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Who is Likely to Benefit from Public and Private Sector Investments in Farmer-led Irrigation Development? Evidence from Ethiopia

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ABSTRACT *In recent years, farmer-led irrigation development has gained the interest of development partners and governments in the Global South following its success in enhancing agricultural production and livelihoods in South Asia. However, little is known about the socio-economic situation of farmers who receive public support for its expansion. Considering its rapid expansion in sub-Saharan Africa, we take the case of Ethiopia and explore the relationship between irrigation suitability and farmers' socio-economic status. We find that high-value crop producers and wealthier farmers are most likely to make private investments and also benefit from public support in farmer-led irrigation expansion if investments are directed to land areas highly suitable for irrigation. Cultivation of high-value crops (fruit, vegetables) was common in areas more suitable for irrigation but staple crop cultivation (cereals, legumes) was negatively associated with irrigation suitability. Wealth status (consumption expenditure, asset index, and land size) was also positively correlated with irrigation suitability. A 10 per cent increase in groundwater irrigation suitability score was associated with a 2 per cent increase in per-capita consumption expenditure. Results imply that policies aiming to facilitate farmer-led irrigation development should combine biophysical information on land and water suitability for irrigation with household socio-economic characteristics and existing agricultural systems.*

KEYWORDS: farmer-led irrigation; groundwater; irrigation suitability; socio-economic status; Ethiopia

1. Introduction

Irrigation development in developing countries has seen a fundamental shift from large-scale canal irrigation to small-scale localised irrigation also known as farmer-led irrigation. Farmer-led irrigation development is defined as a process where individual farmers or small farmer groups drive the establishment, improvement, and expansion of irrigation (de Bont & Veldwisch, 2020; Izzi, Denison, & Veldwisch, 2021; Woodhouse et al., 2017). Therefore, farmer-led irrigation (FLI) can be characterised by attributes such as: (1) *entrepreneurship* and risk-taking behaviour of the farmer; (2) *heterogeneity* of irrigation technologies and farming systems; (3) *capitalisation* which follows the commercial nature of (re)investments and logic into irrigation technologies and agricultural input; and (4) *collaboration* of farmers with other actors along agricultural value chains (Minh & Schmitter, 2021). This paper focuses on individually managed micro-irrigation systems owned by individual

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households and studies how suitability of such irrigation systems is associated with farmer's socio-economic status and crop choices.

The shift towards FLI started decades ago in China and South Asia and was marked by a rapid expansion of boreholes or community-level private service markets for irrigation (Shah, Namara, & Rajan, 2020). In sub-Saharan Africa (SSA), it was first described in late 1980's by Adams and Anderson (1988) but gained increased attention from the international development community only in the late 2000's (see Giordano & de Fraiture, 2014; Molden et al., 2007). In Asia, where more than 35 per cent of the cultivated land is estimated to be irrigated, smallholder groundwater irrigation is reputed as a key driver of the Green Revolution (Mukherji et al., 2009; Pingali, 2012; Spielman & Pandya-Lorch, 2010). The region's success in smallholder irrigation is credited to proactive policy support, involvement of the private sector as market players, and a 'big-push' approach for irrigation instead of incremental development (Shah et al., 2020).

In sub-Saharan Africa, despite a huge potential for irrigation development (Altchenko & Villholth, 2014; Xie, You, Wielgosz, & Ringler, 2014; You et al., 2011), the progress on advancing farmer-led irrigation development have been limited in the last two decades (Shah et al., 2020; Wiggins & Lankford, 2019), partly due to lack of adequate resources and appropriate enabling environment (African Union, 2020; Woodhouse et al., 2017). In recent years, FLI has been viewed as a key to expansion of irrigated agriculture and higher agricultural productivity (de Bont, 2018; Woodhouse et al., 2017) and it has received considerable attention from donors, development organisations, and governments (Shah et al., 2020). Considering that policy efforts to strengthen enabling environment for FLI are underway (African Union, 2020; Woodhouse et al., 2017), this paper investigates who is likely to make private investment and benefit from public investment in FLI development. As African policymakers and investors are considering where to extend public support to resource-poor farmers in irrigation development, understanding who is able to make private investment and who likely benefits from public support in farmer-led irrigation expansion is critical. We investigate this question using the case of individually managed micro-irrigation systems in Ethiopia. Other forms of irrigation development such as small, medium, or large-scale irrigation schemes are not considered.[1]

Public support in FLI expansion are particularly important for small-scale farmers because we suspect that the documented evidence of positive relationship between irrigation and poverty reduction may be a manifestation of classic sorting based on economic wellbeing (see Manstead, 2018). Existing body of literature from sub-Saharan Africa and elsewhere shows that public and private investments in irrigation may benefit the wealthier farmers disproportionately (Bhattarai, Sakthivadivel, & Hussain, 2002; Lipton, Litchfield, & Faurès, 2003; Manero, 2017; Manero et al., 2020; Sharma, Varma, & Joshi, 2008) because irrigation investments have long been concentrated in areas that are connected to formal markets (Kahan, 2013; Shah et al., 2020; Warner & Kahan, 2008), and such areas are likely occupied by wealthier farmers. In addition, most efforts for FLI expansion in SSA are guided by biophysical drivers such as groundwater availability, depth, and land use pattern, while paying less attention to farmers' socio-economics. For example, multiple studies have estimated the suitability of farmer-led irrigation in the region (Addisu, Kassawmar, Mekuriaw, & Haileslassie, 2019; Altchenko & Villholth, 2014; MacDonald, Bonsor, Dochartaigh, & Taylor, 2012; Schmitter, Kibret, Lefore, & Barron, 2018; Worqlul et al., 2017; Xie et al., 2014; You et al., 2011), but none of these studies considered in-depth socio-economic factors.

Studies that have estimated the suitability of farmer-led irrigation in Ethiopia also have paid less attention to farmer's socio-economic characteristics (Addisu et al., 2019; Schmitter et al., 2018; Worqlul et al., 2017; You et al., 2011). For example, Worqlul et al. (2017) assessed the land suitability for groundwater-based irrigation using biophysical indicators (for example, land use pattern, groundwater storage, rainfall, road proximity and so forth) and population density. Likewise, Schmitter et al. (2018) assessed the suitability of solar irrigation (solar water-lifting pumps) for smallholder farmers based on land use pattern, water availability and depth, road and market proximity, population density, solar irradiation and so forth. While these suitability maps address questions such as '*where to invest in a pump*', additional assessments are needed to understand '*who invests in the* *pump*', that is characteristics of farmers and existing farming systems. This study connects these dots by investigating the relationship between biophysical irrigation suitability maps with socio-economic characteristics (consumption expenditure, asset index, and land size) and agricultural attributes (number and types of crops grown).

We match the irrigation suitability maps developed in Worqlul et al. (2017) and Schmitter et al. (2018) with socioeconomic data from the Ethiopian census data and nationally representative data from an integrated household and agriculture sample survey – LSMS-ISA – for the years 2011, 2013, and 2015. Relying on the irrigation suitability maps, we use panel data estimators to explore the correspondence between land suitability for groundwater (and solar pump) irrigation and household characteristics (wealth status and crop choices). Given the lack of appropriate data to test for the direction of causality between household characteristics and irrigation suitability, we estimate the relationship between the two by controlling for household demographics, agricultural details, and time fixed effects. We also estimate the relationship between irrigation suitability and crop choices and show that households residing in irrigation suitable areas are more likely to produce high-value crops.

This analysis makes an important contribution to the literature. To our knowledge, this is the first attempt to connect farmers' household level socio-economic and agricultural data with irrigation suitability maps based primarily on biophysical information. We show that public investments aimed at facilitating or supporting the enabling environment for FLI development may likely benefit wealthier households and overlook the needs of resource-poor farmers. Our effort also responds to the calls to redirect research focus on smallholder farmers to support policymakers (Laborde, Porciello, & Smaller, 2020; Nature, 2020) and interdisciplinary research linking agricultural water management and poverty (Balasubramanya & Stifel, 2020). Hence, this study fills a research gap by presenting missing evidence on the relationship between irrigation suitability and farm households' socio-economic characteristics.

The rest of the paper is organised as follows. In section 2, we discuss research hypothesis and provide analytical methods. Section 3 describes study area, data, matching between irrigation suitability data and socio-economic data, and summary statistics. Section 4 presents results and discussion. Section 5 concludes.

2. Methods

2.1. Research hypothesis

Our primary hypothesis is that, in rural areas, households that are relatively well-off reside in places that are more suitable for irrigation and closer to markets or roads (hence produce more high-value crops). Therefore, public support in strengthening the enabling environment for FLI development targeted at areas highly suitable for irrigation is more likely to be accessed by (1) wealthier farmers than poor farmers, and (2) high-value crop producers than staple producers. Farmer's wealth status is measured with per-capita consumption expenditure, household asset index, and land holding size. The first hypothesis can be simplified as '*farmers' wealth status (per-capita consumption, asset index, and land size) is positively correlated with irrigation suitability*'. The underlying argument behind this hypothesis is that land areas that are highly suitable for irrigation are more likely to be occupied by well-off households.

