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Who benefits from farmer-led irrigation expansion in Ethiopia?

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Abstract

Despite increasing popularity of farmer-led irrigation in Ethiopia, little is known about socio-economics of farmers who receive public support in accelerating its expansion. We investigate this question by combining spatial land suitability for groundwater- and solar irrigation with pre-existing socio-economic data. We find that if public support in farmer-led irrigation expansion were to be provided to farmers who own land areas that are also spatially highly suitable for irrigation, high-value crop cultivators and wealthier farmers would most likely benefit from such investments. Specifically, we find evidence that farmers in land areas more suitable for groundwater irrigation cultivated more high value crops such as vegetables, fruits, and cash crops. Cultivation of staple crops such as cereals, oilseeds, legumes and root crops were negatively associated with groundwater irrigation suitability. In addition, we find a positive correlation between farmers' wealth status (measured by consumption expenditure, asset index, and land size) and groundwater irrigation suitability. Controlling for regional differences and current irrigation coverage, one percent increase in irrigation suitability score was associated with 0.2% increase in per-capita consumption expenditure. Land areas that were suitable for irrigation were more likely to belong to large-holders than small-holders. Results imply that policies which aim to facilitate farmer-led irrigation development in Ethiopia should not rely only on spatial suitability for irrigation. Household socio-economics and existing agricultural practices are equally important.

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Who benefits from farmer-led irrigation expansion in Ethiopia?[1]

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1. Introduction

Sub-Saharan Africa (SSA) has a huge potential for small-scale (farmer-led) irrigation, but most of that remains unexploited (African Union, 2020; Giordano and de Fraiture, 2014; Xie et al., 2014; You et al., 2011). Existing evidence shows that investment in irrigation technologies, especially farmer-led irrigation, in which case farmers themselves drive the establishment and expansion as well as the purpose and design of on-farm irrigation development, reduces poverty and improves food security by increasing agricultural productivity (Balana et al., 2020; Baye et al., 2019; Burney and Naylor, 2012; Gebregziabher et al., 2009; Giordano et al., 2012; Giordano and de Fraiture, 2014; Namara et al., 2010; Passarelli et al., 2018; Tesfaye et al., 2008). In addition, sustainable water management solutions, primarily, improved access to irrigation and better irrigation technologies have been touted as effective climate change adaptation strategies for smallholder farmers in the region (Alemayehu and Bewket, 2017; Amede, 2015; Kurukulasuriya et al., 2006). As such, expansion of farmer-led irrigation through creation of enabling environment in SSA has received a significant attention from policymakers, donors, and development organizations alike (African Union, 2020; Woodhouse et al., 2017). Even though farmers themselves drive the development of farmer-led irrigation, governments can play a role in strengthening the enabling environment by providing credit access, stable and reliable market access, agricultural price support, technical capacity for installation as well as repair and maintenance of pumps, agricultural extension services etc. Such efforts are particularly important for Ethiopia where the government has identified irrigated agriculture as the primary avenue for economic growth.

The Government of Ethiopia is poised to make big investment in supporting the enabling environment for farmer-led irrigation, especially small-scale solar irrigation (Agricultural Transformation Agency, 2016; Amede, 2015; Chanyalew et al., 2010). Under the *Growth and Transformation Plan II, 2016-2020,* the Ministry of Agriculture aimed to facilitate expansion of farmer-led irrigation from then estimated 2.3 million hectares to 4.1 million hectares by 2020. The government is expected to ramp up these efforts beyond 2020 as well. From policy standpoint, these efforts in facilitating the expansion of farmer-led irrigation are justified for multiple reasons. First, in an era of climate change, lack of irrigation can lead to over exploitation of limited land and water resources contributing to unsustainable agricultural intensification (Jayne et al., 2014; Josephson et al., 2014). Second, smallholders' dependence on rainfed agriculture with no proper water management systems can have serious repercussions on food insecurity and poverty (Devereux, 2000; Gebrehiwot and van der Veen, 2013; Ittersum et al., 2016; Rockström et al., 2003). Third, despite high potential for irrigation, Ethiopian agriculture continues to be mainly rainfed with less than 5% of arable land being irrigated (Awulachew and Ayana, 2011; Seleshi and Camberlin, 2006; Worqlul et al., 2017) and the lack of irrigation is considered as one of the major reasons behind dismal agricultural productivity (Jayne et al., 2014; Passarelli et al., 2018). Given that the agricultural sector alone employs more than 70% of the population, and contributes up to 40% to the national GDP (ILO, 2017; World Bank Group, 2016), expansion of farmer-led irrigation may be necessary, though not sufficient, to keep the ever growing population food secure and less vulnerable to climate change.

