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ORIGINAL PAPER

Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania

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Abstract

Interventions that aim to increase water availability for agriculture hold great potential for improving nutrition through increasing food production, generating income, enhancing water access and sanitation and hygiene conditions, and through strengthening women's empowerment. Yet there is scarce evidence on the linkages between small-scale irrigation and the pathways through which nutrition outcomes can be achieved. Using data from a cross-sectional household survey collected in Ethiopia and Tanzania, we explored the potential for small-scale irrigation to contribute to improved diets, and identify the pathways through which irrigation affects dietary diversity as measured by the Household Dietary Diversity Score. Unadjusted comparisons show that irrigating households in both countries produced more vegetables, fruits and cash crops, are less food insecure, have a higher value of production, and have higher production diversity and dietary diversity compared to non-irrigating households. Econometric results of a simultaneous equation (3SLS) model showed that irrigation leads to better household dietary diversity mainly through the pathway of increasing household incomes. However, these results are statistically significant only in the case of Ethiopia, and not in Tanzania. While irrigation increased production diversity in Ethiopia, the benefits of increased dietary diversity cannot be attributed to these changes in production after controlling for the effect of income. Other factors, such as gender of the household head and having off-farm income, also influence dietary diversity in Ethiopia. These findings suggest that the potential for irrigation to influence diets is highly context-specific. Understanding the particular pathways and entry points for nutrition-sensitive agriculture approaches could help to improve their benefits for nutrition.

Keywords Irrigation · Nutrition · Dietary diversity · Income pathway · Ethiopia · Tanzania

1 Introduction

Despite recent momentum towards improving nutrition and reducing poverty globally, undernutrition still affects billions of people worldwide. According to the 2017 Global Food Policy Report, approximately two billion people experience micronutrient malnutrition, 155 million children under five are stunted, 52 million children are wasted, and 815 million people are chronically undernourished worldwide. The burden of child stunting represents losses in cognitive function, income, productivity, and increased likelihood of chronic disease that can affect subsequent generations and limit economic growth. Poor nutrition contributes to approximately 45% of all deaths of children under five annually (IFPRI 2017).

Nutrition-sensitive agricultural interventions, like biofortification, crop diversification, and value-added processing, have the potential to improve nutritional outcomes

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in agrarian communities (Ruel et al. 2017). Yet evidence on direct agriculture-nutrition linkages is lacking, which prevents the implementation and scale-up of successful approaches (Ruel and Alderman 2013). A recent review suggests that the potential for irrigation to impact nutrition and health outcomes has not been thoroughly explored (Domènech 2015).

Irrigation expansion has been regarded as a promising approach to ensure food and livelihood security in the face of climate change and population growth. While only 4% of cultivated area in sub-Saharan Africa is currently irrigated, the potential for the expansion of irrigation in the region is large and investments are accelerating (Giordano et al. 2012). Previous investments in irrigation by donors and governments have focused on developing large-scale irrigation schemes, but evidence suggests that the greatest gains in terms of profitability and sustainability will come from investments in small-scale irrigation (Xie et al. 2014; You et al. 2011).

Previous studies show increased yields and income following the adoption of small-scale irrigation technologies. Xie et al. (2014) found that small-scale irrigation has the potential to boost agricultural yields by at least 50%, with the majority of the income benefits accruing to the smallholders themselves. Lipton et al. (2003) showed that irrigation increased productivity by reducing crop losses that were due to limited water supply, enabling cultivation during the lean season, and making crop production possible on lands where rainfed agriculture is infeasible. As a result of a project that introduced 50,000 tubewells in Nigeria, farmers experienced increases in returns per hectare from 65 to 500%—with an average rate of return on investment close to 40% (Burney and Naylor 2012). Similarly in Malawi, treadle pump irrigation increased income per hectare by over 500% (Mangisoni 2008). Irrigation enables farmers to participate in market-oriented production, thereby increasing income from agriculture. A study from Kenya and Tanzania found that 73 and 83% of irrigated crops grown were commercialized (Nkonya et al. 2011). In addition to the overall economic benefits, irrigation may improve food security and nutrition outcomes where they are most needed —early childhood wasting is more prevalent in the arid and semi-arid zones of sub-Saharan Africa, where agricultural water management is particularly crucial for food security and nutrition (Azzarri et al. 2016).

Through the Sustainable Development Goals, the global development agenda is moving towards more integrated approaches that aim to maximize goals across sectors. However, more research is needed on the potential for nutrition-sensitive agriculture interventions to deliver multiple benefits simultaneously. As countries like Ethiopia and Tanzania invest in small-scale irrigation expansion to increase agricultural productivity and improve climate resilience, there is an opportunity to also examine the implications of these interventions for nutrition.

As Domènech (2015) highlights, irrigation interventions and their evaluations are rarely designed to address nutrition outcomes, with few exceptions. A recent study by Alaofè et al. (2016) found increased production and consumption of fruits and vegetables, greater income, and more spending on food, education, and health care in villages receiving a solar-powered drip irrigation intervention compared to control villages. Other studies that explore the association between irrigation and nutrition found that irrigation is associated with a reduced risk of stunting (height-for-age z-scores) and increased household dietary diversity (Benson 2015; van der Hoek et al. 2002). Bhagowalia et al. (2012) similarly showed a positive relationship between irrigation and dietary diversity and between irrigation and crop diversity in India. On the other hand, Kibret et al. (2014) observed increased malaria transmission in irrigated villages of Central Ethiopia and suggest that proper canal water management could address this health hazard. Given the sparse evidence available on this topic, research identifying the specific pathways through which irrigation affects nutrition and health outcomes is needed to inform the design of successful policies and programs.

This paper explores the potential for small-scale irrigation to impact household dietary diversity, with the ultimate goal of improving nutrition outcomes, in Ethiopia and Tanzania. Specifically, it analyzes the pathways through which these impacts may occur. Because irrigation influences nutrition indirectly through several different pathways, this paper focuses on the relationship between irrigation and the intermediate steps through which it could affect nutrition, namely income, production diversity and household dietary diversity, using an instrumental variable approach to estimate a system of four equations simultaneously.

2 The policy context for agriculture and small-scale irrigation in Ethiopia and Tanzania

2.1 Ethiopia

Ethiopia has experienced rapid economic growth over the last decade. This transformation has been driven by government investments in agriculture, infrastructure, and rural services, leading to substantial increases in cereal yields. Despite these gains, agricultural production is still characterized by low levels of modern inputs in remote parts of the country, including virtually no mechanization, limited animal draft power, and under-application of fertilizers, pesticides, and improved seeds (Sheahan and Barrett 2017). Yet agriculture is still a mainstay of the economy, contributing about 37% of GDP (World Bank/OECD 2016) and employing 73% of the population (International Labour Organization 2017).

In 2010, only four to 5% of the cultivated area in Ethiopia was irrigated, including traditional forms of small-scale irrigation like hand-dug wells and buckets (Awulachew et al. 2010). Given the country's considerable irrigation potential, expansion of irrigated area is a key priority of the government's policy and investment framework for the period from 2010 to 2020 (Demese et al. 2010). Investments in irrigation are also targeted under the second Growth and Transformation Program (the Government of Ethiopia's five-year economic development plans) and comprise the largest share (over one-third) of the total budget of US$582 million of the Ministry of Agriculture's Agricultural Growth Program (World Bank 2015). Irrigation plans give priority to high-value horticultural crops, so that farmers can maximize the returns on irrigation. The target is to expand coverage of small-scale irrigation schemes from a current government-estimated 2.3 million hectares to 4.1 million hectares, and to expand medium and large-scale schemes from approximately 658,000 ha to 954,000 over the same period (The Federal Democratic Republic of Ethiopia 2016).

Household irrigation technologies promoted in Ethiopia include water-lifting technologies, water-harvesting technologies, and water-saving technologies. Water-lifting technologies consist of different types of irrigation pumps (manual and motor pumps) and other lifting mechanisms (like pulleys), that tap into surface or groundwater sources. Water-harvesting technologies catch and store water from various sources, such as rainwater, rivers, and pumped groundwater or surface water. Harvested water is stored in small or large tanks depending on the regularity of water supply, and plastic sheeting is used to line tanks and reduce seepage. Water-saving technologies, including drip, micro sprinkler, bubbler, and micro jet irrigation systems, enable frequent application of small amounts of water to reduce water use and preserve soil conditions. Many smallholder producers, lacking access to these irrigation technologies, apply water by hand using buckets and watering cans.