The second hypothesis can be re-written as '*farmers residing in areas that are more suitable for irrigation are more likely to grow high-value crops than staple crops*'. Here, the point is that those who reside in high irrigation suitable areas also have better access to markets, transportation, and market information. Better access to markets and transportation incentivises farmers to grow high-value crops such as fruits and vegetables. To test this hypothesis, cultivated crops are grouped into two different categories – high-value crops (fruits, vegetables, cash crops, and spices) and staples (cereals, legumes, oilseeds, and root crops).

2.2. Econometric methods

Our primary interest is to understand how irrigation suitability is associated with household wealth status and the types of crops cultivated. Due to data limitations, we are unable to establish a causal relationship between irrigation suitability and household wealth or crop types. Nevertheless, we do control for both household and farm characteristics that can affect household wealth status and crop choices.

Let i indicate a household and j indicate outcome variable. In this case, the outcome variables are: (1) consumption expenditure, (2) asset index, (3) land holding size, (4) number of crops grown, (5) dummy for high-value crop cultivation, and (6) dummy for staple-crop cultivation. Let Y_{ijt} denote outcome j of farm household i at time t, and X_i indicate a vector of demographic characteristics and farm characteristics of household i. Let Θ be a vector of coefficient estimates on control covariates, and ε_{ijt} indicate idiosyncratic error. Equation 1 provides the econometric relationship between wealth status, crop types, and irrigation suitability.

$$Y_{ijt} = \alpha_0 + \alpha_{ij}\ Irrigation\ suitabilit\ y_i + \Theta X_{it} + \varepsilon_{ijt}, \quad j = 1, 2, ..6 \tag{1}$$

We estimate equation 1 with the panel random effects estimator. Panel fixed-effects is not applicable because irrigation suitability does not change over time in our data.[2] In equation 1, $\alpha_{ij}, \quad j = 1, 2, 3$ provides the estimated relationship between irrigation suitability and household wealth status (consumption expenditure, asset index, and land holding size, respectively). Similarly, $\alpha_{ij}, \quad j = 4, 5, 6$ provides the estimated relationship between irrigation suitability and crop choices (number of crops cultivated, high-value crops, and staple crops). For example, a positive and statistically significant estimates of α_{i1} indicates a positive association between irrigation suitability and consumption expenditure suggesting that policies aimed at facilitating farmer-led irrigation development would more likely benefit wealthier farmers. Similarly, a positive and statistically significant estimates of α_{i5} suggests that such investment would more likely benefit high-value crop cultivators.

3. Data and descriptive statistics

3.1. Data

We used data from four different sources: (i) groundwater irrigation suitability map from Worqlul et al. (2017), (ii) solar irrigation suitability map from Schmitter et al. (2018), (iii) a nationally representative household and agriculture sample survey data collected by World Bank's Living Standard Measurement Study (LSMS) surveys, and (iv) 2007 Population and Housing Census data of Ethiopia. Criteria used by Worqlul et al. (2017) in determining land suitability for groundwater irrigation are presented in appendix Table A1. Similarly, criteria used by Schmitter et al. (2018) in determining solar irrigation suitability under water resource scenario of groundwater depth between zero and 25 m are presented in appendix Table A2. The LSMS data is described in appendix Table A3.

Data for both solar irrigation suitability and groundwater irrigation suitability (collectively called irrigation suitability data) are available at a 30-m resolution. Even though the LSMS data were collected at household and plot levels, household and plot geo-locations are hidden for privacy reasons. As the modified geo-locations for LSMS households were available at kebele level, matching between the two data sources is done at the kebele level.[3]

The kebele with LSMS data were overlaid with the irrigation suitability maps using ArcGIS software. More than 84 per cent of LSMS kebeles were successfully located in areas with groundwater irrigation suitability maps. The remaining 16 per cent of LSMS kebeles either fell in areas excluded in the irrigation suitability map or had the geocodes missing in the LSMS data. Analysis of groundwater irrigation suitability data is based on 2,964 sample households from 357 matched kebeles from rural areas and small towns. Similarly, the LSMS data were overlaid with the solar irrigation suitability map for solar-based irrigation pumps, considering groundwater depth up to 25 m. Among the 357 sample kebeles available in the LSMS data, 38.7 per cent of kebeles were located in constrained areas not suitable for solar irrigation while 61.3 per cent of the LSMS kebeles were located in areas suitable for solar irrigation. A large share of the kebeles were located in the constrained areas for solar irrigation primarily due to those areas being either protected land use (forests, urban areas and so forth) or due to unsuitability of groundwater resources (for example, aquifer productivity, groundwater storage or depth) (Schmitter et al., 2018).

Finally, the irrigation suitability data were matched with the 2007 census data based on the zone, region, woreda, and kebele names. No other common identifiers were available for matching. The name matching was fairly accurate because more than 95 per cent of kebeles in groundwater irrigation suitability data were successfully matched with the census data (see Appendix Table A4). Solar irrigation suitability data (scenario: groundwater depth 0–25 m) were matched with the census data by using a common identifier that was created while the two irrigation suitability maps were overlaid. Even though the two data sources were successfully matched for more than 90 per cent of kebeles, about 45 per cent of the census kebeles fell under land areas constrained for solar irrigation suitability.

3.2. Irrigation suitability index

Groundwater irrigation suitability scores from Worqlul et al. (2017) are available as percentage suitability values. We categorise the suitability scores into three different irrigation suitability levels using distribution of groundwater irrigation suitability scores. Areas with less than 60 per cent suitability score are considered *least suitable* for groundwater irrigation, while areas between 60 per cent and 85 per cent suitability scores are considered *moderately suitable*, and areas above 85 per cent suitability scores are considered *highly suitable* for groundwater irrigation. Figure 1 illustrates the groundwater suitability mapping for Ethiopia; brown colour indicates least suitability and green colour indicates high suitability for groundwater irrigation.

Solar irrigation suitability scores in Schmitter et al. (2018) are available as distinct suitability categories. When groundwater depth up to 25 m is considered, land areas are classified into three different categories of suitability – *very highly suitable, highly suitable*, or *constrained* for solar irrigation. For consistency with groundwater irrigation suitability categories, we re-labelled the first two solar irrigation suitability categories '*very highly suitable*' and '*highly suitable*' as '*highly suitable'* and '*moderately suitable'*.[4]

Since different data sources are matched at kebele level, the irrigation suitability scores which were available for 30 m x 30 m pixels were also aggregated to the kebele level. The mode of the suitability scores for all pixels within a kebele is used to represent irrigation suitability of that kebele. As a result, all LSMS sample households within a kebele fall under the same category of irrigation suitability. Therefore, in case of solar irrigation suitability, a kebele is considered constrained for solar irrigation if and only if all pixels within the kebeles are constrained for solar irrigation.

3.3. Descriptive statistics

This section provides descriptive statistics on irrigation suitability, population demographics, agricultural practices, and irrigation status. Statistics reported here are based on the data on irrigation suitability, LSMS-ISA data, and the 2007 census data.

3.3.1. Irrigation suitability. Figure 2 presents the share of kebeles under different levels of suitability for groundwater irrigation and solar irrigation. Data show that the majority of rural and small town kebeles are at least moderately suitable for groundwater and solar-based irrigation in Ethiopia. Mapping the census data with solar irrigation suitability maps, four per cent kebeles are highly

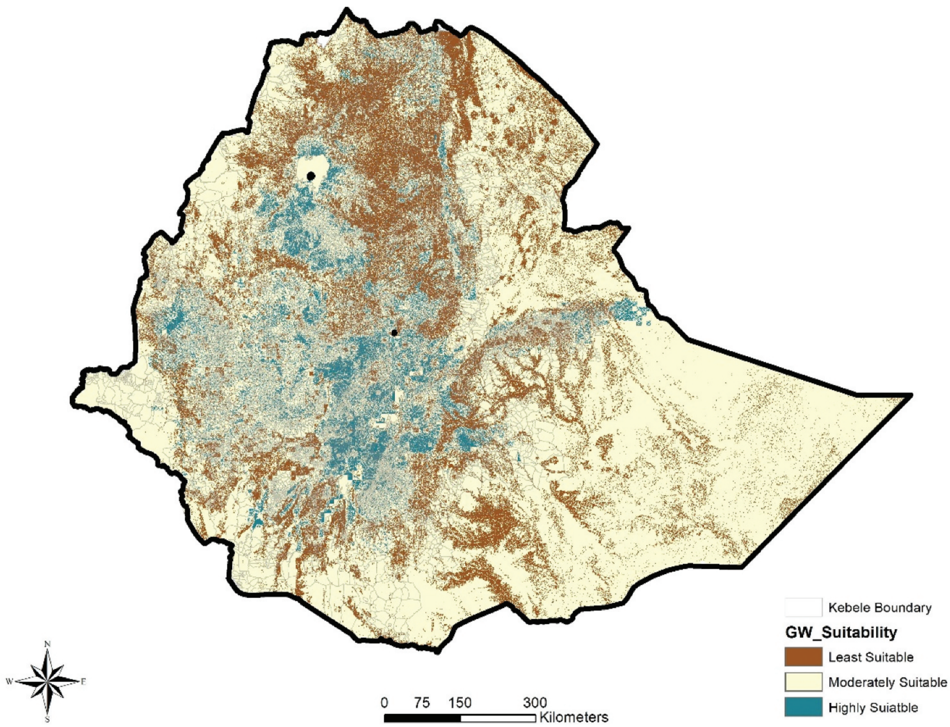

Figure 1. Mapping groundwater irrigation suitability in Ethiopia.

