0.070) | (0.071) | (0.14) | (0.14) |
| Controls | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 3.95*** | 3.93*** | 3.62*** | 3.60*** | 3.20*** | 3.19*** | 1.71*** | 1.66*** |
| | (0.081) | (0.082) | (0.087) | (0.087) | (0.11) | (0.11) | (0.18) | (0.18) |
| **Observations** | **4,445** | **4,445** | **4,445** | **4,445** | **4,445** | **4,445** | **4,445** | **4,445** |

*Notes*: Results come from the panel fixed effects estimator. Standard errors are in parentheses. Level of significance $^{*}$ $p < .10$, $^{**}$ $p < .05$, $^{***}$ $p < .01$. Control covariates include household demographics, agricultural variables, and housing characteristics.

**Table 6. Effects of irrigation on crop diversification, sales, and revenue**

| | Dependent variables | | |
|---|---|---|---|
| | Number of crops cultivated | Share of harvest sold | Crop revenue |
| | *1* | *2* | *3* |
| Irrigation | 1.82*** | 0.66*** | 8.06*** |
| | (0.14) | (0.032) | (0.39) |
| Sold to regional/national traders | -0.015 | 0.0046 | 0.074 |
| | (0.039) | (0.013) | (0.14) |
| Regional sales x irrigation | -0.41** | -0.11* | -1.11 |
| | (0.19) | (0.064) | (0.78) |
| Sold to local shops, neighbors | -0.046* | -0.013* | -0.15* |
| | (0.024) | (0.0069) | (0.078) |
| Local sales x irrigation | 0.24 | 0.13* | 1.62** |
| | (0.23) | (0.065) | (0.77) |
| Drought | -0.0088 | -0.0032 | -0.015 |
| | (0.018) | (0.0057) | (0.066) |
| Irrigation x drought | -0.16 | 0.080 | 0.12 |
| | (0.17) | (0.060) | (0.71) |
| Controls | Yes | Yes | Yes |
| Constant | -0.75*** | -0.29*** | -3.43*** |
| | (0.15) | (0.045) | (0.54) |
| **Observations** | 2,339 | 2,339 | 2,339 |

*Notes*: Results come from the ordinary least squares estimator on 2011 data. Standard errors are in parentheses. Level of significance * $p < .10$, ** $p < .05$, *** $p < .01$

**Table 7. Effects of irrigation on economic or food loss from drought and coping strategies**

| | Loss from drought | | | Drought coping strategies | |
|---|---|---|---|---|---|
| | Income loss | Asset loss | Food loss | Did nothing | Used savings |
| | *1* | *2* | *3* | *4* | *5* |
| Irrigation | -0.16** | -0.21*** | -0.17*** | 0.074 | -0.19*** |
| | (0.063) | (0.063) | (0.059) | (0.060) | (0.063) |
| Sold to regional/national traders | -0.11* | -0.086 | -0.095 | 0.026 | -0.20*** |
| | (0.060) | (0.063) | (0.060) | (0.058) | (0.061) |
| Regional sales x irrigation | -0.013 | -0.12 | 0.097 | 0.17* | 0.037 |
| | (0.11) | (0.13) | (0.10) | (0.10) | (0.12) |
| Sold to local shops, neighbors | -0.077** | -0.060* | -0.016 | -0.054 | -0.028 |
| | (0.035) | (0.035) | (0.033) | (0.035) | (0.034) |
| Local sales x irrigation | -0.011 | 0.20** | 0.043 | 0.060 | 0.13 |
| | (0.087) | (0.091) | (0.089) | (0.099) | (0.088) |
| Controls | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.45** | 0.011 | -0.20 | 0.30 | -0.43* |
| | (0.18) | (0.19) | (0.18) | (0.18) | (0.22) |
| **Observations** | **3,754** | **3,754** | **3,754** | **3,754** | **3,754** |

*Notes*: Results come from the panel fixed effects estimator. Standard errors are in parentheses. Level of significance * $p < .10$, ** $p < .05$, *** $p < .01$

## APPENDIX

**Table A1. Relationship between instrumental variables and key variables of interest**

| | Food insecurity | Dietary diversity | Total consumption expenditure | Food expenditure | Drought |
|---|---|---|---|---|---|
| *Instrumental variables* | *1* | *2* | *3* | *4* | *5* |
| Distance to drinking water source in dry season | 0.023 | -0.029 | 0.010 | 0.010 | 0.045*** |
| | (0.015) | (0.049) | (0.011) | (0.012) | (0.017) |
| Slope of parcel | -0.0061 | 0.083 | -0.0070 | -0.014 | 0.052* |
| | (0.032) | (0.10) | (0.024) | (0.026) | (0.029) |
| Perceived late rain | -0.12*** | -0.083 | -0.0094 | -0.015 | -0.053** |
| | (0.021) | (0.074) | (0.016) | (0.017) | (0.022) |
| Controls | Yes | Yes | Yes | Yes | Yes |
| **Observations** | **4,445** | **4,445** | **4,445** | **4,445** | **4,445** |

*Notes*: Results are obtained from panel fixed effects. Robust standard errors are in parentheses. Level of significance * $p < .10$, ** $p < .05$, *** $p < .01$.
Variables in the first 4 columns are outcome variables. Drought (column 5) is the endogenous variable.