2.2 Tanzania

In 2015, the agriculture sector contributed 29% of the country's GDP and employed 70% of the population (Deloitte 2016). Despite government initiatives aimed at promoting agricultural development, the country has only achieved an average growth rate of 4% per year in agriculture from 1998 to 2007 due to constraints in infrastructure, institutions, and market conditions (Mdee et al. 2014).

The National Irrigation Master Plan launched in 2002 estimated the potential for expansion of irrigated area at 29.4 million hectares, of which 2.3 million ha were identified as high-potential. However, only an estimated 450,392 ha are currently irrigated (FAO/AGWA/IFAD 2014). Tanzania's most recent Irrigation Policy prioritizes development and rehabilitation of formal, mainly large, irrigation schemes (Ministry of Water and Irrigation 2009). Traditional, small-scale irrigation practices are viewed as less desirable and inefficient, and government efforts aim to formalize these small-scale schemes by improving infrastructure, organizing farmers into formal registered entities, and attracting private sector participation. Many traditional and informal schemes are considered illegal given that the farmers do not have formal water-user associations and have not been issued water permits, despite the existence of established informal water-sharing mechanisms and success in producing and selling horticultural crops through these systems (Mdee et al. 2014).

The National Irrigation Policy focuses on strengthening institutional coordination of irrigation and water management but recognizes the limitations imposed by a lack of human resource capacity and inadequate financing to undertake irrigation development and enforce by-laws (Ministry of Water and Irrigation 2009). Following the election of a new government in October 2015, there seems to be more interest in a range of small-scale irrigation technologies. A National Irrigation Commission was established and is looking for guidance on how to further promote irrigation in the country, which suggests that irrigation policies will continue to evolve.

3 Conceptual framework

There are several potential pathways through which irrigation can influence food security, nutrition, and health outcomes including 1) a production pathway, 2) an income pathway, 3) a water supply pathway, and 4) a women's empowerment pathway (FAO 2014; Domènech 2015). To illustrate these pathways, we adapted the agriculture-nutrition conceptual framework of Herforth and Harris (2014) to include irrigation (see Fig. 1). Irrigation enters the framework as a productive asset that enables the transformation of agricultural livelihoods through pathways of food production, agricultural income, water supply, and women's empowerment, which can ultimately lead to changes in child and maternal nutritional outcomes.

3.1 The production pathway

The shift from strictly rainfed to irrigated agriculture can result in substantial increases in agricultural yields, increasing the availability of food for household consumption. By enabling dry season (often called the hunger or lean season) cultivation, irrigation can increase the availability of food throughout the year. Furthermore, irrigation is most often used to grow horticultural crops like fruits and vegetables, which generally provide both greater economic and nutritional benefits.

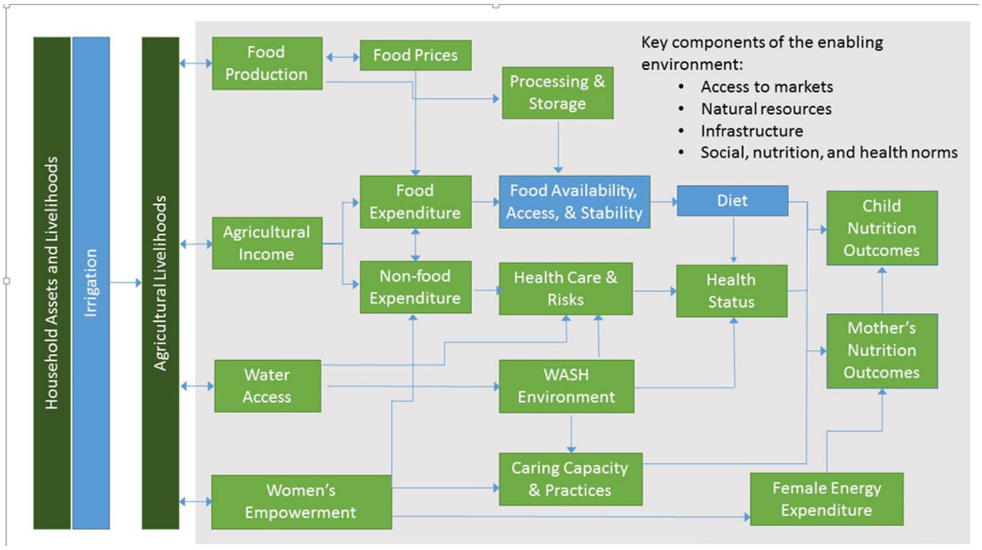

Fig. 1 Pathways from irrigation to nutrition. Source: Adapted from Herforth and Harris (2014)

3.2 The income pathway

Small-scale irrigation has a demonstrated potential to increase the income of smallholder farmers. As shown in Fig. 1, this can lead to greater expenditures on food and non-food items, including on health care and the prevention of health risks. It can also lead to improved food availability and access, changes in diet choices, and improved health status, all of which have implications for maternal and child nutrition outcomes.

3.3 The water supply pathway

The importance of water, sanitation, and hygiene (WASH) in improving childhood nutrition is well recognized in the literature (Chambers and Von Medeazza 2013; Dangour and Watson 2013; Humphrey 2009; Ngure et al. 2014; Spears 2013; Spears et al. 2013). Inadequate sanitation and hygiene conditions are associated with poor child nutrition and growth outcomes. Reliable access to clean water for irrigation has the potential to improve nutrition through an improved WASH environment to the extent that systems are designed to meet the needs of both agricultural production and domestic uses. At the same time, changes in the water supply from the introduction of irrigation have the potential to increase health risks, for example by increasing the incidence of vector-borne diseases like malaria (e.g. see Kibret et al. 2010). The water supply pathways could thus affect food utilization through both changes to food preparation practices, and through changes to food consumption and absorption due to (positively or negatively) affected health status.

3.4 The women's empowerment pathway

The literature shows that elements of women's empowerment, including decision-making authority and access to and control over resources, are associated with better diet quality and nutrition outcomes (Malapit et al. 2015; Malapit and Quisumbing 2015; Sraboni et al. 2014; Yimer and Tadesse 2015). Improving women's empowerment can be a slow and challenging process—a recent study found that even the most gender-responsive and gender-transformative interventions often fail to affect women's empowerment (Johnson et al. 2016). Whether and how irrigation influences women's empowerment depends on many factors, including women's control over decisions regarding which technologies are adopted and how they are used, who contributes the labor for irrigation, and who controls the output and income from irrigated crops. Studies of irrigated agricultural interventions targeted towards women, of which there are few, have found that these interventions can result in improved diet quality, food security, and nutrition outcomes in some contexts (Burney et al. 2010; Iannotti et al. 2009; Olney et al. 2009). Irrigation could also influence a woman's energy expenditure and/or food utilization, to the extent that it reduces or increases her labor burden.

4 Methods

Given data limitations, including the small sample size, the model used in this paper focuses primarily on two of the pathways through which irrigation could influence nutrition: food production diversity and agricultural income. Household dietary diversity is used as a proxy for the diet quality of the household. We control for proxies of women's empowerment (women's input into plot-level agricultural decisions and women's education) and a proxy of water supply (distance to domestic water source) to address these pathways in our model.