As rapid expansion of farmer-led irrigation is underway, questions loom large about who would truly benefit from such efforts. While most of the expansion efforts take care of biophysical aspects such as groundwater depth, land use pattern, solar irradiation (for solar irrigation) etc., socio-economics of potential beneficiaries is less understood. For example, in recent years, multiple studies have estimated the biophysical potential of farmer-led irrigation in Ethiopia (Addisu et al., 2019; Schmitter et al., 2018; Worqlul et al., 2017; You et al., 2011) as well as for the greater sub-Saharan African region (Altchenko and Villholth, 2014; MacDonald et al., 2012; Xie et al., 2014), but none of these considered socio-economic factors. Worqlul et al. (2017) assessed the land suitability for groundwater-based irrigation using biophysical indicators (e.g. land use pattern, groundwater storage, rainfall, road proximity etc.) and population density. Their model produced a map of land suitability for groundwater irrigation and showed that Ethiopia has more than 6 million hectares of land suitable for groundwater-based irrigation. Likewise, Schmitter et al. (2018) assessed the suitability of solar irrigation (solar water-lifting pumps) for smallholder farmers in Ethiopia. Disaggregating the currently cultivated land into irrigated and rainfed land, Schmitter et al. found that only about 9% of currently irrigated land and 18% of rainfed land is suitable for solar irrigation.

While the spatial irrigation suitability[2] maps developed in these studies are critical in determining whether and where to expand farmer-led irrigation, these models are unable to assess who would likely benefit from such expansion. Even though farmers themselves drive

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[2] The term 'irrigation suitability' is used to jointly refer to groundwater irrigation suitability (suitability for irrigation based on groundwater) and solar irrigation suitability (suitability for irrigation by using solar photovoltaic pumps). Several factors were considered in determining irrigation suitability including land use pattern, groundwater depth, slope, population density, and market access (travel time to main roads and proximity to main cities).

the development/expansion of farmer-led irrigation, it does require careful assessment of where pumps get installed and who gets to use it – i.e. what are the socioeconomic characteristics of the farmers who use the pump? Approaches that only look at biophysical suitability get the '*where to install a pump*' part right but may miss the '*who gets to use the pump*' part. Studies that look only at the socio-economic side also completely miss the point as they fail to take account of biophysical features which are pivotal for irrigation development. The present study connects these dots. We combine irrigation suitability maps with pre-existing socio-economic data and investigate the relationships between spatial irrigation suitability and household socio-economic characteristics – wealth status, demographics, and crop choices. Household wealth status is measured by consumption expenditure, asset index, and land size.

Our efforts to connect spatial irrigation suitability and socio-economic characteristics are motivated by the rich body of prior evidence that access to irrigation (*where irrigation is already in place*) reduces poverty and increases food security, particularly by increasing productivity of high-value crops (Balana et al., 2020; Baye et al., 2019; Burney and Naylor, 2012; Gebregziabher et al., 2009; Giordano et al., 2012; Giordano and de Fraiture, 2014; Namara et al., 2010; Passarelli et al., 2018; Tesfaye et al., 2008). We suspect that the positive correlation between access to irrigation and poverty reduction and food security may be a manifestation of classic sorting based on economic wellbeing (e.g., see Manstead, 2018). Even though many have argued that access to irrigation increases household well-being, there lies a possibility of reverse causality. Specifically, those who are already well-off inhabit areas that are more suitable for irrigation development and closer to markets or roads (hence produce more cash crops and high value crops). Given the lack of appropriate data to test the direction of casualty between household wealth status (measured by consumption expenditure, asset index, and land holding size) and irrigation suitability, we estimate the relationship between the two and show that they are positively correlated. We also estimate the relationship between irrigation and suitability and crop choices and show that households residing in irrigation suitable areas are more likely to produce high value crops.