suitable, 51.3 per cent kebeles are moderately suitable, and 44.6 per cent kebeles are constrained (or not suitable) for solar irrigation. Even though 28 per cent of kebeles are least suitable for groundwater irrigation, about 45 per cent of kebeles are not suitable (or constrained) for solar irrigation using off-grid small solar pumps. The discrepancy between groundwater irrigation suitability and solar irrigation suitability has to do with the way these maps are created. Constraints for solar irrigation suitability are more restrictive than for groundwater irrigation suitability. The groundwater irrigation suitability map developed by Worqlul et al. (2017) does not consider different technologies for pumping water at a specific depth (see Table A1), but the solar irrigation suitability map considers a specific type of technology – solar photovoltaic pumps with a limited capacity to not pump beyond 25 m deep (see Table A2). In addition, solar irrigation suitability maps required availability of solar irradiation, which was not a criterion for groundwater irrigation suitability.

Table 1 presents the shares of households in each region with distinct levels of groundwater irrigation suitability. About two-thirds of rural households reside in areas suitable for groundwater irrigation; 17 per cent in highly suitable areas, 49 per cent in moderately suitable areas, and 31 per cent households in least suitable areas. SNNP region has the highest shares of rural households in areas highly suitable for groundwater-based irrigation (24%), followed by Oromia (17%), Amhara (16%), and other regions. Tigray was the least suitable region for groundwater-based irrigation with 61 per cent rural households residing in the least suitable areas followed by Amhara (53%). This observation is consistent with the agro-ecological zones of the country. Since prevailing climate and topography influence both available water resources and cropping patterns, cool and sub-humid mid highland regions such as SNNPR and Oromiya are expected to have more irrigation suitable land than arid and semi-arid highland regions such as Tigray.

Table 2 provides estimated share of households in each region that are under each of three suitability categories – *highly suitable, moderately suitable*, and *not suitable* (constrained) for solar

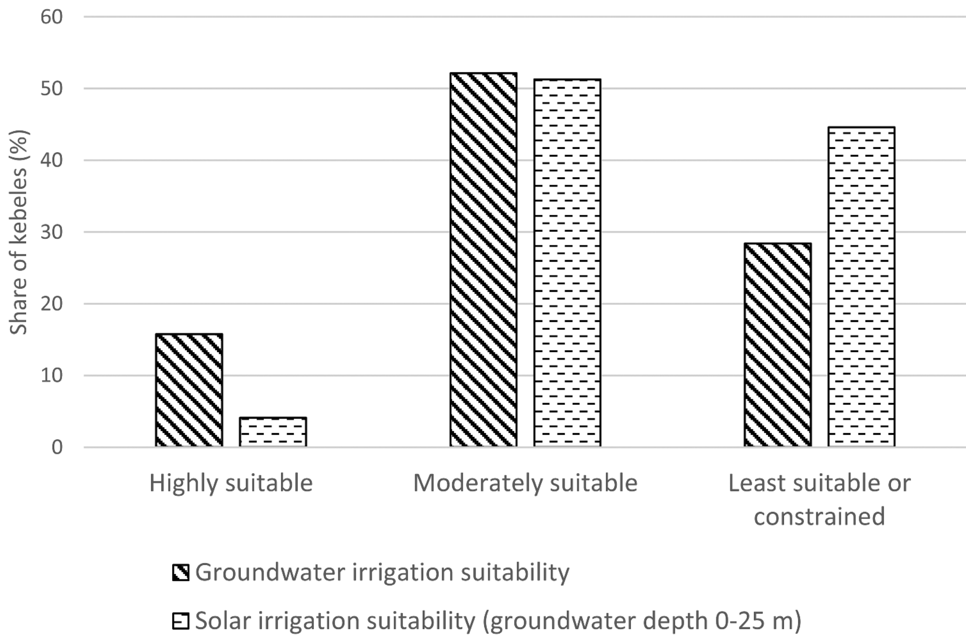

Figure 2. Share of census kebeles (%) under different levels of irrigation suitability.

Table 1. Shares of households (%) under different levels of groundwater irrigation suitability, by region

	Highly suitable	Moderately suitable	Least suitable	Not matched	Number of households
Ethiopia	17.15	48.58	31.13	3.14	10,728,390
Regions					
Afar	0.58	64.41	23.57	11.44	188,023
Amhara	15.79	30.46	52.69	1.05	2,909,926
Benishangul-Gumuz	5.73	67.12	25.61	1.55	134,973
Gambella	1.61	84.14	4.41	9.84	46,007
Harari	8.07	79.71	4.78	7.44	15,181
Oromia	17.09	56.12	22.39	4.39	4,167,860
SNNP	24.42	57.60	14.45	3.53	2,572,273
Tigray	4.17	34.86	60.57	0.40	694,147
Number of kebeles	2,285	7,564	4,122	541	

Notes: Point estimates are shares of households in each region. It is not possible to calculate bounds on the point estimates because there is no variation in the shares of households across kebeles or categories of groundwater irrigation suitability which is invariant within a kebele.

irrigation. The sum of the shares in the first two categories gives the share of households likely to benefit from investment in solar irrigation. When considering solar pumps that can extract ground-water from a depth of up to 25 m, more than 55 per cent households fall is land areas where it is feasible to expand solar irrigation.

Provided groundwater is available up to a depth of 25 m, more than 50 per cent households can benefit from strengthening solar irrigation supply chains and services (for example, financial payment schemes) in Amhara, Harari, Oromiya, and SNNP. Under the same circumstances, only a small proportion of households would benefit from solar irrigation in Afar, Tigray, and Benishangul Gumuz

Table 2. Shares of households (%) under different levels of solar irrigation suitability, by region

	Scenario: Groundwater depth 0–25 m			
	Highly suitable	Moderately suitable	Constrained	Number of households
Ethiopia	3.83	51.82	44.34	10,728,390
Regions				
Afar	2.87	5.53	91.60	188,023
Amhara	1.74	58.65	39.58	2,909,926
Benishangul-Gumuz	0.38	25.80	73.81	134,973
Gambella	6.24	41.79	51.83	46,007
Harari	0.00	92.56	7.44	15,181
Oromia	6.95	51.39	41.65	4,167,860
SNNP	2.41	55.79	41.80	2,572,273
Tigray	0.00	28.43	71.56	694,147
Number of kebeles	630	7,835	6,269	

Notes: Point estimates are shares of households in each region. It is not possible to calculate bounds on the point estimates because there is no variation in the shares of households across kebeles or categories of solar irrigation suitability which is invariant within a kebele.

regions. These shares do not consider credit constraints and other obstacles that prevent farmers from accessing and installing the pumps. As most farmers in SSA are credit constrained and government subsidies cover only a small fraction, the actual share of households able to invest in solar irrigation is likely much lower (Dalberg, 2019).

3.3.2. Irrigation, agriculture practices, and household demographics. Table 3 presents summary statistics for model variables that include current irrigation, agricultural practices, and household demographics. These statistics are based on the LSMS data successfully matched with irrigation suitability data as described in section 3.1. Statistics are representative of rural and small-town areas. Urban areas are excluded from the analysis. Based on the LSMS data, access to irrigation is low – only about 9 per cent households have at least one plot irrigated. Share of irrigated households drops slightly over time, 9 per cent in 2010/11 to 8 per cent in 2015/16. Considering the share of irrigated plots, the data show that, on average, only about 2 per cent of the cultivated plots are irrigated. Since most of the arable land is suitable for irrigation, the low irrigation coverage indicates a huge potential for irrigation investment such as farmer-led irrigation in Ethiopia.

More than 80 per cent of rural and small-town households in Ethiopia are engaged in agriculture. On average, an agricultural household cultivates about 10 plots of land, but the average landholding size is just about a hectare. Farming households cultivate about 6 different crops over the two seasons and more than 26 per cent of farming households cultivate high-value crops (fruits, vegetables, and cash crops). The share of households cultivating high-value crops has increased over time – 26 per cent in 2010/11 up to 34 per cent in 2015/16 whilst the share of households cultivating staple crops (cereals, legumes, root crops and so forth) varies over time – 48 per cent in 2010/11, 57 per cent in 2012/13 and 54 per cent in 2015/16.