4.1 Data

The household survey data used for this analysis were collected in Ethiopia from November to December of 2014 and in Tanzania from June to July of 2015. The recall period for all agricultural data included the previous full rainy and dry (or second rainy) seasons. In order to observe the impacts of irrigation on agricultural, nutrition, health, and gender outcomes, data were collected from a random selection of both irrigating and non-irrigating households. In two of the 14 villages in Tanzania and four of the 15 villages in Ethiopia, households were selected due to their involvement in the Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI) project,[1] which involves the introduction of small-scale irrigation technologies, such as different types of motorized and manual pumps, and water management practices, such as irrigation scheduling tools and agronomic practices, in three case study countries: Ethiopia, Tanzania, and Ghana.[2] These villages were selected based on their irrigation potential (availability of surface and groundwater for irrigation) and feasibility to test different types of irrigation technologies and approaches. Site visits and stakeholder consultations also influenced the final selection of intervention sites. Given the prioritization of intervention sites with high potential for irrigation, control sites were randomly selected from the same administrative boundaries as the intervention sites (to ensure comparable agro-ecological and socio-economic conditions) using an irrigation suitability score, designed as a composite index of slope, surface water access, groundwater access, distance to existing large-scale irrigation schemes, and market access. Control villages had irrigation suitability scores comparable to targeted intervention villages. Within control villages, a random selection of both irrigating and non-irrigating households was taken; the number of irrigators selected in control sites was lower, such that we achieved equal numbers of irrigators and non-irrigators in each of the administrative boundaries when considering the control and intervention sites collectively. In Ethiopia, 439 households were surveyed from 15 *kebeles* (villages) in the *woredas* (districts) of Bahir Dar Zuria, Dangila, Adami Tulu and Lemu. In Tanzania, a total of 14 villages in Kilosa and Mvomero Districts were selected, with 451 households surveyed.[3] The identification of irrigating and non-irrigating households was done in consultation with agricultural extension agents in the identified villages. The household survey protocol contains modules on basic demographic data, crop and livestock production, irrigation practices, food security, assets, water, sanitation and hygiene, household diseases, household dietary diversity, infant and young child feeding and health, and the Women's Empowerment in Agriculture Index, and is available on the Harvard Dataverse (International Food Policy Research Institute 2015). The data used in this paper were collected before any interventions were carried out in the ILSSI villages and can be considered as a baseline. Therefore, the analysis in this paper compares outcomes of households that were already irrigating with outcomes of households dependent on rainfed production.

4.2 Estimation

To understand the linkages between improved access to agricultural water and nutrition, our primary explanatory variable of interest is a binary variable that equals one if a household practiced irrigation in either season (referring to the past rainy and/or past dry season), and zero otherwise.

The principal outcome variable of interest is the Household Dietary Diversity Score, a measure of household food access comprised of 12 food groups (Swindale and Bilinsky 2006). Dietary diversity was chosen due to its association with nutritional status in many different country contexts (Arimond and Ruel 2004), which is relevant to a multi-country study, and its strong associations with micro- and macronutrient adequacy (Ruel 2003). While this variable does not measure nutritional outcomes directly, our sample size was too small to be able to measure changes in anthropometric indicators of nutritional status. Although there are always drawbacks to using one indicator, we felt that household dietary diversity is a commonly used, well-understood, and well-validated measure that captures an intermediary step between food availability and nutritional status at the household level.

Because the study was interested in examining the role of women in dietary diversity, only households with a woman over the age of 18 who was identified as the primary woman decision-maker were included in the sample. In woman-headed households, the woman respondent was considered the primary woman decision-maker.

Income from production was imputed using price per unit of production available at the lowest administrative level available. Production diversity was assessed using the same categorizations as the Household Dietary Diversity Score.[4] This has the advantage of accounting for household

[1] More details about the ILSSI project can be found at: http://ilssi.tamu.edu/

[2] Ghana is excluded from this analysis because of differences in sampling and survey timing.

[3] Since regressions can only be run with complete data on all variables, observations containing missing and extreme values for some variables had to be dropped. This reduced the final sample size to 373 in Ethiopia and 402 in Tanzania.

[4] The Household Dietary Diversity Score (HDDS) and (household-level) production diversity score were defined using the same categories: cereals, roots/tubers, vegetables, fruits, meat/poultry/offal, eggs, fish/seafood, pulses/legumes/nuts, milk/milk products, oils/fats, sugar/honey, and miscellaneous. Our survey collected data on the production of animal products, including honey from bees (included in the sugar/honey), and aquaculture (included in fish and seafood). Production of coffee, tea, and spices were included in the "miscellaneous" category.

production of both animal and crop products, while also allowing for measurement on the same scale as the HDDS (Berti 2015).

Our principal methodological challenge is the possible endogeneity of a household's practice of irrigation. Farmers who choose to irrigate may be inherently different from farmers who do not, based on levels of motivation, knowledge, access to information, and resources. Though we can control for certain measured variables, like education and village-level characteristics, we cannot address the unobservable factors that differ between irrigating and non-irrigating households. To address these sources of bias, we used an instrumental variable approach for consistent estimation of the impact of irrigation on household dietary diversity. Due to data limitations and the complexity of a system of equations, we have not explicitly modeled the women's empowerment and water supply pathways. Hence, our results on irrigation-nutrition linkages need to be cautiously interpreted in the sense that findings of no associations must be interpreted as no association *through the production and income pathways*. Similarly, findings of statistically significant associations must be taken as lower bounds in the association or as associations without the effect of irrigation through the women's empowerment and water-supply pathways. However, variables related to women's empowerment and water supply that can directly affect dietary diversity, which can also be considered as proxies for these pathways, have been controlled for in the dietary diversity equations using variables on education of the primary woman decision-maker, whether women have input into decision-making on irrigated plots, and hours spent collecting domestic water.

The empirical model reflects the different pathways, in particular, the production diversity and agricultural income pathways, through which irrigation is expected to affect nutritional status. As a result, we estimated a system of four structural equations—a household dietary diversity equation, a production diversity equation, an agricultural income equation, and an irrigation equation.

Access to irrigation is the main explanatory variable both in the production diversity and agricultural income equations, but is excluded from the nutrition equation, along with other covariates that impact nutrition *through* agricultural production and income, based on our conceptual framework. From the production diversity and agricultural income equations, we observe the impact of irrigation on production diversity and agricultural income. Production diversity and agricultural income, in turn, explain dietary diversity in the dietary diversity equation. We also explicitly model factors affecting access to irrigation in a fourth equation.

The dietary diversity equation is defined as:

$$HDDS = \mathrm{f}_{\mathrm{hdds}}(PD; Aginc; off\text{-}farm; X_{hh}; DM, DW, VD) \quad (1)$$

where *HDDS* is the Household Dietary Diversity Score; *PD* is the production diversity score; *Aginc* is the natural logarithm of the imputed value of total agricultural crop production harvested in the past year in US dollars (using the previous major and minor agricultural seasons); *off-farm* is a dummy variable indicating whether the household had income from off-farm employment, X_{hh} refers to household characteristics, including household size, number of children under age five, gender and age of the household head, and education of the primary woman decision-maker[5]; *DM* refers to distance to markets; *DW* refers to time spent collecting domestic water (hours); and *VD* refers to village level dummy variables to control for unobserved, location-specific variables that may influence dietary diversity, like market diversity, prices, and local dietary preferences and customs, for example.

The production diversity (*PD*) equation is defined as:

$$PD = \mathrm{f}_{\mathrm{pd}}\left(Irrigation; Elevation; Rain; Woman; X_{hh}; X_{farm}; DM; VD\right) \quad (2)$$

where *Irrigation* is an indicator variable that shows whether the household has at least one irrigated plot; *Elevation* refers to the natural logarithm of elevation levels; *Rain* refers to the natural logarithm of average precipitation per year; *Woman* is an indicator variable showing whether the adult woman in the household is involved in plot-level decision-making; X_{farm} refers to farm characteristics such as soil fertility, number of livestock (as measured in tropical livestock units[6]) and size of

[5] The education data for the main decision-making men and women in the household were collected through interviews with these decision-makers separately. Unfortunately, in the Tanzania dataset, there are many missing values for education of the main woman decision-makers. Rather than excluding a significant number of households due to this problem, we used education of the household head (irrespective of gender) in Tanzania, whereas the Ethiopia model includes education of the woman decision-maker.

[6] The TLU variable is not logged in the Tanzania regression, unlike that of Ethiopia, because of basic differences in the importance of animal draft in the two systems. In the Tanzania data, the role of animal draft and livestock is so small that 93% of respondents have less than 1 TLU with an average of 0.4 TLU. In Ethiopia, only 5 % of respondents have TLUs below 1, with an average of seven TLUs. In Tanzania, about one-fourth of the sample has zero TLUs. Thus, using logarithmic transformation in Tanzania implies replacing one-fourth of the observation with arbitrary small numbers, which is problematic in a context where two-thirds have genuine near-zero (less than one) values. Due to this limited range and variability of TLU data in the Tanzania sample, we kept it in linear rather than logarithmic form.

agricultural land holdings in hectares; and X_{hh}, *DM*, and *VD* are as defined in Eq. (1).