**Table A2. Effects of irrigation on food insecurity, dietary diversity, and consumption expenditure – IV results**

| | Food insecurity | Dietary diversity | Total expenditure | Food expenditure |
|---|---|---|---|---|
| | *1* | *2* | *3* | *4* |
| Irrigation | -0.11$^{**}$ | 0.39$^{**}$ | 0.060$^{*}$ | 0.098$^{***}$ |
| | (0.046) | (0.16) | (0.034) | (0.037) |
| Drought | 0.30 | 0.59 | 0.16 | 0.18 |
| | (0.28) | (0.80) | (0.19) | (0.21) |
| Controls | Yes | Yes | Yes | Yes |
| **Observations** | **3,956** | **3,956** | **3,956** | **3,956** |
| **IV validity tests** | | | | |
| Weak IV | | | | |
| *Crag-Donald Wald F statistic* | 5.29$^{***}$ | 5.61$^{***}$ | 5.61$^{***}$ | 5.61$^{***}$ |
| Under-identification | | | | |
| *Kleibergen-Paap LM statistic* | 10.13$^{***}$ | 16.12$^{***}$ | 16.12$^{***}$ | 16.12$^{***}$ |
| Over-identification | | | | |
| *Hansen J statistic* | 0.928 | 2.11 | 0.55 | 1.21 |

*Notes*: Results come from the panel fixed effects IV estimator. Standard errors are in parentheses. Level of significance $^{*}$ $p < .10$, $^{**}$ $p < .05$, $^{***}$ $p < .01$
Control covariates include household demographics, agricultural variables, and housing characteristics.

**Table A3. Placebo test results**

| | Food insecurity | Dietary diversity | Total expenditure | Food expenditure | Value of purchased food | Value of home produced food |
|---|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* | *6* |
| False irrigation | -0.022 | 0.098 | 0.0035 | 0.016 | 0.0041 | 0.067 |
| | (0.040) | (0.14) | (0.033) | (0.037) | (0.044) | (0.066) |
| Sold to regional traders | 0.11** | 0.19 | 0.15*** | 0.17*** | 0.19*** | 0.17*** |
| | (0.048) | (0.16) | (0.035) | (0.039) | (0.055) | (0.064) |
| Irrigation x regional sales | -0.11 | 0.51 | 0.037 | 0.0023 | -0.070 | 0.094 |
| | (0.10) | (0.35) | (0.067) | (0.075) | (0.087) | (0.17) |
| Sold locally | -0.027 | 0.028 | 0.041* | 0.034 | 0.023 | 0.15*** |
| | (0.029) | (0.096) | (0.022) | (0.024) | (0.030) | (0.040) |
| Irrigation x local sales | 0.086 | 0.60** | 0.15*** | 0.19*** | 0.19*** | -0.055 |
| | (0.086) | (0.24) | (0.057) | (0.065) | (0.066) | (0.12) |
| Drought | 0.18*** | -0.047 | -0.00022 | 0.0060 | 0.027 | -0.013 |
| | (0.024) | (0.086) | (0.020) | (0.022) | (0.027) | (0.041) |
| Irrigation x drought | -0.067 | 0.31 | -0.0084 | -0.011 | 0.073 | 0.0087 |
| | (0.075) | (0.25) | (0.055) | (0.062) | (0.067) | (0.14) |
| Constant | 0.64*** | 8.46*** | 3.95*** | 3.62*** | 3.22*** | 1.65*** |
| | (0.11) | (0.37) | (0.082) | (0.088) | (0.11) | (0.18) |
| **Observations** | **4507** | **4507** | **4445** | **4445** | **4445** | **4445** |

*Notes*: Results come from the panel fixed effects estimator. Standard errors are in parentheses. Level of significance * $p < .10$, ** $p < .05$, *** $p < .01$
Control covariates include household demographics, agricultural variables, and housing characteristics.

**Table A4. Multiple testing adjusted p-values for effects of irrigation**

| Outcome variables | P-values | BKY adjusted p-values |
|---|---|---|
| *Food security* | | |
| Food insecurity | 0.012 | 0.013 |
| Dietary diversity | 0.117 | 0.053 |
| *Consumption frequency* | | |
| Cereal days | 0.64 | 0.178 |
| Vegetable days | 0.058 | 0.028 |
| Fruit days | 0.003 | 0.006 |
| Meat days | 0.00001 | 0.001 |
| *Consumption expenditure* | | |
| Total expenditure | 0.13 | 0.055 |
| Food expenditure | 0.009 | 0.012 |
| Value of purchased food | 0.012 | 0.013 |
| Value of home produced food | 0.254 | 0.088 |
| *Crop diversification, sales, and revenue* | | |
| Number of crops cultivated | 0.00001 | 0.001 |
| Share of harvest sold | 0.00001 | 0.001 |
| Crop revenue | 0.00001 | 0.001 |
| *Loss from drought and coping strategies* | | |
| Income loss | 0.018 | 0.017 |
| Asset loss | 0.001 | 0.003 |
| Food loss | 0.0001 | 0.001 |
| Did nothing to cope with drought | 0.528 | 0.178 |
| Used savings to cope with drought | 0.007 | 0.01 |

*Notes*: P-values were adjusted for multiple hypotheses testing by using Anderson-BKY adjustment method (Anderson 2008; Benjamini et al. 2006).