We match the spatial suitability for groundwater-based irrigation and solar irrigation with the census data as well as integrated household and agriculture data from a nationally representative sample survey. Relying on spatial suitability of irrigation from Worqlul et al. (2017) and Schmitter et al. (2018), we investigate 1) how does the suitability for groundwater (and solar pump) irrigation correspond to household wealth status, demographics, and crop choices in Ethiopia. Perhaps, the relationship between household wealth status and irrigation suitability is more important from an equity standpoint because it examines whether the wealthier or marginal farmers would be the likely beneficiaries of public investments aimed at facilitating farmer-led irrigation development. Provided that the land areas highly suitable for irrigation are occupied by wealthier households, public investments aimed at creating or supporting the enabling environment for farmer-led irrigation development may likely go to wealthier households, potentially contributing to social inequality.

We make two contributions to the literature. First, to our knowledge, this is the first attempt to connect household level socio-economic and agricultural data with spatial data for irrigation suitability and to examine the confluence between the two. Specifically, we unpack the relationship between the estimated spatial suitability for irrigation and wealth status, population density, and crop choices. The linkage between access to irrigation and household socio-economic status has been well documented in the literature (Balana et al., 2020; Baye et al., 2019; Burney and Naylor, 2012; Gebregziabher et al., 2009; Giordano et al., 2012; Giordano and de Fraiture, 2014; Namara et al., 2010; Passarelli et al., 2018; Tesfaye et al., 2008) but the relationship between land suitability for irrigation and household socio-economic status is less understood. Second, our effort responds to the call from researchers about the need for interdisciplinary research to better understand the uses and management of water for agriculture as well as the links between agricultural water management and poverty (Balasubramanya and Stifel, 2020). Hence, this analysis fills a research gap by presenting missing evidence on the relationship between biophysical irrigation suitability and household socio-economic characteristics, which may potentially help policymakers or investors interested in accelerating farmer-led irrigation development in Ethiopia.

The rest of the paper is organized 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 with study limitations and policy recommendations.

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 investments in supporting the enabling environment for farmer-led irrigation development targeted at areas highly suitable for irrigation are 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 highly irrigation suitable areas also have better access to markets, transportation, and market information. Better access to markets and transportation incentivizes farmers to grow high value crops such as fruits and vegetables. To test this hypothesis, types of 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).

Multi-linear regressions are used to estimate the relationship between farmer's wealth status and irrigation suitability as well as the relationship between crop types and irrigation suitability. Assuming that spatial irrigation suitability correlates with potential irrigation investment, a positive relationship between irrigation suitability and farmer's wealth status indicates that investment in farmer-led irrigation would likely benefit wealthier farmers. Likewise, a positive relationship between irrigation suitability and the indicator for high-value crops indicates that investment in farmer-led irrigation would likely benefit high-value crop cultivators.

2.2. Econometric methods

Since our primary interest is to understand how spatial irrigation suitability is correlated with socio-economic characteristics and crop types, our analysis only suggest association between the variables of interest. We make no attempt to establish causal relationship between irrigation suitability and socio-economic characteristics or crop types due to data limitations. Suppose Y_{1it} denotes wealth status of farmer *i* at time *t*, Y_{2it} denotes farmer *i*'s crop choices at time *t*, and X_i indicates a vector of demographic characteristics and farm characteristics of household *i*. Equation 1 provides the econometric relationship between wealth status, crop types, and irrigation suitability.

$$Y_{jit} = \alpha_0 + \alpha_{j1} Irrigation\, suitability_i + \Theta X_i + \varepsilon_{jit}, \ \forall j = 1, 2 \qquad (1)$$

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. A positive and statistically significant estimates of α_{11} indicates that public investment aimed at facilitating farmer-led irrigation development would more likely benefit wealthier farmers. Similarly, a positive and statistically significant estimates of α_{21} indicates that such investment would more likely benefit high-value crop cultivators.

The estimates of α_{j1} may not be unbiased because irrigation suitability is likely endogenous. Irrigation suitability is determined based on biophysical factors and proximity to roads and towns which also can influence farmer wealth status and crop choices.