The household agricultural income (Aginc) equation is defined as:

$$Aginc = \mathrm{f}_{\mathrm{income}}\left(Irrigation; Rain; Seed; Fertilizer; off{-}farm; X_{hh}; X_{farm}; \mathrm{PD}, DM; VD\right) \quad (3)$$

where *Seed* and *Fertilizer* are dummy variables for whether the farmer used improved seeds and chemical fertilizers, respectively, on any plot; and the rest of the variables are as defined in Eqs. (1) and (2) above.

The irrigation equation (*Irrigation*) is defined as:

$$Irrigation = \mathrm{f}_{\mathrm{irrigation}}\left(DMR; DSW; Depth; slope; X_{hh}; X_{farm}; DM; VD\right) \quad (4)$$

where *DMR* refers to distance to a major river in km; *DSW* refers to distance to surface water in km; *Depth* refers to the log of the depth of groundwater in meters; *slope* refers to the log of the average slope of all household plots in degrees; and the other variables are as defined in Eqs. 1 to 3 above.

Thus, for irrigation to influence nutrition outcomes through the production diversity pathway, two conditions need to be fulfilled. First, irrigation needs to improve the diversity of crops produced by the farmer. Second, production diversity should be an important factor in determining nutrition outcomes through improved dietary diversity. Likewise, for irrigation to influence nutrition outcomes through the income pathway, first irrigation must lead to higher agricultural income, and second there needs to be a strong relationship between household earnings and nutrition outcomes (as measured by household dietary diversity).

This simultaneous equation model is estimated using three-stage least squares (3SLS) (Zellner and Theil 1962). The 3SLS model allows us to account for potentially endogenous variables that are common to all equations using instrumental variables, while the system estimation provides efficiency gains as the error terms are likely to be correlated across the four structural equations. In the 3SLS estimation, all exogenous variables in the system are used as instruments for endogenous variables in any of the equations. In equations for which we have more exogenous instruments than the number of endogenous explanatory variables, we tested the validity of the additional instruments. In all cases, we failed to reject the null hypothesis that the additional instruments are valid, as shown at the bottom of Tables 2 and 3.

5 Results

5.1 Characteristics of irrigating and non-irrigating households

A comparison of household- and individual-level characteristics (Table 1) shows significant differences in the populations of irrigators and non-irrigators, arguably in ways that would be expected. In Ethiopia and Tanzania respectively, household heads are, on average, 2.5 and 4.8 years younger in irrigating households compared to non-irrigating households. The primary woman decision-makers are also younger in irrigating households, by about 1.7 years in Ethiopia and 4.9 years in Tanzania. Household sizes were fairly similar across the two groups, with only a slightly higher average size in irrigating households in Tanzania of about 0.4 members. Education levels across irrigators and non-irrigators seem to be similar for both the primary man and woman decision-makers, with the only statistically significant difference seen in Tanzania, where women in irrigating households have on average 0.7 more years of education compared to women in non-irrigating households.

Substantial differences are observed between irrigating and non-irrigating households with regard to crop production and value. While households in both countries cultivate similarly-sized land areas, whether or not they irrigate, irrigating households produce approximately three times the value of output in terms of US dollars. The descriptive statistics also indicate that irrigating households have better access to markets and have slightly more resources (including TLUs owned and total hectares of land holdings) compared to non-irrigators in Ethiopia, but we do not observe these same associations in Tanzania. Irrigating households also cultivate more land during the dry season. All of this is expected as both livestock and dry season production can be increased through water access and market access facilitates the sale of irrigated commodities. While virtually all households reported growing grains, irrigators are much more likely to grow vegetables, fruits and other cash crops, while non-irrigating households are more likely to grow pulses and oil crops. This confirms our knowledge that fruit and vegetable production are likely to increase with small-scale irrigation given their higher water demands and/or increased sensitivity to water stress, and to the higher

Table 1 Comparison of selected variables for irrigating and non-irrigating households

Variable	Ethiopia			Tanzania		
	Without irrigation	With irrigation	*p*-value	Without irrigation	With irrigation	p-value
Age of HH head	45.83	43.34	0.035	48.91	44.14	0.000
Education of HH head, years	3.57	3.31	0.467	6.17	6.16	0.902
Education of primary woman decisionmaker head, years	1.64	1.60	0.890	5.49	6.17	0.033
Age of primary woman decisionmaker	39.22	37.45	0.110	41.70	36.84	0.000
Household size	6.17	6.12	0.807	4.56	4.94	0.039
Number of children under 5	0.58	0.70	0.124	0.54	0.67	0.050
Household is woman-headed	0.14	0.12	0.426	0.18	0.11	0.036
Agricultural income, USD	$907	$2851	0.000	$814	$2341	0.000
Total land cultivated in rainy season, hectares	1.40	1.37	0.707	1.44	1.46	0.888
Total land cultivated in dry season, hectares	0.06	0.18	0.000	0.27	0.48	0.000
Total land holdings of household, hectares	1.69	2.00	0.003	1.61	1.74	0.387
Distance to market where crops are sold, hours	0.95	0.81	0.049	1.94	1.97	0.834
HH Food Insecurity Access Scale	5.87	3.93	0.000	3.81	2.68	0.003
TLU's owned	6.13	8.06	0.000	0.52	0.29	0.065
HH production diversity	5.36	6.06	0.000	2.71	3.04	0.006
HDDS	5.70	6.06	0.002	5.00	5.50	0.014
HH produces starch	0.99	0.98	0.438	0.99	0.93	0.002
HH produces pulse	0.57	0.42	0.002	0.39	0.30	0.034
HH produces vegetable	0.17	0.47	0.000	0.09	0.55	0.000
HH produces inedible cash crops	0.43	0.77	0.000	0.00	0.02	0.051
HH produces fruit	0.06	0.30	0.000	0.01	0.12	0.000
N	190	249		218	230	

Dollar amounts are converted using exchange rates of the month of data collection and rounded to the nearest dollar. *P*-values are of a two-sided t-test. TLU stands for "tropical livestock units", HH stands for "household" and USD for "US Dollars." HDDS stands for Household Dietary Diversity Score. All values reported are mean averages. Binary variables are defined as follows: household is woman-headed: 1 = yes, 0 = no; household produces starch, pulse, vegetable, inedible cash crops, fruit: 1 = yes, 0 = no. N has some variation by the variable based on missing data; N refers to the maximum. Distance to market is reported in the "usual" mode of transportation

financial return on investment from horticultural crops compared to other crops. We see significantly higher food security among irrigators compared to non-irrigators by more than two points in Ethiopia and one point in Tanzania based on the Household Food Insecurity Access Scale.[7] Lastly, in these unadjusted analyses, we observed both higher production diversity and dietary diversity among irrigators compared to non-irrigators in both countries. Production diversity was about 0.7 and 0.3 food groups higher, and dietary diversity was about 0.4 and 0.5 food groups higher in Ethiopia and Tanzania, respectively. Overall, we see that production diversity is nearly twice as high in Ethiopia compared to Tanzania.

In the sampled sites in Ethiopia, 51% of irrigating households used bay-border strip irrigation, while approximately 30% used surface flooding, 15% used drip, and the remainder use a variety of other methods (data not shown). The most common methods of obtaining water included diesel pump (41%), buckets or hose (40%), gravity (11%) and hand or foot pumps (5%). Approximately 16% of households in Ethiopia and 9% of households in Tanzania reported using an irrigation pump that was not solely owned by one household. In the Tanzania sites, approximately 40% of irrigating households were watering with a bucket or watering can, 30% used surface or flood irrigation, 10% used furrow, and 8% used drip irrigation. About 35% of irrigating households used buckets or hoses to obtain water, 25% used gravity, 20% used diesel pumps, and 8% used a hand or foot pump. It should be noted that these methods of obtaining and applying water are not necessarily representative of typical irrigation methods in these countries, given that irrigating households were over-sampled from areas with high potential for irrigation. However, the diversity of methods used, including a strong reliance on traditional methods such as buckets, hoses, and watering cans, are descriptive of the types of techniques currently used in these areas by smallholder farmers practicing small-scale irrigation.

[7] The Household Food Insecurity Access Scale is a 27-point measure of food insecurity, with higher numbers indicating that a household has poorer food security. See Coates et al. 2007.