The average household size of rural and small-town Ethiopian households varies between 5 and 6 over time. Household size increased over time. The rural and small-town sample consists of about 88 per cent rural households. On average, household heads are about 45 years old. About 25 per cent of households have female heads and more than 75 per cent of households have a married head. Only about 41 per cent of household heads are literate. Among those who are educated, the average grade completed by the household heads is primary school indicating rather low educational attainment. In 2010/11 about 20 per cent of households had at least one migrant member but migration decreased over time reaching to 11 per cent in 2015/16. Examination of access to financial institutions and services shows that only about 25 per cent of household have access to loan or credit services

Table 3. Summary statistics of model variables

	Survey year		
	2010/11	2012/13	2015/16
Current irrigation			
At least one plot is irrigated (1 = Yes, 0 = No)	0.094	0.073	0.082
	(0.005)	(0.005)	(0.005)
Share of irrigated plots (%)	1.98	1.73	2.06
	(0.175)	(0.150)	(0.173)
Agricultural variables			
Agricultural households (1 = Yes, 0 = No)	0.763	0.846	0.838
	(0.008)	(0.007)	(0.007)
Land holding size (Ha)	1.09	1.25	1.27
	(0.045)	(0.065)	(0.148)
Number of crops cultivated	6.59	6.15	6.08
	(0.079)	(0.071)	(0.074)
Cultivate high-value crops (1 = Yes, 0 = No)	0.261	0.287	0.337
	(0.008)	(0.008)	(0.009)
Cultivate staple crops (1 = Yes, 0 = No)	0.480	0.570	0.540
	(0.009)	(0.009)	(0.009)
Household characteristics			
Household size	4.87	5.55	6.03
	(0.043)	(0.045)	(0.048)
Access to loan (1 = Yes, 0 = No)	0.251	0.280	0.225
	(0.008)	(0.008)	(0.008)
Has one or more migrants (1 = Yes, 0 = No)	0.196	0.179	0.113
	(0.007)	(0.007)	(0.006)
Rural	0.877	0.877	0.877
	(0.006)	(0.006)	(0.006)
Household head characteristics			
Age (years)	44.60	46.03	47.77
	(0.286)	(0.282)	(0.280)
Female head (1 = Yes, 0 = No)	0.244	0.259	0.271
	(0.008)	(0.008)	(0.008)
Married (1 = Yes, 0 = No)	0.769	0.739	0.738
	(0.008)	(0.008)	(0.008)
Head can read or write (1 = Yes, 0 = No)	0.410	0.414	0.417
	(0.009)	(0.009)	(0.009)
Education level (grade)	2.12	2.21	2.33
	(0.070)	(0.072)	(0.076)
Number of households	2,964	2,964	2,964

Notes: Point estimates are weighted means; standard errors are in parentheses. †Other sources include boreholes, piped water, spring water, and so forth.

(including both formal and informal sources). Considering the importance of credits in expanding the farmer-led irrigation, the existing credit coverage seems low.

4. Results and discussion

In this section, we explore how irrigation suitability correlates with farmer's wealth status and crop choices using the model in equation (1). Wealth status is measured with per-capita consumption expenditure, asset index,[5] and land holding size. Crop choice is measured with number of crops grown, binary indicators for high-value crops and staple crops. Relationship between irrigation suitability and individual crops is also presented. For the purpose of econometric analysis, groundwater irrigation suitability scores are converted to a continuum between 0 and 1 by dividing by 100.

Solar irrigation suitability categories are converted into a binary indicator.[6] We mark land areas under the *highly suitable* and *moderately suitable* categories as *suitable* for solar irrigation and the constrained area as *not suitable* for solar irrigation.

4.1. Wealthier households are situated in areas more biophysically suitable to farmer-led irrigation

Table 4 presents the relationship between groundwater irrigation suitability, solar irrigation suitability, and household wealth status. Regional differences are controlled for by including regional dummies in the estimating model. Relationship between groundwater irrigation suitability and household wealth appear in the first three columns. Results show that a one per cent increase in

Table 4. Relationship between irrigation suitability and household wealth (Panel random effects)

	Groundwater irrigation			Solar irrigation		
	Log(cons. expenditure)	Asset index	Log (land size)	Log(cons. expenditure)	Asset index	Log (land size)
Irrigation suitability	0.13*	0.45**	0.25***	−0.022	0.057	0.018
	(0.074)	(0.23)	(0.057)	(0.020)	(0.059)	(0.014)
Current irrigation						
Irrigation	0.067*	0.099	0.14***	0.072*	0.089	0.15***
	(0.037)	(0.12)	(0.022)	(0.038)	(0.13)	(0.024)
Share of irrigated areas	0.13	0.013	−0.52***	−0.017	−0.056	−0.57***
	(0.12)	(0.33)	(0.058)	(0.12)	(0.34)	(0.059)
Household characteristics						
Household size	−0.25***	0.087***	0.043***	−0.26***	0.094***	0.045***
	(0.0044)	(0.013)	(0.0028)	(0.0048)	(0.014)	(0.003)
Access to loan	−0.018	−0.09**	0.011	−0.016	−0.095*	0.019*
	(0.015)	(0.045)	(0.0096)	(0.016)	(0.049)	(0.010)
Has one or more migrants	−0.041**	0.14**	0.0058	−0.035*	0.13*	0.002
	(0.017)	(0.064)	(0.010)	(0.018)	(0.066)	(0.012)
Farming households	−0.19***	−0.17**	0.40***	−0.14***	−0.14	0.41***
	(0.022)	(0.081)	(0.015)	(0.025)	(0.088)	(0.016)
Rural	−0.11***	−2.34***	0.31***	−0.10**	−2.23***	0.32***
	(0.033)	(0.14)	(0.018)	(0.036)	(0.15)	(0.019)
Household head characteristics						
Age (years)	0.0025***	0.004**	−0.0003	0.0027***	0.004**	−0.0003
	(0.0006)	(0.002)	(0.0004)	(0.0006)	(0.002)	(0.0004)
Female head	0.044	0.26**	−0.12***	0.038	0.32***	−0.12***
	(0.027)	(0.087)	(0.015)	(0.029)	(0.095)	(0.017)
Married	−0.067**	0.25**	0.017	−0.049*	0.28**	0.0030
	(0.026)	(0.084)	(0.014)	(0.028)	(0.091)	(0.016)
Head can read or write	0.070***	0.14**	0.019	0.062**	0.13**	0.018
	(0.020)	(0.059)	(0.013)	(0.021)	(0.063)	(0.014)
Education level (grade)	0.031***	0.13***	−0.006***	0.035***	0.13***	−0.007***
	(0.0028)	(0.011)	(0.0017)	(0.0031)	(0.012)	(0.002)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	8.25***	0.43*	−0.39***	8.45***	0.53**	−0.24***
	(0.074)	(0.24)	(0.050)	(0.064)	(0.21)	(0.039)
Observations	8,435	8,782	8,787	7,328	7,638	7,642

Notes: Standard errors are in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .001$. Unless otherwise noted, all variables are binary indicator with 1 = Yes, and 0 = No.

groundwater irrigation suitability score is associated with 0.13 per cent increase in per-capita consumption expenditure. In our data, groundwater irrigation suitability score ranges between 0.45 and 0.97. Applying the estimated effects in our data, per-capita consumption expenditure for the households that cultivate the highest irrigation suitable land (a suitability score of 97) would be 16 per cent higher than for households that own the least irrigation suitable land (suitability score of 45). Likewise, a one per cent increase in groundwater irrigation suitability score is associated with 0.45 unit increase in asset index and 0.25 per cent increase in land holding size. Taking together, the results show that lands that are more suitable for groundwater-based irrigation are occupied by wealthier and larger landholding households. Relationship between solar irrigation suitability and household wealth are presented in the last three columns in Table 4. Unlike groundwater irrigation suitability, solar irrigation suitability is not statistically significantly correlated with household wealth status.

Several other variables are controlled for in these regressions. All three wealth variables, consumption expenditure, asset index and land holding size increase with farmer's access to (current use of) irrigation but the effects on asset index is not statistically significant. Current irrigation is associated with 0.7 per cent increase in consumption expenditure and 0.15 per cent increase in the average land holding size compared to non-irrigating households. This finding is consistent with the existing evidence that has shown positive impacts of irrigation development on poverty reduction (Gebregziabher, Namara, & Holden, 2009; Namara et al., 2010; Passarelli, Mekonnen, Bryan, & Ringler, 2018; van den Berg & Ruben, 2006). Among the control covariates, household size is positively correlated with asset index and land holding size but negatively correlated with per-capita consumption.