3. Data and descriptive statistics

3.1. Data

We use data from four different sources: i) spatial suitability of groundwater irrigation data from Worqlul et al. (2017), ii) spatial suitability of solar irrigation from Schmitter et al. (2018), iii) 2007 census data obtained from the Central Statistical Agency (CSA) of Ethiopia, and iv) a nationally representative household and agriculture sample survey data collected by World Bank's Living Standard Measurement Study (LSMS) surveys. Biophysical criteria used to determine spatial suitability of groundwater irrigation are presented in appendix Table A1. Similarly, biophysical criteria and different scenarios used to determine spatial suitability of solar irrigation (using photovoltaic pumps) are presented in appendix Table A2. The LSMS data is described in appendix Table A3.

Both solar and groundwater-based irrigation suitability information (collectively called irrigation suitability data) were available at 30m x 30m resolution, but the census data were available at kebele level – the smallest administrative unit in Ethiopia. The LSMS data were available at household and plot levels but household and plot geo-locations were hidden for privacy reasons. Modified household geocodes were available at kebele level. Therefore, matching between different data sources was done at kebele level.

First, the irrigation suitability data were matched with the census data using the names for zone, region, woreda, and kebele. No other common identifiers were available for matching. The name matching was fairly accurate in that more than 95% of kebeles in groundwater irrigation suitability data were successfully matched with the census data (Table 1). Analysis of groundwater irrigation suitability data is based on 14,512 matched kebeles from rural areas and small towns.

--Table 1 about here --

Second, matching between solar irrigation suitability and the census data varied by different scenarios used to assess solar irrigation suitability. The scenarios differed in groundwater depth (scenario 1: 0-7 m; scenario 2: 0-25 m) and surface water (scenario 3: access to rivers, lakes and reservoirs). A large share of kebeles were excluded from solar irrigation suitability mapping in Schmitter et al. (2018). Among the included kebeles, about 91% of kebeles successfully matched with the census data (appendix Table A4).

Third, LSMS data were overlaid with the irrigation suitability maps using ArcGIS. More than 84% of LSMS kebeles were successfully matched with the groundwater irrigation suitability data. The remaining 16% of LSMS kebeles either fell in areas excluded in the irrigation suitability map or had the geocodes missing. Solar irrigation suitability maps and LSMS data were poorly matched and therefore excluded from the analysis.

3.2. Irrigation suitability index

Groundwater irrigation suitability scores were available as percentage suitability values. We categorized the suitability scores into three different irrigation suitability levels using distribution of groundwater irrigation suitability index from Worqlul et al. (2017). Areas with less than 60% suitability score was considered least suitable for groundwater irrigation, while areas between 60% and 85% suitability scores were considered moderately suitable, and areas above 85% suitability scores were considered highly suitable for groundwater irrigation. Solar irrigation suitability scores in Schmitter et al. (2018) were available as distinct suitability categories – 1) very highly suitable, 2) highly suitable, 3) moderately suitable, 4) less suitable, 5) least suitable, and 6) not suitable (or constrained). Appendix Table A5 provides details on this. For consistency with groundwater irrigation suitability levels, we merged the first two categories into highly suitable category and the fourth and fifth categories into least suitable category.

Since different data sources were matched at kebele level, irrigation suitability scores were aggregated at kebele level. The mode was used to represent irrigation suitability of each kebele. As a result, all LSMS sample households within a kebele fell under the same category of groundwater irrigation suitability. Figure 1 illustrates the groundwater suitability mapping for Ethiopia; brown colour indicates least suitability and green colour indicates high suitability for groundwater irrigation.

--Figure 1 about here—

3.3. Descriptive statistics

This section provides descriptive statistics on irrigation suitability, population demographics, agricultural practices, irrigation status as well as interrelationships between them. Statistics reported here are based on census data (2007), data on spatial suitability for irrigation, and 2015/16 LSMS-ISA data. The LSMS data were available for two additional time periods

(2011/12 and 2013/14) but these data are used only in the regression analysis with results presented in section 4.

3.3.1. Irrigation suitability and population demographics

Figure 2 presents share of kebeles under different levels of suitability for groundwater irrigation and solar irrigation. Data show that the majority of rural kebeles are at least moderately suitable for groundwater irrigation in Ethiopia. However, when it comes to solar irrigation pumping water from depths 0-25 m, about 4% kebeles are highly suitable. More than 45% of kebeles are not suitable (or constrained) for solar irrigation, despite only 28% kebeles are least suitable for groundwater irrigation. 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.