5.2 Regression results

We present the results of the simultaneous equation model for the Ethiopia sample in Table 2 and for the Tanzania sample in Table 3. Results from Ethiopia show that access to irrigation significantly improved both household income and the diversity of crops that farmers produce. Increasing household income, in turn, led to higher dietary diversity, suggesting that irrigation influences household nutritional status through the income pathway, at least in the four districts where this study took place. However, the relationship between production diversity and dietary diversity was not statistically significant. That is, even though irrigation leads to diversification of the number of crops being produced by the farmers, production diversity did not directly translate into increased dietary diversity after controlling for the income effect of irrigation on dietary diversity. Results from Tanzania (Table 3) show no evidence to support the income or production pathways of irrigation to dietary diversity. Even the effects of irrigation on agricultural income and production diversity are not statistically significant in the Tanzania sample after controlling for other factors.

We also found that dietary diversity was higher among woman-headed households in Ethiopia. This influence of woman headship on dietary diversity was after accounting for the effect of agricultural income and production diversity. In fact, woman headship had no influence on production diversity or agricultural income in the other equations. This suggests that woman household heads in Ethiopia eat more diversified diets for reasons that cannot be explained by differences in agricultural income and diversity of own production, which suggests the need for more research into this relationship. The Tanzania results show that woman household heads have lower production diversity and are less likely to irrigate their crops, but there were no differences between man- and woman-headed households in terms of dietary diversity or agricultural income.

As with agricultural income, the results of the estimation using the Ethiopia data show a positive association between household dietary diversity and income earned from off-farm employment. Results from the Tanzania data show that there is a positive association between years of education of the household head and the household dietary diversity score. Statistically significant results on village dummies in the dietary diversity equation from the Tanzania data lends support to the fact that dietary habits are strongly influenced by cultural characteristics and local environments.

Production diversity is positively influenced by the size of land holdings in both Ethiopia and Tanzania and by household size in Ethiopia. While only woman headship and land holding size influenced production diversity in Tanzania, production diversity appears to be lower in households located further away from markets in Ethiopia. In addition, households with less fertile lands in Ethiopia are more likely to produce a diverse set of crops, a possible risk-mitigation measure. Village-level dummies partially explain the differences in production diversity among households in both countries.

Agricultural income from crop production increases significantly with access to irrigation (in Ethiopia) and total land holdings (in both countries). The results from Ethiopia show that increasing production diversity reduces agricultural income. Size of land holdings was positively associated with access to irrigation in both Tanzania and Ethiopia. In Ethiopia, farmers with marginal quality of land, and those that were located further away from rivers and other surface water bodies were less likely to have irrigation on their plots. In Tanzania, in addition to woman-headed households, households with older household heads were less likely to have access to irrigation. Village fixed effects were strong predictors of access to irrigation in Ethiopia.

6 Discussion

The results of this analysis show substantially different results for the two case study countries. In Ethiopia, irrigation leads to increased agricultural income and production diversity, and increased income leads to improved diets. In Tanzania, irrigation has no effect on the diversity of crops produced or on income from agricultural production after controlling for other factors. As suggested by the descriptive statistics from the two countries, this could be partly driven by differences in irrigation methods, practices, and technologies observed in the study sites in the two countries—more households in Ethiopia use modern irrigation technologies such as motor pumps. In addition, agro-ecological conditions of the sampled sites in Tanzania, specifically adequate rainfall for six to eight months of the year, may lead to less dramatic differences in outcomes between irrigators and rainfed producers. It is also important to note that the sampled villages in Tanzania were concentrated in just two districts, so these results may not be reflective of the potential for irrigation in other agricultural areas of the country. Furthermore, the survey in Tanzania was conducted immediately after a rainfall season, when most households likely had enough income to purchase a wide range of foods, while the Ethiopia survey was conducted about three months after the rainfall season. Finally, policies and investments in Ethiopia have favored the development and proliferation of small-scale irrigation approaches, while in Tanzania less emphasis and funding has been directed to such schemes.

Ultimately this study was concerned with identifying any association between irrigation and nutrition. The results suggest that irrigation does have the potential to improve nutrition outcomes through the income pathway but not through increased production diversity. There could be at least three reasons for the lack of strong associations between production diversity and dietary diversity. First, it is possible for higher levels of production diversification to lead to a loss of income from specialization. In this regard, Sibhatu et al. (2015) using data from Indonesia, Kenya, Ethiopia, and Malawi

Table 2 3SLS results of a simultaneous system of equations of household dietary diversity, production diversity, household agricultural income, and irrigation use in Ethiopia

Variables	(1) HDDS	(2) Production diversity	(3) Log of agricultural income	(4) Irrigation
Production diversity	−0.427		−0.838***	
	(0.347)		(0.301)	
Log of agricultural income (USD)	0.940**			
	(0.477)			
Employment income dummy (1 = yes, 0 = no)	4.253**		−0.729	
	(1.809)		(1.202)	
Woman is household head (1 = yes, 0 = no)	0.732*	−0.339	−0.500	0.031
	(0.434)	(0.267)	(0.317)	(0.076)
Education of primary woman decisionmaker (years)	0.016	−0.011	0.023	0.010
	(0.049)	(0.030)	(0.034)	(0.010)
Age of the primary woman decisionmaker (years)	0.089			
	(0.489)			
Log of age of household head			−0.064	−0.047
			(0.576)	(0.089)
Number of children under 5	0.151			
	(0.164)			
Average time to collect domestic water and return (hours)	0.142			
	(0.417)			
Distance to market (hours)	−0.264	−0.206*	−0.249	−0.007
	(0.212)	(0.125)	(0.208)	(0.041)
Soil infertility (higher value implies less fertile land)	−0.013	0.373*	0.087	−0.111**
	(0.343)	(0.195)	(0.257)	(0.055)
Village-level dummies	Yes	Yes	Yes	Yes
	(0.631)	(0.857)	(0.658)	(0.151)
Irrigation (yes = 1, 0 = no)		2.446**	2.548***	
		(1.107)	(0.979)	
Total land holdings of household (hectares)		0.399***	0.603***	0.066***
		(0.104)	(0.200)	(0.024)
Household size (# members)		0.060*	0.073	
		(0.034)	(0.060)	
Woman involved in plot decisionmaking (yes = 1, 0 = no)		0.420		
		(0.670)		
Log of rainfall (millimeters)		0.054	0.238	
		(0.221)	(0.266)	
Log of elevation (meters)		1.606		
		(5.760)		
Used improved seed on any plot (yes = 1, 0 = no)			−0.120	
			(1.706)	
Used fertilizer on any plot (yes = 1, 0 = no)			0.423	
			(2.568)	
Log of tropical livestock units			0.256	
			(0.601)	
Distance to major river (kilometers)				−0.052***
				(0.014)
Distance to surface water (kilometers)				−0.038**
				(0.019)

Table 2 (continued)

Variables	(1) HDDS	(2) Production diversity	(3) Log of agricultural income	(4) Irrigation
Log of groundwater depth (meters)				−0.025
				(0.027)
Log of average slope of plots (degrees)				0.001
				(0.034)
Constant	0.598	−9.935	7.107**	0.972***
	(2.999)	(43.051)	(3.151)	(0.374)
Observations	373	373	373	373
R-squared	−1.991	0.350	−0.867	0.235
Tests of overidentifying restrictions:				
Sargan (score)	chi2(5) = 4.257 (p = 0.5130)	chi2(4) = 3.509 (p = 0.4765)	no overidentifying restrictions (the model is just identified).	No endogenous explanatory variables
Basmann	chi2(5) = 3.954 (p = 0.5561)	chi2(4) = 3.272 (p = 0.5134)		

Standard errors in parentheses. Log of agricultural income is estimated using the lowest available administrative level of crop price per harvest weight, based on the previous major and minor agricultural seasons in US dollars, and the natural log is then taken. A village-level dummy is an indicator variable = 1 for households from that village, and = 0 otherwise. The employment income dummy variable is =1 if the household had income from off-farm employment in the previous year, and is =0 otherwise. Production diversity is the number of food categories produced by the household in the past year, based on the HDDS categorizations. HDDS refers to Household Dietary Diversity Score. Irrigation is a dummy variable =1 if the household practiced irrigation on any plot in the past two seasons, and = 0 otherwise. Age and education of primary woman decisionmaker were missing for many observations and was thus excluded for Tanzania, but included for Ethiopia. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

showed that when production diversity is already high, the association between production diversity and dietary diversity is insignificant or even turns negative, because of foregone income benefits from specialization. The argument for this tradeoff between production and dietary diversity is strengthened when one considers the fact that the average size of land cultivated by farmers is as low as 1.9 ha (4.7 acres) in the Ethiopia sample and 1.7 ha (4.2 acres) in our Tanzania sample. For farmers cultivating such small pieces of land, with, on average, 7 crops in Ethiopia and 3 crops in Tanzania for all types of producers, it is unsurprising that further diversification does not affect dietary diversity, likely because economies of scale result in an inverse relationship between the number of crops produced and the efficiency of production and marketing for each type of crop.