Use of loan is negatively correlated with consumption or asset index but positively correlated with land holding size.[7] Consumption expenditure and asset index also are positively associated with household head's age, female headship, and education level. However, land holding size has a negative relationship with the head's age, female headship and education level. This further reinforces the importance of understanding how irrigation investment changes with farmers' age groups and household socioeconomic status (Namara, Hope, Sarpong, Fraiture, & Owusu, 2019).

Overall, results in Table 4 indicate that wealthier households are more likely to have access to land areas which are more suitable for farmer-led irrigation using groundwater resources with or without the use of solarised pumps. Distribution of consumption expenditure and asset index against the levels of groundwater irrigation suitability validate these econometric findings (Appendix Figures A1 and A2). Results imply that if farmer-led irrigation development were primarily financed through private investment (that is the farmers themselves make the investment), it disproportionately benefits wealthier farmers because land areas highly suitable for groundwater irrigation or solarised pumps are also home to wealthier households. This is consistent with findings in Giordano, de Fraiture, Weight, and van der Bliek (2012) who found that over 80 per cent of the owners of pumps and other irrigation equipment use their own or household savings for irrigation investment in Ghana, Zambia and Ethiopia. Marginal farmers who likely own small pieces of land could be left out because (1) their land is less suitable for irrigation development and (2) they are more likely to be credit constrained, hence unable to finance the cost of irrigation development. This reiterates the need for tailored investment in small-scale irrigation that can minimise negative social and environmental impacts (Lefore, Giordano, Ringler, & Barron, 2019).

Involving private sector in providing financial and technical services is being piloted in different contexts and scales but likely will be insufficient to address credit constraints for the most vulnerable groups. In most cases, the usual upfront payments between 10 per cent and 20 per cent are still too high and repayment schemes do not follow key agricultural seasons. In addition, investment for farmer-led irrigation development in bottom of the pyramid markets can be way too risky for the private sector which is entirely profit driven. Even if collateral free credits are provided, resource poor farmers may not be able to pay their loan instalment in a bad crop season. One potential solution could be a hybrid model of blended financing to de-risk private sector investment in base of pyramid markets in combination with insurance products and smart subsidy schemes by governments based on farmers' socio-economics, land, and water conditions. Alternatively, *pay as you go* models where payments are made for irrigation service delivery and do not require asset procurement and management can be a helpful.

4.2. Higher crop diversification and less staples in areas more biophysically suitable to farmer-led irrigation

Table 5 presents the relationship between crop choices and irrigation suitability. Crops are grouped into two different categories: (1) high-value crops (vegetables, fruits, and cash crops), and (2) staple crops (cereals, root crops, legumes, and oilseeds). Number of crops grown is used as a measure for crop diversification. Results show that farmers who cultivated land areas suitable for irrigation, are more diversified and cultivated more high-value crops and less staple crops. Specifically, a hundred

Table 5. Relationship between irrigation suitability and crop choices (Panel random effects)

	Groundwater irrigation			Solar irrigation		
	Num. of crops	High-value crops	Staple crops	Num. of crops	High-value crops	Staple crops
Irrigation suitability	3.09***	0.11**	−0.16***	0.24**	0.0056	−0.028**
	(0.47)	(0.043)	(0.045)	(0.12)	(0.011)	(0.011)
Current irrigation						
Irrigation	1.18***	0.077**	−0.064**	1.25***	0.070**	−0.067**
	(0.18)	(0.029)	(0.029)	(0.19)	(0.030)	(0.031)
Share of irrigated areas	−0.54	0.12	−0.17*	−0.82	0.12	−0.15
	(0.57)	(0.091)	(0.090)	(0.58)	(0.095)	(0.094)
Household characteristics						
Household size	0.14***	0.006**	−0.0002	0.13***	0.0071**	−0.0019
	(0.022)	(0.002)	(0.002)	(0.024)	(0.0023)	(0.0024)
Access to loan	0.13*	−0.010	0.024**	0.14*	−0.013	0.030**
	(0.068)	(0.010)	(0.010)	(0.073)	(0.011)	(0.011)
Has one or more migrants	0.16**	−0.007	−0.0032	0.17**	0.0004	−0.011
	(0.075)	(0.011)	(0.012)	(0.082)	(0.012)	(0.013)
Farming households	−0.27	0.28***	0.63***	0.042	0.27***	0.65***
	(0.50)	(0.012)	(0.012)	(0.41)	(0.013)	(0.013)
Rural	2.78***	−0.031*	0.073***	2.62***	−0.043**	0.076***
	(0.20)	(0.016)	(0.016)	(0.21)	(0.017)	(0.017)
Household head characteristics						
Age (years)	0.0081**	0.001**	−0.0005	0.009**	0.0009**	−0.0005
	(0.0034)	(0.0003)	(0.0004)	(0.004)	(0.0004)	(0.0004)
Female head	−0.64***	0.021	−0.023	−0.65***	0.018	−0.025
	(0.14)	(0.014)	(0.014)	(0.16)	(0.015)	(0.015)
Married	0.25*	−0.002	0.0094	0.25*	−0.0043	0.006
	(0.13)	(0.014)	(0.015)	(0.14)	(0.016)	(0.015)
Head can read or write	0.30**	0.021*	−0.020	0.32**	0.021	−0.021
	(0.10)	(0.012)	(0.013)	(0.11)	(0.013)	(0.014)
Education level (grade)	−0.061***	0.0027*	−0.002	−0.053**	0.0018	−0.002
	(0.018)	(0.002)	(0.0015)	(0.019)	(0.0017)	(0.002)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−1.43**	−0.30***	0.26***	0.35	−0.22***	0.17***
	(0.67)	(0.040)	(0.041)	(0.53)	(0.031)	(0.032)
Observations	7,015	8,787	8,787	6,108	7,642	7,642

Notes: Standard errors are in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .001$. Unless otherwise noted, all variables are binary indicator with 1 = Yes, and 0 = No.

per cent increase in groundwater irrigation suitability score is associated with about three more crops cultivated, 0.11 per cent higher share of farmers growing high-value crops, and 0.16 per cent lower share of the producers of staple crops – cereals, root crops, legumes, and oilseeds. Similarly, solar irrigation suitability is associated with 0.24 more crops, 0.6 per cent more high-value crops and 2.8 per cent less staple crops.

Current use of irrigation is also positively associated with crop diversification. On average, use of irrigation is associated with 1.2 per cent more crops, 7.7 per cent more high-value crop cultivation but 6.4 per cent less staple crop cultivation. This finding is consistent with the existing body of evidence that shows improved access to irrigation is associated with increased cultivation of market-oriented high-value crops such as fruits and vegetables (Garbero & Songsermsawas, 2018; Hagos, Makombe, Namara, & Awulachew, 2008). Our results go beyond that and show a positive association between land suitability for small-scale irrigation and crop choices. While improved access to irrigation may incentivise farmers to expand cultivation areas or switch to high-value crops which are also more water thirsty (Grafton et al., 2018), we show that land suitability for irrigation is also strongly correlated with the types and number of crops grown. Farmers who cultivate land areas highly suitable for small-scale irrigation are more likely to diversify farming activities by cultivating a greater number of high-value crops such as fruits and vegetables.

Among the control covariates, household socio-demographic characteristics also had significant effects on crops choices. The number of crops grown was positively associated with household size, household's access to loan, migrant households, household head's age, and literacy. However, it was negatively related with female headship and household head's education level. Rural households cultivate about three more crops than small town households, but rural households are less likely to cultivate high-value crops and more likely to cultivate staple crops than small town households. Not only are small town households closer to output markets, they also have better access to inputs (fertiliser, hybrid seeds, agro-chemicals) and therefore can specialise in a few high-value crops as opposed to rural households that cultivate many staple crops for subsistence.

The probability of high-value crop cultivation decreases with access to loan, migrant households, and household head's literacy but it increases with household size, female headship, and household head's education level. The opposite is true for the probability of staple crop cultivation. These findings can be explained in the way the agricultural markets are organised in Ethiopia where loans for agricultural inputs are provided by micro finance institutions tailored to staple crop cultivation. Furthermore, the shift from subsistence farming to agricultural intensification through irrigation is labour demanding (Lefore et al., 2019), hence households with less access to labour forces (for example, migrant household members) are less likely to cultivate high-value crops. The increase in high-value crops under female leadership supports earlier studies by Theis, Lefore, Meinzen-Dick, and Bryan (2018) where women are often in control of vegetable gardens or income generating activities below a certain threshold.

In Table 6, we disaggregate the high-value crops and staple crops categories into multiple sub-categories and estimate the relationship between irrigation suitability and the probability of cultivation of different types of crops. Results confirm the finding in Table 5. Overall, irrigation suitability is positively associated with cultivation of fruits, vegetables, and legumes but negatively correlated with cultivation of cereals, oilseeds, and root crops. On average, one per cent increase in land suitability for groundwater irrigation is associated with 0.13 per cent increase in fruit cultivation, 0.02 per cent increase in vegetables, and 0.07 per cent increase in legume cultivation. The same change in groundwater irrigation suitability is associated with about 0.11 per cent decrease in both cereal and root crops cultivation.