--Figure 2 about here—

Table 2 presents the shares of households in rural kebeles with distinct levels of groundwater irrigation suitability. Ethiopia had about 11 million rural households in 2007. About two-thirds of rural households were residing in areas suitable for groundwater irrigation; 17% in highly suitable areas, 49% in moderately suitable areas, and 31% households in least suitable areas. In 2007, SNNPR had 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% rural households residing in the least suitable areas followed by Amhara (53%), Afar (24%), and Benishangul-Gumuz (26%). 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 highlands such as SNNPR and Oromiya are expected to have more irrigation suitable land than arid and semi-arid highlands such as Tigray.

--Table 2 about here--

Figure 3 shows the distribution of population densities across kebeles with distinct levels of groundwater irrigation suitability. Population density and groundwater irrigation suitability are positively correlated. It was highest in kebeles highly suitable for groundwater irrigation and lowest in kebeles least suitable for groundwater irrigation. Similar pattern held for each of the eight regions (see Figure A1 in Appendix). This is not surprising because rural Ethiopian populations cluster partly based on agro-ecological production potentials, availability of water, and proximity to roads and markets (Jayne et al., 2014). However, this highlights a need for creating enabling environment for farmer-led irrigation expansion in relatively densely populated rural areas because high population density often leads to land intensification with no apparent gain in crop yields in the absence of irrigation (Jayne et al., 2014; Josephson et al., 2014; Ricker-Gilbert et al., 2014).

---Figure 3 about here---

Unlike the groundwater irrigation suitability, population density was negatively correlated with solar irrigation suitability (Table 3). Under the first scenario, which assesses solar irrigation suitability for groundwater depth up to 25 m, areas that were highly suitable for solar irrigation had a smaller number of households per kebele, lower population, and lower population density than areas that were less suitable. Similar pattern held under both second and third scenarios which consider groundwater depth up to 7m and surface water, respectively. Considering surface water as the primary source of water, a vast majority of kebeles were not suitable for solar irrigation.

---Table 3 about here---

Population density was 204/km^2 in areas least suitable for solar irrigation, but it decreased to below 143/km^2 for areas that were moderately or highly suitable for solar irrigation. This implies that any public investment in creating enabling environment for solar irrigation technologies might not reach as much people as such investment in non-solar groundwater lifting technologies could potentially benefit. It is important to note, however, that there is no one-to-one comparison between these two. The groundwater irrigation suitability map developed by Worqlul et al. (2017) does not take into account the different technologies for pumping water at a specific depth. Solar irrigation suitability map takes into account one specific type of technology – the solar photovoltaic pumps with a limited capacity to not pump beyond 25m.

Table 4 provides estimated share of households in each region likely to benefit from investment in solar irrigation. The share is calculated as a ratio of the number of households in kebeles that are at least moderately suitable for solar irrigation and the total number of households in the region. The likelihood of benefitting from investment in solar irrigation increases with groundwater depth, provided only up to 25 m of groundwater depth is considered. Under the first scenario, which considers groundwater depth up to 25 m, more than 55% households are likely to benefit from investment in solar irrigation. The share decreases to 25% under the second scenario (groundwater depth 7 m) and to 9% under the third scenario which considers surface water only.

---Table 4 about here---

Provided groundwater depth considered is up to 25 m, more than 58% households could benefit from strengthening solar irrigation supply chains and services in Amahara, SNNP, and Oromiya. Under the same circumstances, only a small proportion of households would benefit in Afar, Tigray, and Benishangul Gumuz regions. Harari and Tigray are the most suitable regions for surface water based solar irrigation investment with at least 60% households in these regions likely to benefit from such investment. This is not surprising because both of these regions have numerous small reservoirs (Dejenie et al., 2008).