Second, high diversification in the context of smallholder farmers implies that farmers might produce small amounts of many different crops, which may positively influence dietary diversity during harvest time but may not be enough to last for months after harvest. This makes the timing of the survey important in understanding the relationship between production diversity and dietary diversity. In both Tanzania and Ethiopia, the household surveys were carried out before or during the main harvest. The income from agricultural production, therefore, refers to the value of harvested crops from the previous two seasons, and does not include income from crops harvested at the time of the survey to avoid bias between households' responses. Household dietary diversity refers to foods consumed during the previous 24 h. Therefore, while income from previous seasons could have been used for food purchases made during the time of the survey, dietary diversity is more likely to be sensitive to the types of crops that were currently available in-season rather than crops produced during previous seasons. Moreover, many households irrigated their horticultural crops during the dry season; since our dietary data were from during or after the main harvest, it is unlikely that diets at this time reflected crops produced under dry season irrigation. Further research would benefit from the use of measures of long-term diet or repeated dietary measures that would help to address issues of seasonality.

Third, dietary diversity is a reflection of food preferences and behaviors, which change slowly when new crops are introduced. Crops that become possible to produce with irrigation likely respond to market demand, but without social and behavior change communication interventions and nutrition education, producers may not necessarily change their consumption, child feeding, and food preparation behaviors. Consumers may also be hesitant to grow new crops or sufficient marketable crops to improve their household's diet, especially when high-value crops like fruits and vegetables achieve high returns in the market.

This study has several limitations. One is that the data are cross-sectional rather than longitudinal, so findings should be interpreted as estimated causal associations rather than actual causal relationships. In addition, the use of a single indicator, household dietary diversity, to measure household diet quality

Table 3 3SLS results of a simultaneous system of equations of household dietary diversity, production diversity, household agricultural income, and irrigation use in Tanzania

Variables	(1) HDDS	(2) Production diversity	(3) Log of agricultural income	(4) Irrigation
Production diversity	−1.123		0.132	
	(1.320)		(1.840)	
Log of agricultural income (USD)	0.964			
	(0.716)			
Employment income dummy (1 = yes, 0 = no)	3.141		1.017	
	(3.835)		(3.655)	
Woman is household head (1 = yes, 0 = no)	−0.451	−0.753**	0.175	−0.181**
	(0.735)	(0.330)	(0.921)	(0.071)
Education of household head (years)	0.121*	0.035	0.096	−0.009
	(0.068)	(0.023)	(0.078)	(0.009)
Log age of household head (years)	1.276		1.201	−0.395***
	(1.041)		(2.291)	(0.093)
Number of children under 5	0.073			
	(0.207)			
Average time to collect domestic water and return (hours)	−0.320			
	(0.612)			
Distance to market (hours)	0.030	0.133	0.352	−0.036
	(0.225)	(0.135)	(0.319)	(0.036)
Soil infertility (higher value implies less fertile land)	0.438	0.117	0.057	0.043
	(0.438)	(0.150)	(0.632)	(0.053)
Village-level dummies	Yes	Yes	Yes	Yes
	(0.978)	(0.338)	(0.712)	(0.174)
Irrigation (1 = yes, 0 = no)		0.237	3.853	
		(0.744)	(4.035)	
Total land holdings of household (hectares)		0.168***	0.084	0.049***
		(0.047)	(0.316)	(0.017)
Household size (# members)		0.026	0.000	
		(0.035)	(0.094)	
Woman involved in plot decisionmaking (yes = 1, 0 = no)		1.126		
		(0.942)		
Log of rainfall (millimeters)		−0.199	2.121	
		(1.431)	(4.258)	
Log of elevation (meters)		−0.905		
		(0.875)		
Used improved seed on any plot (yes = 1, 0 = no)			−0.300	
			(1.420)	
Used fertilizer on any plot (yes = 1, 0 = no)			0.384	
			(6.263)	
Tropical livestock units			−0.185	
			(0.622)	
Distance to major river (kilometers)				−0.009
				(0.009)
Distance to surface water (kilometers)				−0.007
				(0.032)
Log of groundwater depth (meters)				0.006
				(0.008)

Table 3 (continued)

Variables	(1) HDDS	(2) Production diversity	(3) Log of agricultural income	(4) Irrigation
Log of average slope of plots (degrees)				0.024
				(0.031)
Constant	−4.627	7.477	−11.540	2.119***
	(5.766)	(7.349)	(20.028)	(0.396)
Observations	402	402	402	402
R-squared	−0.831	0.045	−0.800	0.119
Tests of overidentifying restrictions:				
Sargan (score)	chi2(5) = 7.154 (p = 0.2094)	chi2(5) = 3.031 (p = 0.6952)	No overidentifying restrictions (the model is just identified).	No endogenous explanatory variables
Basmann	chi2(5) = 6.759 (p = 0.2392)	chi2(4) = 2.833 (p = 0.7256)		

Standard errors in parentheses. Log of agricultural income is estimated using the lowest available administrative level of crop price per harvest weight, based on the previous major and minor agricultural seasons in US dollars, and the natural log is then taken. A village-level dummy is an indicator variable = 1 for households from that village, and = 0 otherwise. The employment income dummy variable is = 1 if the household had income from off-farm employment in the previous year, and is = 0 otherwise. Production diversity is the number of food categories produced by the household in the past year, based on the HDDS categorizations. HDDS refers to Household Dietary Diversity Score. Irrigation is a dummy variable =1 if the household practiced irrigation on any plot in the past two seasons, and = 0 otherwise. Age and education of primary woman decisionmaker were missing for many observations and was thus excluded for Tanzania, but included for Ethiopia. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

is not without its limitations. Dietary diversity measures the diversity of foods consumed across 12 different food groups. However, irrigation may lead to shifts in the types of food groups consumed or changes in the quantity of foods consumed from individual groups. Such changes may have positive implications for nutrition—for example consuming more types of fruits and vegetables—that would not be picked up by the measure of dietary diversity. In addition, using one definition of dietary diversity in different settings may pose issues, since different foods are available and consumed in different contexts, and as a result, household dietary diversity could be measuring different phenomena depending on the location (Jones et al. 2013). The indicator also equates dietary diversity with household food access, which does not capture many of the within-household variations in diet diversity and quality. Lastly, some analyses have shown that the HDDS lacks construct validity for use as a measure of food security across different contexts (Vellema et al. 2016). As such, we do not intend to compare directly across the contexts of Ethiopia and Tanzania in any causal way, but rather present two case studies using our methodology.

This paper also benefits from several strengths of note. First, the instrumentation methodology helps to address many of the issues in measuring the pathways that influence dietary patterns by removing endogeneity of variables. For example, household dietary diversity is often criticized as a metric of diet quality because it may just be a measure of purchasing power and socioeconomic status. Our methodology aimed to address this issue by separating out the pathways that influence dietary diversity using simultaneous equations. Additionally, we were able to benefit from a rich dataset that included variables related to nutrition, livestock, irrigation techniques, women's empowerment, and in-depth, plot-level agricultural input and production data. Having data from a number of domains allowed us to apply valid instruments and include the appropriate variables for all estimation equations.

We recognize that there can be variable effects of irrigation for nutrition and household incomes based on the availability and ownership of resources for irrigation. Such factors include access to water sources, the quality of that water, access to technology (such as motorized pumps) for extraction and application of irrigation water, and institutional factors such as community ownership and management of water resources. All of these factors are likely to modify the feasibility of nutrition-sensitive irrigation efforts; however, an analysis of the effectiveness of various technologies and approaches and environmental and institutional conditions under which irrigation can provide the greatest benefits is beyond the scope of this study. Further research is needed to identify the conditions under which irrigation development can provide the greatest economic benefits in a socially equitable and nutrition-sensitive way.