Similar results were found for areas where solarised off-grid pumps are suitable up to a groundwater depth of 25 m. Farmers in these areas are more likely to grow fruits, vegetables, and legumes but less likely to grow cereals, oilseeds, and root crops. The magnitude of these effects is rather small, but a clear pattern emerges – suitability for small-scale irrigation is positively correlated with cultivation of high-value crops and crop diversification. This is not unsurprising as the investment in irrigation equipment,

Table 6. Irrigation suitability and choice of specific crops (Panel random effects)

	High value crops			Staple crops			
	Fruits	Vegetables	Cash crops	Cereals	Legumes	Oilseeds	Root crops
Panel A							
Groundwater irrigation	0.13***	0.015	0.0003	−0.11**	0.072**	−0.036*	−0.12***
suitability	(0.033)	(0.036)	(0.044)	(0.054)	(0.031)	(0.019)	(0.035)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−0.069	0.11	0.16*	0.64***	−0.0028	0.046**	0.090**
	(0.079)	(0.076)	(0.081)	(0.11)	(0.050)	(0.021)	(0.040)
Observations	**7,015**	**7,015**	**7,015**	**7,015**	**7,015**	**7,015**	**7,015**
Panel B							
Solar irrigation	0.014*	0.006	−0.010	−0.009	0.011	−0.003	−0.016*
suitability	(0.0081)	(0.0090)	(0.011)	(0.014)	(0.0077)	(0.0049)	(0.0089)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.047	0.13*	0.17**	0.50***	0.030	0.035*	0.023
	(0.077)	(0.076)	(0.079)	(0.098)	(0.049)	(0.018)	(0.033)
Observations	**6,108**	**6,108**	**6,108**	**6,108**	**6,108**	**6,108**	**6,108**

Notes: Standard errors are in parentheses. Level of significance * $p < .1$, ** $p < .05$, *** $p < .001$. Controls include current access to irrigation, share of currently irrigated land, household characteristics (household size, access to loan, migration indicator), household head characteristics (gender, age, marital status, literacy rate, education level), and regional dummies.

particularly solar-based irrigation, is often not viable when solely considering the irrigation of staple crops given low market prices. On the other hand, the cultivation of fruits, vegetables and cash crops do provide higher return on investments but also can be riskier for smallholder farmers. Our results can imply that, public and private sector investments in farmer-led irrigation to support agricultural development and climate adaptation goals could require incentive mechanisms to balance staple and high-value crop production to address food and nutrition security in the future.

5. Conclusion and recommendations

Policy efforts to strengthen enabling environment for farmer-led irrigation (FLI) expansion are underway in sub-Saharan Africa. However, it is less known who would likely be able to invest in or benefit from such expansion. Using the case of Ethiopia, this study examined the relationships between land suitability for FLI using groundwater and solarised off-grid pumps, and household wealth status and crop choices. We found a positive correlation between household wealth status (measured by consumption expenditure, household asset index, and land size) and land suitability for FLI. Furthermore, in these areas we noted a higher crop diversification and more cultivation of high-value crops such as vegetables, fruits, and cash crops. Staple crops, however, were more commonly cultivated in land areas that are less suitable for irrigation and are mainly under subsistence farming.

The results in this study add a question to the rich set of existing body of evidence that show a positive linkage between access to irrigation and poverty reduction. Our results indicate that the documented positive linkage between irrigation and household wealth may simply be a manifestation of classic economic sorting because land areas that are more suitable for FLI are in fact occupied by wealthier households. Results imply that if public and private sector investments for irrigation technology supply chains and services are targeted in areas with high suitability of natural resources (land and water), they will likely benefit the wealthier households and boost high-value as well as more water-intensive crop production. This, in combination with the lack of access to loans for irrigation technologies and in particular the barriers to female headed and marginal households, can deter the goals of food security and poverty reduction.

Our results have important policy implications. First, policies aimed at facilitating farmer-led irrigation development using shallow groundwater resources (including off-grid solar pumps) might want to look beyond physical suitability of land and water resources. While irrigation suitability is a critical first step, it is equally important to consider socio-economic characteristics of households and communities to avoid *elite* capture as wealthier households tend to reside in areas of higher suitability to groundwater use in irrigation.

Secondly, there is a need for combined public and private financing approaches to support the different needs of wealthier and resource-poor farmers, especially in areas where irrigation development is suitable. Whilst wealthier households would benefit from strengthened irrigation supply chain and services (for example, financial or repair services), improved market access and agricultural extension services through private sector investments, resource-poor households would require tailored financing mechanisms specific to bottom of the pyramid markets. These tailored financing mechanisms are often not financially viable or considered as high risk by the private sector. Hence, blended financing by donors or smart subsidy programmes by governments, carefully designed to not distort markets, and based on both irrigation suitability mapping and socio-economic status, would enhance marginal farmers' access to irrigation in areas with high irrigation suitability.

Third, strengthening of irrigation supply chains, financial and repair services should go hand in hand with incentives to stimulate high-value crops and staple food production in Ethiopia's efforts towards climate, food, and nutrition security. Results show that aside from crop diversification, high-value fruit, vegetables and other cash crops are favoured by households investing in irrigation. Extra financing or subsidy schemes tailored to FLI to support staple food production and livestock value chains will be crucial going forward.

Based on the results of this study, we argue that tailored investments are required in areas where there is a high potential for expanding FLI. In these areas, farmers who can make private investment (hence initiate the FLI development) are likely wealthier farmers. Public support for FLI expansion may be needed in minimising resource-poor farmers' financial barriers for irrigation development. Such tailored investments alongside strengthening agricultural markets can have positive impacts on rural livelihoods as well as help in climate change adaptation. These findings can imply that failure to account for socio-economic characteristics of farmers in determining public support for irrigation expansion may exacerbate existing inequalities, but this should not mean that public support for FLI expansion can be used as an inequality reducing tool.

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Notes

1. We acknowledge, however, that in areas where irrigation schemes have been poorly performing, farmers tend to invest in farmer-led irrigation leading to potential additional 'hot spots'. These hotspots are not included in our analysis as no information was available at national level on the current irrigation performance of small-medium and large-scale irrigation schemes.
2. We also estimated equation 1 with the correlated random effect (CRE) estimator. CRE results are qualitatively identical with the random effects results.
3. In the census data, the average size of kebele was 800 households. The average sample size in the LSMS data was 11 households per kebele.
4. Land suitability map for groundwater-based irrigation completely overlaps solar-powered irrigation map because the latter is a subset of the former. A farmland that is suitable for solar-powered groundwater irrigation is always suitable for groundwater irrigation, but the opposite is not true.
5. Asset index is a weighted index of household durable assets, livestock, agricultural equipment, and housing quality characteristics. These assets were weighted using principal component analysis. The weight was based on the first principal component which captures the most variation in the data and is considered a good measure of socioeconomic status (Booysen, Van Der Berg, Burger, von Maltitz, & du Rand, 2008; Filmer & Scott, 2008; Sahn & Stifel, 2003).
6. Groundwater irrigation suitability score was not converted to a binary indicator because doing so would remove the variations in groundwater irrigation suitability scores that were available as percentage points between 0 and 100.
7. The negative relationship between wealth indicator and use of loan is not surprising because farmers often do not take up credit for irrigation development (such as borehole drilling) due to the absence of suitable lending or credit mechanisms (Gebregziabher, Villholth, Hanjra, Yirga, & Namara, 2013), or unfavourable interest rates for irrigation technologies in rural finance institutions (Lefore et al., 2019).

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References

Adams, W. M., & Anderson, D. M. (1988). Irrigation before development: Indigenous and induced change in agricultural water management in East Africa. *African Affairs*, *87*(349), 519–535.

Addisu, S., Kassawmar, B., Mekuriaw, A., & Haileslassie, A. (2019). Geographic Information System based suitability analysis for potentials and challenges of small-scale irrigation in Lake Tana sub-basin, Ethiopia. *International Journal of River Basin Management*, 1–12. doi:10.1080/15715124.2019.1640227

African Union. (2020). *Framework for irrigation development and agricultural water management in Africa*. Addis Ababa, Ethiopia: African Union Headquarters. Retrieved from https://au.int/en/documents/20200515/framework-irrigation-development-and-agricultural-water-management-africa

Altchenko, Y., & Villholth, K. G. (2014). Mapping irrigation potential from renewable groundwater in Africa – A quantitative hydrological approach. *Hydrology and Earth System Sciences Discussions*, *11*(6), 6065–6097.

Balasubramanya, S., & Stifel, D. (2020). Viewpoint: Water, agriculture & poverty in an era of climate change: Why do we know so little? *Food Policy*, *93*, 101905.