These shares do not account for credit constraints and other obstacles that prevent farmers from installing the pumps. As most farmers in SSA are credit constrained and government subsidies cover only a small fraction of needy farmers, the actual share of households that can truly benefit from investment in solar irrigation may be much lower (Dalberg, 2019)

3.3.2. Irrigation suitability, agriculture practices, and irrigation status

Table 5 provides statistics on agricultural practices and irrigation status across different levels of groundwater irrigation suitability. Using LSMS data from 2015/16, more than 80% of rural and small-town households in Ethiopia were engaged in agriculture. On average, an agricultural household cultivated about 10 plots of land, but the size of a plot was small (<0.2 hectare). About 2% of cultivated plots were irrigated and the share of agricultural households with at least one irrigated plot was less than 8% suggesting a heavy reliance on rainfed agriculture. Since the majority of arable land was suitable for irrigation, the low irrigation coverage indicates a huge potential for investment in farmer-led irrigation in Ethiopia.

---Table 5 about here---

Despite a huge potential for groundwater irrigation, most irrigating households used surface water. For instance, in 2015/2016, 64% of irrigating households used river water for irrigation followed by lake/pond water (6.2%), and harvested rainwater (5.8%). The remaining 24% of irrigating households used water from other sources such as borehole, piped water, and spring water. That surface water sources were more commonly used than groundwater sources is not surprising. Without public assistance, groundwater irrigation can be unaffordable to smallholders because drilling boreholes and lifting water to the surface is costly (Easter and Liu, 2005; Gebregziabher et al., 2013; Giordano et al., 2012). Uncertainty about finding water after incurring drilling expenses and expensive water-lifting technologies (pumps) can prevent small farmers from accessing available groundwater source Awulachew et al. (2019).

The last three columns in Table 5 present the statistics on agricultural practices, irrigation status, and source of water by level of groundwater irrigation suitability. There were no discernible differences on any of the statistics among the different levels of irrigation suitability. Neither agricultural practices nor the access to irrigation differed by groundwater irrigation suitability. Households in areas that were highly suitable for groundwater irrigation were slightly more likely to be currently irrigated (9.9%) than households living in areas that are less suitable for groundwater irrigation, but the difference was not statistically significant. The lack of correspondence between land suitability for irrigation and current irrigation is not surprising because most of the current irrigation is surface water-based irrigation and the land suitability assessment of Worqlul et al. (2017) was for groundwater.

On average, plot sizes did not differ with different levels of groundwater irrigation suitability. However, households in highly suitable irrigation areas cultivated higher number of plots and crops compared to households in moderately and least suitable areas. Similar pattern held for the number of irrigated plots. Unlike the number of plots, plot size was smaller in areas highly suitable for groundwater irrigation than in areas less suitable for groundwater irrigation. Perhaps, households in highly irrigation suitable areas cultivate a greater number of high value crops such as vegetables leading to greater number of small sized plots.[3]

4. Results and discussion

In this section, we explore how spatial suitability for irrigation correlates with farmer's wealth status and crop choices. Wealth status is measured with per-capita consumption expenditure, asset index, and land holding size. Crop choice is measured with number of crops grown, indicators for high-value crops and staple crops. Relationship between irrigation suitability and individual crops is also presented. Practically, equation 1 is estimated with panel random effects estimator which is a more efficient estimator than a pooled OLS estimator. Panel fixed effects is not applicable because irrigation suitability is time invariant.

4.1. Irrigation suitability and household wealth

Table 6 presents the relationship between household wealth status (measured by consumption expenditure, asset index[4], and land size) and groundwater irrigation suitability. Regional differences are taken care of by including regional dummies in the estimating model. Results

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[3] For clarity, the LSMS survey defines a plot as a contiguous piece of land under the same crop management system.

[4] 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 et al., 2008; Filmer and Scott, 2008; Sahn and Stifel, 2003).

show that a one percent increase in groundwater irrigation suitability score was associated with 0.15% increase in per-capita consumption expenditure. In our data, the irrigation suitability score ranged between 45 and 95. Applying the estimated effects in our data, per-capita consumption expenditure for the households that own the highest irrigation suitable land (a suitability score of 95) would be 16% higher than for households that own the least irrigation suitable land (suitability score of 45). Likewise, a one percent increase in irrigation suitability score was associated with 0.21-hectare higher land size. Asset index was also positively correlated with irrigation suitability, but the coefficient was not statistically significant. Taking together, the results show that lands that are more suitable for groundwater-based irrigation are occupied by wealthier and large-holder households.