7 Conclusion

Results from this study suggest that the relationship between irrigation and nutrition is complex and that contextual factors, such as agro-ecological conditions, access to technology, gender dynamics, and policy and institutional factors, determine the potential for irrigation to influence production decisions, income, and diet. Descriptive analyses from both countries revealed that irrigating households produce more vegetables, fruits, and cash crops, are less food insecure, have a higher value of production, and have higher production diversity and dietary diversity compared to non-irrigating households. However, the econometric results showed stronger benefits of irrigation in Ethiopia compared to Tanzania. While we do not find statistically significant linkages between irrigation and dietary diversity in Tanzania through either the production or income pathways, the findings from Ethiopia show that irrigation can contribute to agricultural income, production diversity, and improved diets (through increases in income). These differences may be attributed to different growing conditions, policy priorities for agricultural development, and levels of investment directed at efforts to expand small-scale irrigation. In Ethiopia, where small-scale irrigation is a priority in agricultural development programs, we find more farmers using modern irrigation technologies like motor pumps, and greater economic and nutrition benefits overall.

Results from Ethiopia show that access to irrigation has the potential to improve both household income and the diversity of crops that farmers produce. Increasing household income, in turn, leads to higher dietary diversity, while increases in production diversity do not contribute to increases in dietary diversity over and above the effect of income. Thus, irrigation in these study areas is likely to influence nutrition through higher incomes rather than directly through production. At least three different reasons could account for this outcome, including foregone income benefits from specialization when production diversity is already high; the tendency to commercialize rather than consume crops due to competing interests; and the fact that the recall period for the dietary diversity indicator fell in a period when sufficient rainfed production might have been available. Future studies will need to probe for each of these hypotheses.

We also found that dietary diversity was higher in woman-headed households in Ethiopia, while woman headship was associated with lower participation in irrigation and lower production diversity in Tanzania. This could imply two things. One, improving agricultural productivity and income by addressing the constraints particular to woman-headed households could lead to even stronger improvement in households' nutritional status; and, two, gender-based preferences play an important role in dietary diversity, in addition to production diversity and agricultural income. This finding further supports the notion that women's empowerment can lead to improved nutritional outcomes—for example, increasing women's input into production decisions and control over income may lead to improved expenditures on health care costs and nutritious foods. Further exploration of the preferences that influence household decisions on what to produce, purchase, sell, and consume in different contexts is needed to identify entry points for improving food choices among agricultural households.

So, does it pay to invest in irrigation? This study shows that irrigation does contribute to improved diets by increasing agricultural income in some cases but not in others. Nutrition benefits that are not captured by our diversity measures are likely, such as the production and consumption of more types of fruits and vegetables. Moreover, irrigation provides other important benefits, like achieving greater agricultural income on smaller pieces of land, improving WASH conditions, smoothing consumption (especially during the dry season), and providing income for the purchase of other goods for health and well-being. These benefits are likely to increase as land in sub-Saharan Africa becomes scarcer and the weather more variable. More studies are needed to understand irrigation-nutrition linkages so that irrigation interventions can be specifically designed to deliver nutrition benefits in addition to agricultural gains. Such nutrition-sensitive irrigation projects should also ensure that women not only participate in, but also benefit from irrigation (Theis et al. 2017). As farmers shift away from traditional irrigation practices and technologies, which were used by a majority of irrigating households in our sample, to more modern technologies and approaches, like motorized or solar pumps, the benefits of irrigation for agricultural production, income, and nutrition are likely to become even more pronounced. In order to maximize these benefits, interventions should take the local context into account, including gender roles and preferences, water supply and environmental considerations, market access and conditions, and appropriateness of technologies.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The study received ethics approval from the IFPRI and Texas A&M Institutional Review Boards.

References

Alaofè, H., Burney, J., Naylor, R., & Taren, D. (2016). Solar-powered drip irrigation impacts on crops production diversity and dietary diversity in northern Benin. *Food and Nutrition Bulletin, 37*(2), 164–175. https://doi.org/10.1177/0379572116639710.

Arimond, M., & Ruel, M. T. (2004). Dietary diversity is associated with child nutritional status: Evidence from 11 demographic and health surveys. *The Journal of Nutrition, 134*(10), 2579–2585. https://doi.org/10.1093/jn/134.10.2579.

Awulachew, S. B., Erkossa, T., & Namara, R. E. (2010). *Irrigation potential in Ethiopia. Constraints and opportunities for enhancing the system. IWMI Report.* Addis Ababa, Ethiopia.

Azzarri, C., Bacou, M., Cox, C. M., Guo, Z., & Koo, J. (2016). Subnational socio-economic dataset availability. *Nature Climate Change, 6*(2), 115–116. https://doi.org/10.1038/nclimate2842.

Benson, T. (2015). Association between irrigated farming and improved nutrition in farm households in Malawi. *Agrekon, 54*(3), 62-86.

Berti, P. R. (2015). Relationship between production diversity and dietary diversity depends on how number of foods is counted. *Proceedings of the National Academy of Sciences, 112*(42), 1. https://doi.org/10.1073/pnas.1517006112.

Bhagowalia, P., Headey, D., & Kadiyala, S. (2012). Agriculture, income, and nutrition linkages in India: Insights from a nationally representative survey. *IFPRI Discussion Papers, 31*(28), 1–31.

Burney, J. A., & Naylor, R. L. (2012). Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. *World Development, 40*(1), 110–123. https://doi.org/10.1016/j.worlddev.2011.05.007.

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences, 107*(5), 1848–1853. https://doi.org/10.1073/pnas.0909678107.

Chambers, R., & Medeazza, G. Von. (2013). Sanitation and stunting in India. *Economic & Political Weekly, 48*(25), 15.

Coates, J., Swindale, A., & Bilinsky, P. (2007). *Household Food Insecurity Access Scale (HFIAS) for measurement of food access: Indicator guide. Food and Nutrition Technical Assistance Project (FANTA)*. Washington, D.C. https://doi.org/10.1007/s13398-014-0173-7.2.

Dangour, A. D., Watson, L., Cumming, O., Boisson, S., Che, Y., Velleman, Y., ... & Uauy, R. (2011). Interventions to improve water quality and supply, sanitation and hygiene practices, and their effects on the nutritional status of children. Cochrane Database Syst Rev, 3.

Deloitte. (2016). *Tanzania A Leader among Africa's Emerging Markets*. https://www2.deloitte.com/content/dam/Deloitte/za/Documents/africa/za_Tanzania_Country_Overview.pdf. Accessed 1 Feb 2017.

Chanyalew, D., Adenew, B., & Mellor, J. (2010). *Ethiopia's agricultural sector policy and investment framework: 2010–2020*. http://gafspfund.org/sites/gafspfund.org/files/Documents/Ethiopia_5_of_6_CAADP_Post_compact_Investment_Plan_(PIF)_0.pdf. Accessed 1 Jun 2017.

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. *Global Food Security, 6*, 24–33. https://doi.org/10.1016/j.gfs.2015.09.001.

FAO/AGWA/IFAD. (2014). *National Investment Profile: Water for Agriculture and Energy: Tanzania*. http://www.fao.org/fileadmin/user_upload/agwa/docs/NIP-TANZANIA-MAY%202014-GC-AM-MD-to%20print.pdf. Accessed 1 Jun 2016.

Food and Agriculture Organization of the United Nations. (2014). *Nutrition-Sensitive Agriculture: Second International Conference on Nutrition (ICN2)*. Rome, Italy.

Giordano, M., de Fraiture, C., Weight, E., & van der Bliek, J. (2012). *Water for wealth and food security: Supporting farmer-driven investments in agricultural water management. Synthesis report of the AgWater Solutions Project.* International Water Management Institute, Colombo.

Herforth, A., & Harris, J. (2014). Understanding and Applying Primary Pathways and Principles Brief #1. *Improving Nutrition through Agriculture Technical Brief Series*, (March).

Humphrey, J. H. (2009). Child undernutrition, tropical enteropathy, toilets, and handwashing. *The Lancet, 374*(9694), 1032–1035. https://doi.org/10.1016/S0140-6736(09)60950-8.

Iannotti, L., Cunningham, K., & Ruel, M. (2009). *Improving diet quality and micronutrient nutrition: Homestead food production in Bangladesh. International Food Policy Research Institute.*

IFPRI. (2017). *2017 Global Food Policy Report. International Food Policy Research Institute. Washington, DC.* https://doi.org/10.2499/9780896292529

International Food Policy Research Institute. (2015). ILSSI/IFPRI study on irrigation, gender, and nutrition. *Harvard Dataverse*. https://doi.org/10.7910/DVN/DH1O3J.