Bhattarai, M., Sakthivadivel, R., & Hussain, I. (2002). *Irrigation impacts on income inequality and poverty alleviation: Policy issues and options for improved management of irrigation systems* [Working Paper]. International Water Management Institute. Retrieved from https://cgspace.cgiar.org/handle/10568/39287

Booysen, F., van der Berg, S., Burger, R., von Maltitz, M., & du Rand, G. (2008). Using an asset index to assess trends in poverty in seven sub-Saharan African countries. *World Development*, *36*(6), 1113–1130.

Dalberg. (2019). *Solar water pump outlook 2019: Global trends and market opportunities*. Efficiency for Access. Retrieved from https://storage.googleapis.com/e4a-website-assets/Solar-Water-Pump-Outlook-2019.pdf

de Bont, C. (2018). The continuous quest for control by African irrigation planners in the face of farmer-led irrigation development: The case of the lower Moshi Area, Tanzania (1935–2017). *Water Alternatives*, *11*(3), 893–915.

de Bont, C., & Veldwisch, G. J. (2020). State engagement with farmer-led irrigation development: Symbolic irrigation modernisation and disturbed development trajectories in Tanzania. *The Journal of Development Studies*, *56*(12), 2154–2168.

Filmer, D., & Scott, K. (2008). *Assessing asset indices*. The World Bank. Retrieved from http://elibrary.worldbank.org/doi/book/10.1596/1813-9450-4605

Garbero, A., & Songsermsawas, T. (2018). *Impact of modern irrigation on household production and welfare outcomes: Evidence from the Participatory Small-Scale Irrigation Development Programme (PASIDP) project in Ethiopia* (SSRN Scholarly Paper ID 3285073; IFAD RESEARCH SERIES 31). Social Science Research Network. Retrieved from https://papers.ssrn.com/abstract=3285073

Gebregziabher, G., Namara, R. E., & Holden, S. (2009). Poverty reduction with irrigation investment: An empirical case study from Tigray, Ethiopia. *Agricultural Water Management*, *96*(12), 1837–1843.

Gebregziabher, G., Villholth, K. G., Hanjra, M. A., Yirga, M., & Namara, R. E. (2013). Cost-benefit analysis and ideas for cost sharing of groundwater irrigation: Evidence from north-eastern Ethiopia. *Water International*, *38*(6), 852–863.

Giordano, M., & de Fraiture, C. (2014). Small private irrigation: Enhancing benefits and managing trade-offs. *Agricultural Water Management*, *131*, 175–182.

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) [Synthesis report]. International Water Management Institute (IWMI). Retrieved from http://www.iwmi.cgiar.org/Publications/Other/Reports/PDF/Water_for_wealth_and_food_security.pdf

Grafton, R. Q., Williams, J., Perry, C. J., Molle, F., Ringler, C., Steduto, P., … Allen, R. G. (2018). The paradox of irrigation efficiency. *Science*, *361*(6404), 748–750.

Hagos, F. G., Makombe, G., Namara, R. E., & Awulachew, S. B. (2008). *Does access to small scale irrigation promote market oriented production in Ethiopia*. Pelawatte, Sri Lanka: International Water Management Institute (IWMI).

Izzi, G., Denison, J., & Veldwisch, G. J. (2021). *The farmer-led irrigation developmetn guide. A what, why, and how-to for intervention design*. Washington, DC: World Bank.

Kahan, D. (2013). *Market-oriented farming: An overview* (Farm Management Extension Guide). Rome, Italy: Food and Agricultural Organization (FAO).

Laborde, D., Porciello, J., & Smaller, C. (2020). *Ceres2030: Sustainable solutions to end hunger summary report* [Report]. Ceres2030. Retrieved from https://ecommons.cornell.edu/handle/1813/72799

Lefore, N., Giordano, M., Ringler, C., & Barron, J. (2019). Viewpoint: sustainable and equitable growth in farmer-led irrigation in sub-Saharan Africa: What will it take? *Water Alternatives*, *12*(1), 13.

Lipton, M., Litchfield, J., & Faurès, J.-M. (2003). The effects of irrigation on poverty: A framework for analysis. *Water Policy*, *5*(5–6), 413–427.

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, *7*(2), 024009.

Manero, A., Bjornlund, H., Wheeler, S., Zuo, A., Mdemu, M., Rooyen, A. V., & Chilundo, M. (2020). Growth and inequality at the micro scale: An empirical analysis of farm incomes within smallholder irrigation systems in Zimbabwe, Tanzania and Mozambique. *International Journal of Water Resources Development*, *36*(sup1), S224–S245.

Manero, A. (2017). Income inequality within smallholder irrigation schemes in Sub-Saharan Africa. *International Journal of Water Resources Development*, *33*(5), 770–787.

Manstead, A. S. R. (2018). The psychology of social class: How socioeconomic status impacts thought, feelings, and behaviour. *The British Journal of Social Psychology*, *57*(2), 267–291.

Minh, T., & Schmitter, P. (2021). *Towards adaptive scaling of contemporary farmer-led irrigation development: A conceptual framework* (Unpublished manuscript).

Molden, D., Frenken, K., Barker, R., Fraiture, C. D., Mati, B., Svendsen, M., & Finlayson, C. (2007). Trends in Water and agricultural development. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 57–89). London, UK: Earthscan and Colombo, Sri Lanka: International Water Management Institute (IWMI).

Mukherji, A., Facon, T., Burke, J., de Fraiture, C., Faures, J.-M., Fuleki, B., … Shah, T. (2009). *Revitalizing Asia's irrigation: To sustainably meet tomorrow's food needs*. Colombo, Sri Lanka: International Water Management Institute; Rome, Italy: Food and Agriculture Organization of the United Nations.

Namara, R. E., Hanjra, M. A., Castillo, G. E., Ravnborg, H. M., Smith, L., & van Koppen, B. (2010). Agricultural water management and poverty linkages. *Agricultural Water Management*, *97*(4), 520–527.

Namara, R. E., Hope, L., Sarpong, E. O., Fraiture, C. D., & Owusu, D. (2019). *Adoption of water lifting technologies for agricultural production in Ghana: Implications for investments in smallholder irrigation systems*. Retrieved from https://gatesopenresearch.org/documents/3-66

Nature. (2020, October 12). Ending hunger: Science must stop neglecting smallholder farmers (Editorial). *Nature*, *586*, 336. https://doi.org/10.1038/d41586-020-02849-6

Passarelli, S., Mekonnen, D., Bryan, E., & Ringler, C. (2018). Evaluating the pathways from small-scale irrigation to dietary diversity: Evidence from Ethiopia and Tanzania. *Food Security*, *10*(4), 981–997.

Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, *109*(31), 12302–12308.

Sahn, D. E., & Stifel, D. (2003). Exploring alternative measures of welfare in the absence of expenditure data. *Review of Income and Wealth*, *49*(4), 463–489.

Schmitter, P., Kibret, K. S., Lefore, N., & Barron, J. (2018). Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. *Applied Geography*, *94*, 41–57.

Shah, T., Namara, R. E., & Rajan, A. (2020). *Accelerating irrigation expansion in sub-Saharan Africa: Policy lessons from the global revolution in farmer-led irrigation*. Washington, DC: World Bank Group.

Sharma, A., Varma, S., & Joshi, D. (2008). Social equity impacts of increased water for irrigation. In *Conference Papers* (No. h041805; Conference Papers). International Water Management Institute. Retrieved from https://ideas.repec.org/p/iwt/conppr/h041805.html

Spielman, D. J., & Pandya-Lorch, R. (2010). *Proven successes in agricultural development: A technical compendium to millions fed*. Washington, DC: International Food Policy Research Institute.

Theis, S., Lefore, N., Meinzen-Dick, R., & Bryan, E. (2018). What happens after technology adoption? Gendered aspects of small-scale irrigation technologies in Ethiopia, Ghana, and Tanzania. *Agriculture and Human Values*, *35*(3), 671–684.

van den Berg, M., & Ruben, R. (2006). Small-scale irrigation and income distribution in Ethiopia. *The Journal of Development Studies*, *42*(5), 868–880.

Warner, M., & Kahan, D. (2008). *Market-oriented agricultural infrastrucure: Apprisal of public-private partnerships* (Project Briefing No. 9). Rome, Italy: Food and Agriculture Organization of the United Nations.

Wiggins, S., & Lankford, B. (2019). *Farmer-led irrigation in sub-Saharan Africa: Synthesis of current understandings* (DFID-ESRC Growth Research Programme, p. 72) [Synthesis report]. Overseas Development Institute (ODI). Retrieved from https://www.odi.org/publications/11394-farmer-led-irrigation-sub-saharan-africa-synthesis-current-understandings

Woodhouse, P., Veldwisch, G. J., Venot, J.-P., Brockington, D., Komakech, H., & Manjichi, Â. (2017). African farmer-led irrigation development: Re-framing agricultural policy and investment? *The Journal of Peasant Studies*, *44*(1), 213–233.