Several other variables are controlled for in the regression. All three wealth variables, consumption expenditure, asset index and land holding size increased with farmer's access to (current use of) irrigation but the effects on asset index was not statistically significant. Access to irrigation was associated with 0.7% increase in consumption expenditure and the average land holding size was 0.15 hectare higher for irrigated households compared to non-irrigated households. This finding is consistent with the strand of literature that has shown positive impacts of irrigation development on poverty reduction (Namara et al., 2010; Passarelli et al., 2018). Among the control covariates, household size was positively correlated with asset index and land holding size but negatively correlated with per-capita consumption. Perhaps material wealth such as assets and land ownership increase with household size but the per-capita consumption expenditure decreases with it. Access to loan was negatively correlated with consumption or asset index but positively correlated with land holding size. Consumption expenditure and asset index also increased with household head's age, female headship, and education level. However, land holding size decreased with the head's age, female headship and education level.

---Table 6 about here---

Overall, results in Table 6 indicate that wealthier households were more likely to own land areas which are more suitable for groundwater irrigation. Distribution of consumption expenditure and asset index against the levels of groundwater irrigation suitability validate these econometric findings (Appendix figures A2 and A3). Results imply that if farmer-led irrigation development is primarily financed through private investment (i.e. the farmers themselves make the investment), this approach may further exacerbate economic inequality because land areas highly suitable for groundwater irrigation are also home to wealthier households. Marginal farmers who likely own small piece of land that is less suitable for irrigation development 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 calls for a need for tailored investment in small-scale irrigation that can minimize negative social and environmental impacts (Namara et al., 2010). Namara et al. (2010) suggests that for countries like Ethiopia, where abundant water resources are available but financial and institutional constraints have prevented people from accessing them, tailored investment in small-scale irrigation technologies is a way forward.

Involving private sector in providing credit and technical service has been tried but this does not entirely solve the problem of reaching the marginal farmers because these farmers do not have enough resource to use as collateral for loans. In addition, investment on farmer-led irrigation development for marginal farmers is way too risky for the private sector which is entirely profit driven. Even if collateral free credits are provided, in a bad crop season, marginal farmers have nothing else to make their installment payment for loan. One potential solution could be a hybrid model where farmers still drive the development/expansion of irrigation, but government provides subsidized pumps based on both land suitability for irrigation and socio-economic status of the farmers.

4.2. Irrigation suitability and crop choices

Table 7 presents the relationship between crop choices and irrigation suitability. Crops are grouped into two different categories: 1) high-value crops, and 2) staple crops. High-value crops consist vegetables, fruits, and cash crops. Staple crops consist cereals, root crops, legumes, and oilseeds. Panel random effects estimator was used to estimate the relationship between irrigation suitability and number of crops grown and the types of crops grown. Potential regional differences are taken care of by including regional dummies in the estimating model. Number of crops grown is used as a measure for crop diversification. Results show that farmers in land areas more suitable for irrigation were more diversified, cultivated more high value crops, and less staple crops. Specifically, one percent increase in irrigation suitability score was associated with about three more crops, 0.12% increase in the share of farmers growing high-value crops, and 0.14% decrease in the share of the producers of staple crops – cereals, root crops, legumes, and oilseeds.

---Table 7 about here---

Access to irrigation (current use of irrigation) was also positively associated with crop diversification. On average, one percent increase in irrigation coverage was associated with 1.2 more crops. It was also positively related with high-value crop cultivation but significantly negatively correlated with staple crop cultivation. This finding is consistent with the existing body of evidence that an improved access to irrigation is associated with increased cultivation of market oriented high-value crops such as fruits and vegetables (Garbero and Songsermsawas, 2018; Hagos et al., 2008). Our results go beyond that and show a positive association between land suitability for irrigation and crop choices. While improved access to irrigation may incentivize 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 in land areas highly suitable for 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 increased with household size, household's access to loan, household head's age, and literacy. However, it decreased with female headship and household head's education level. The probability of high value crop cultivation was lower for households with access to loan, migrant households, and household head's literacy but it increased with household size, female headship, and household head's education level. The opposite was true for the probability of staple crop cultivation. These findings indicate that households headed by females and more educated heads were less likely to grow more crops but more likely to grow high-value crops. Likewise, households that grow high value crops were less likely to have a migrant family member.