International Labour Organization. (2017). International Labour Organization. *ILOSTAT database*. http://www.ilo.org/ilostat/faces/wcnav_defaultSelection. Accessed 1 Feb 2017.

Johnson, N. L., Kovarik, C., Meinzen-Dick, R., Njuki, J., & Quisumbing, A. (2016). Gender, assets, and agricultural development: Lessons from eight projects. *World Development, 83*, 295–311. https://doi.org/10.1016/j.worlddev.2016.01.009.

Jones, A. D., Ngure, F. M., Pelto, G., & Young, S. L. (2013). What are we assessing when we measure food security? A compendium and review of current metrics. *Advances in Nutrition: An International Review Journal, 4*(5), 481–505. https://doi.org/10.3945/an.113.004119.

Kibret, S., Alemu, Y., Boelee, E., Tekie, H., Alemu, D., & Petros, B. (2010). The impact of a small-scale irrigation scheme on malaria transmission in Ziway area, Central Ethiopia. *Tropical Medicine and International Health, 15*(1), 41–50. https://doi.org/10.1111/j.1365-3156.2009.02423.x.

Kibret, S., Wilson, G. G., Tekie, H., & Petros, B. (2014). Increased malaria transmission around irrigation schemes in Ethiopia and the potential of canal water management for malaria vector control. *Malaria Journal, 13*(1), 360. https://doi.org/10.1186/1475-2875-13-360.

Lipton, M., Litchfield, J., & Faurès, J. M. (2003). The effects of irrigation on poverty: A framework for analysis. *Water Policy, 5*, 413–427.

Malapit, H. J. L., & Quisumbing, A. R. (2015). What dimensions of women's empowerment in agriculture matter for nutrition in Ghana? *Food Policy, 52*, 54–63. https://doi.org/10.1016/j.foodpol.2015.02.003.

Malapit, H. J. L., Kadiyala, S., Quisumbing, A. R., Cunningham, K., & Tyagi, P. (2015). Women's empowerment mitigates the negative effects of low production diversity on maternal and child nutrition in Nepal. *Journal of Development Studies, 51*(8), 1097–1123. https://doi.org/10.1080/00220388.2015.1018904.

Mangisoni, J. (2008). Impact of treadle pump irrigation technology on smallholder poverty and food security in Malawi: A case study of Blantyre and Mchinji districts. *International Journal of Agricultural Sustainability, 6*, 248–266.

Mdee, A., Harrison, E., Mdee, C., Mdee, E., & Bahati, E. (2014). The politics of small-scale irrigation in Tanzania: Making sense of failed expectations. *FAC Working Paper 107* (September). https://www.gov.uk/dfid-research-outputs/fac-working-paper-107-the-politics-of-small-scale-irrigation-in-tanzania-making-sense-of-failed-expectations. Accessed 1 May 2016.

Ministry of Water and Irrigation. (2009). *The National Irrigation Policy Draft*. Dar es Salaam, Tanzania.

Ngure, F. M., Reid, B. M., Humphrey, J. H., Mbuya, M. N., Pelto, G., & Stoltzfus, R. J. (2014). Water, sanitation, and hygiene (WASH), environmental enteropathy, nutrition, and early child development: Making the links. *Annals of the New York Academy of Sciences, 1308*, 118–128. https://doi.org/10.1111/nyas.12330.

Nkonya, E., Iannotti, L., Sakwa, B., & Wielgosz, B. (2011). *Baseline study of KickStart treadle pumps in East Africa. International Food Policy Research Institute (IFPRI).* Washington, D.C.

Olney, D. K., Talukder, A., Iannotti, L. L., Ruel, M. T., & Quinn, V. (2009). Assessing impact and impact pathways of a homestead food production program on household and child nutrition in Cambodia. *Food and Nutrition Bulletin, 30*(4), 355–369. https://doi.org/10.1177/156482650903000407.

Ruel, M. T. (2003). Operationalizing dietary diversity: A review of measurement issues and research priorities. *Journal of Nutrition, 133*, 3911S–3926S.

Ruel, M. T., & Alderman, H. (2013). Nutrition-sensitive interventions and programmes: How can they help to accelerate progress in improving maternal and child nutrition? *Lancet, 382*(9891), 536–551. https://doi.org/10.1016/S0140-6736(13)60843-0.

Ruel, M. T., Quisumbing, A. R., & Balagamwala, M. (2017). Nutrition-sensitive agriculture what have we learned and where do we go from here ? *IFPRI Discussion Paper, 01681*(October). https://doi.org/10.1056/NEJMoa1511939.2.

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in sub-Saharan Africa. *Food Policy, 67*, 12–25. https://doi.org/10.1016/j.foodpol.2016.09.010.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences, 112*(34), 10657–10662. https://doi.org/10.1073/pnas.1510982112.

Spears, D. (2013). How much international variation in child height can sanitation explain? *World Bank Policy Research Working Paper, 6351*(February). http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2013/02/05/000158349_20130205082533/Rendered/PDF/wps6351.pdf.

Spears, D., Ghosh, A., & Cumming, O. (2013). Open defecation and childhood stunting in India: An ecological analysis of new data from 112 districts. *PLoS One, 8*(9), 1–9. https://doi.org/10.1371/journal.pone.0073784.

Sraboni, E., Malapit, H. J., Quisumbing, A. R., & Ahmed, A. U. (2014). Women's empowerment in agriculture: What role for food security in Bangladesh? *World Development, 61*, 11–52. https://doi.org/10.1016/j.worlddev.2014.03.025.

Swindale, A., & Bilinsky, P. (2006). *Household dietary diversity score (HDDS) for measurement of household food access: Indicator guide. Food and Nutrition Technical Assistance III Project (FANTA).* Washington, D.C.

The Federal Democratic Republic of Ethiopia. (2016). *Growth and Transformation Plan II (GTP II) (2015/16–2019/20)* (Vol. I). Addis Ababa, Ethiopia. http://www.mcit.gov.et/documents/1268465/13533561/FDRE+-+National+ICT+Policy+English.pdf/1a626364-1ef3-424f-97ce-33356ca4628f.

Theis, S., Lefore, N., Meinzen-Dick, R. S., & Bryan, E. (2017). *What happens after technology adoption? Gendered aspects of small-scale irrigation technologies in Ethiopia, Ghana, and Tanzania* (No. 1672). Washington, D.C.

van der Hoek, W., Feenstra, S. G., & Konradsen, F. (2002). Availability of irrigation water for domestic use in Pakistan: Its impact on prevalence of diarrhoea and nutritional status of children. *Journal of Health Population and Nutrition, 20*(1), 77–84.

Vellema, W., Desiere, S., & D'Haese, M. (2016). Verifying validity of the household dietary diversity score. *Food and Nutrition Bulletin, 37*(1), 27–41. https://doi.org/10.1177/0379572115620966.

World Bank. (2015). *International development association project appraisal document to the Federal Democratic Republic of Ethiopia for a second agricultural growth project.* http://documents.worldbank.org/curated/en/132941510170946678/pdf/Disclosable-Version-of-the-ISR-Second-Agricultural-Growth-Project-P148591-Sequence-No-05.pdf. Accessed 1 Jun 2016.

World Bank/OECD. (2016). World Bank national accounts data, and OECD national accounts data files. https://data.worldbank.org/. Accessed 1 Jun 2016.

Xie, H., You, L., Wielgosz, B., & Ringler, C. (2014). Estimating the potential for expanding smallholder irrigation in sub-Saharan Africa. *Agricultural Water Management, 131*, 183–193. https://doi.org/10.1016/j.agwat.2013.08.011.

Yimer, F., & Tadesse, F. (2015). *Women's empowerment in agriculture and dietary diversity in Ethiopia.* (No. ESSP II Working Paper 80). Washington, D.C and Addis Ababa, Ethiopia.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., et al. (2011). What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy, 36*(6), 770–782. https://doi.org/10.1016/j.foodpol.2011.09.001.

Zellner, A., & Theil, H. (1962). Three-stage least squares: Simultaneous estimation of simultaneous equations. *Econometrica, 30*(1), 54–78. https://doi.org/10.2307/1911287.

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