Worqlul, A. W., Jeong, J., Dile, Y. T., Osorio, J., Schmitter, P., Gerik, T., … Clark, N. (2017). Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. *Applied Geography*, *85*, 1–13.

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.

You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., … Sun, Y. (2011). What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy*, *36*(6), 770–782.

Appendix

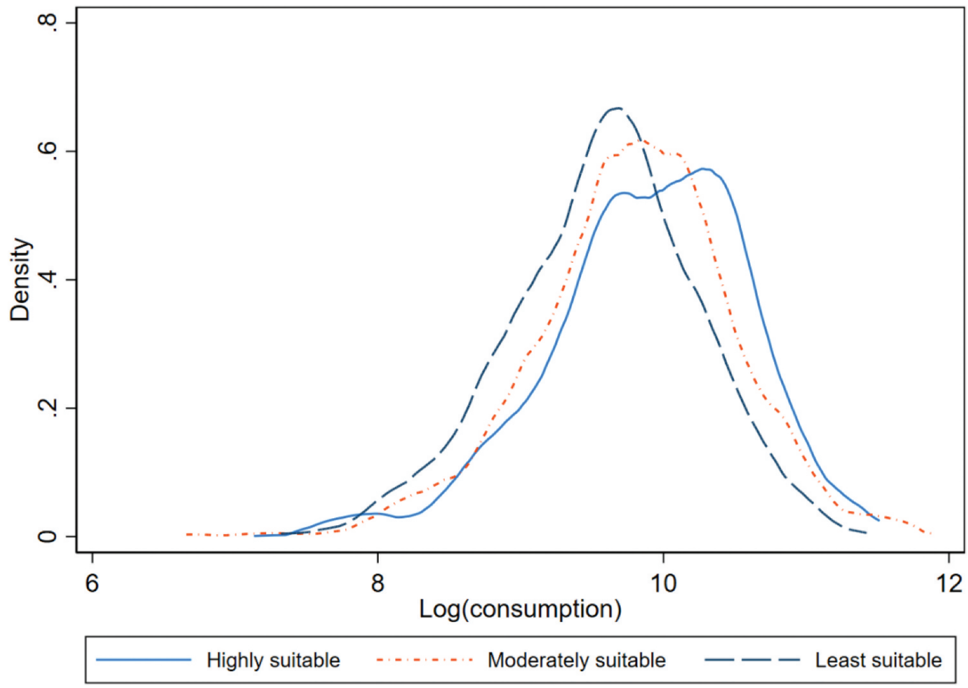

Figure A1. Distribution of household consumption expenditure by groundwater irrigation suitability.

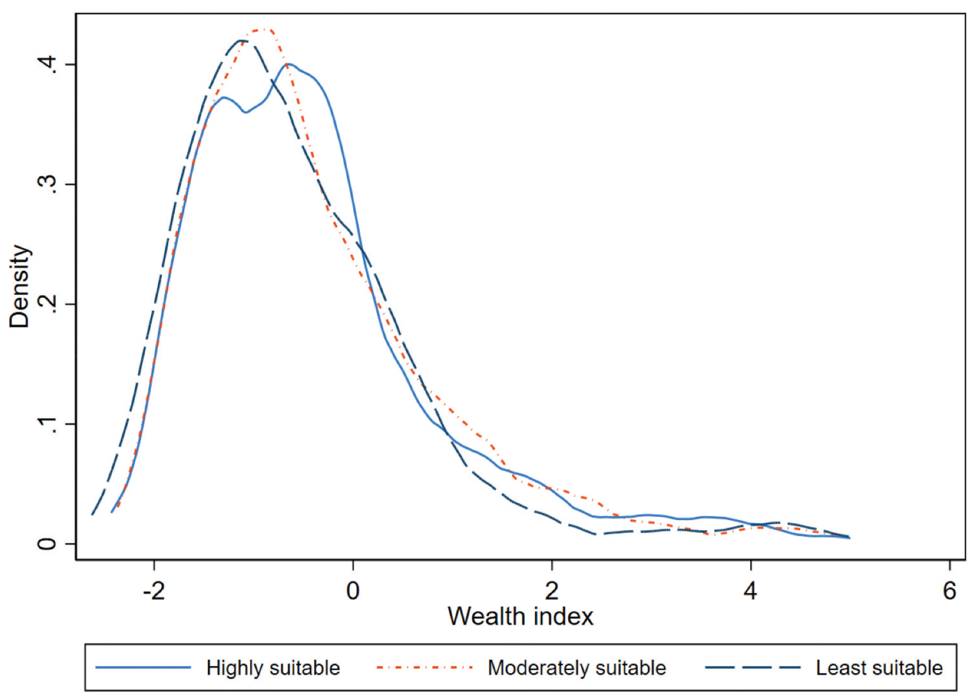

Figure A2. Distribution of household asset index by groundwater irrigation suitability.

Table A1. Groundwater irrigation suitability determination criteria

Data	Description
Land use	1 km resolution land use map from combined FAO GeoNetwork land use data and Spatial Production Allocation Model (SPAM) crop distribution data. Four classes of land use: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (S4).
Soil	Based on Africa Soil Information Systems (AfSIS). Soil texture from first five layers up to 1 m deep were weighted and classified into four classes based on water holding capacity. These are very high holding capacity, high capacity, low capacity and very low capacity.
Slope (%)	Estimated using 30 m resolution Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM). Classification: 0–2% highly suitable, 2–8% moderately suitable, 8–12% marginally suitable, 12–30% less suitable, and >30% not suitable.
Rainfall (mm/year)	Rainfall data from 509 weather stations across Ethiopia from year 2000 to 2010. To estimate spatial rainfall for entire country, annual rainfall was interpolated using inverse distance weighting method.
Groundwater depth (m)	5 km spatial resolution groundwater data acquired from the British Geological Survey (BGS) and validated by the Ethiopian Agricultural Transformation Agency (ATA). Ranged from 0–250 m below surface.
Groundwater storage (mm)	Highly variable, ranging from 1 to 50 million m^3 km^{-2}
Groundwater recharge (mm/year)	Unknown. Not mentioned
Population density	Based on year 2000 data from Global Gridded Population Database. Ranged from 0–69,350 persons per square km.
Proximity to road (km)	Vector data showing all paved and unpaved road networks was sourced from Ethiopian Road Authority (ERA). Euclidean distance computed at 1 km grid. Average distance to paved road is 19 km but farthest point is 119 km away.

Source: Worqlul et al. (2017).

Table A2. Solar irrigation suitability determination criteria

Data	Very highly suitable	Highly suitable	Moderately suitable	Less suitable	Least suitable	Constraint
Solar irradiation (kWh/m2)	3000–2500	2499–2000	1999–1750	1749–1500	1499–1300	<1300
Slope (%)	0–2	2–4	4–8	NA	NA	>8
Groundwater depth (0–25 m)	0–7	7.1–25	NA	NA	NA	>25
Aquifer productivity (l/s)	>0.5	0.5–0.1	-	-	-	<0.1
Groundwater storage (mm)	25–50	10–25	1–10	-	-	<1
Proximity to river (m)	<50	51–100	101–200	201–300	>300	-
Proximity to small reservoirs (m)	<50	51–100	101–200	201–300	>300	-
Proximity to roads (m)	200	100	50	25		-
Proximity to town (m)	>100	45–100	15–45	2.5–15		-

Source: Schmitter et al. (2018).

Table A3. Living Standard Measurement Study-Integrated Survey in Agriculture (LSMS-ISA) data

	Survey year		
Data	2011/12	2013/14	2015/16
Households	3,969	5,287	4,980
Kebeles	333	427	426
Woredas	263	317	316
Zones	69	84	84
Regions	10	11	11

Notes: LSMS-ISA is nationally representative sample survey which collects information about household demographics, socio-economic status, education, employment, consumption as well as detailed agriculture data.

Table A4. Shares of matched kebeles between 2007 Census and groundwater irrigation suitability data†, by region

	Census data		Groundwater irrigation suitability data	
Regions	Number of kebeles	Matched	Number of kebeles	Matched
Afar	329	92.24	321	94.54
Amhara	3,026	98.96	3,040	98.5
Benishangul-Gumuz	410	97.65	415	96.47
Gambella	207	89.0	186	99.04
Harari	17	84.74	18	89.47
Oromiya	6,337	95.57	6,425	94.26
Snnp	3,586	96.11	3,631	94.92
Tigray	600	99.51	607	98.36
Total	14,512	96.2	14,643	95.4

Notes: †Groundwater irrigation suitability data come from Worqlul et al. (2017).
Groundwater irrigation suitability data consisted of a total of 15,405 unique kebeles of which 762 kebeles were urban towns which were dropped before the matching was carried out. Matching was carried out between 14,512 kebeles from census and 14,643 kebeles from groundwater irrigation suitability data.