In Table 8, we disaggregate the high-value crops and staple crops categories into multiple sub-categories and estimate the relationship between groundwater irrigation suitability and probability of cultivation of different types of crops. Potential regional differences are taken care of by including regional dummies in the estimating model. Results confirm the finding in Table 7. Groundwater irrigation suitability was positively associated with cultivation of fruits, vegetables, and legumes but negatively correlated with cultivation of cereals, oilseeds, and root crops. On average, one percent increase in land suitability for groundwater irrigation was associated with 0.07% increase in fruit cultivation, 0.04% increase in vegetables, and 0.08% increase in legume cultivation but the same change in irrigation suitability was associated with 0.1% each decrease in both cereal and root crops cultivation. The magnitude of these effects is rather small, but a clear pattern emerges – land suitability for irrigation is positively correlated with cultivation of high-value crops and crop diversification.

--Table 8 here—

Statistics reported in appendix Table A6 support the findings in Table8. Most cereal cultivating households (58%) lived in the areas that were least suitable for irrigation. The share of cereal cultivating households in areas more suitable for groundwater irrigation was smaller, 38% in moderately suitable areas and 49% highly suitable areas. After cereals, the next three most cultivated crop types (cash crops, roots and tubers, and fruits) were mainly cultivated in the moderately suitable areas. In addition, more households cultivated vegetables in land areas highly suitable for groundwater irrigation (13%) than other suitability categories (10.8% and 7.7% respectively in land areas that are moderately and least suitable for groundwater irrigation).

5. Conclusions

This study examines the relationships between spatially assessed land suitability for irrigation and household wealth status, population density, and crop choices in Ethiopia. Three different types of data were used – spatial irrigation suitability maps based on prior work from literature, 2007 census data, and panel data from nationally representative LSMS-ISA survey. Land suitability for groundwater-based irrigation was acquired from Worqlul et al. (2017) and land suitability for solar irrigation (photovoltaic pumps to lift groundwater or surface water) was acquired from Schmitter et al. (2018). Given the multiple resolutions of data from different sources, the relationship between irrigation suitability and household wealth and crop choices was studied at household level, but analysis of population density and irrigation suitability was done at kebele level.

The main finding from this study show evidence of positive correlation between household wealth status (measured by consumption expenditure, household asset index, and land size) and groundwater irrigation suitability. Our results add to the rich set of existing body of evidence that has shown positive linkage between access to (use of) irrigation and poverty reduction. The results indicate that the positive linkage between irrigation and household wealth may simply be a manifestation of classic sorting because land areas that are more suitable for farmer-led irrigation are in fact occupied by wealthier households. In addition, we also found a positive association between crop choices (crop diversification and cultivation of high-value crops) and irrigation suitability. When households were categorized into agricultural (crop cultivators) and non-agricultural households, we found no discernible differences in irrigation suitability between the two groups. However, households that owned or cultivated land areas more suitable for groundwater-based irrigation cultivated more of high-value crops such as vegetables, fruits, and cash crops. Staple crops, however, were more common in land areas that were less suitable for groundwater irrigation.

Analysis of population density and irrigation suitability showed kebeles that were more suitable for groundwater irrigation also had higher population density, but kebeles that were more suitable for solar irrigation were less densely populated. This might have challenges when strengthening irrigation supply chains and services. Investment in solar irrigation technology supply chains and services targeted at relatively densely populated kebeles may encounter practical difficulties because such kebeles are not highly suitable for solar pump-based irrigation resulting in low demand.

Our results have important policy implications. First, policies that consider facilitating efforts of farmer-led irrigation expansion using shallow groundwater resources (including solar pumps) might want to look beyond spatial irrigation suitability. While spatial irrigation suitability is a critical first step, it is equally important to consider socio-economic characteristics of households and communities that are mapped suitable for farmer-led irrigation development. Second, any investments in groundwater irrigation development with no attention to economic well-being of households has a risk of elite capture because wealthier households tend to reside in areas that are also highly suitable for groundwater irrigation.

The findings suggest a need for combined public and private financing approaches to support wealthier and poor farmers in areas where irrigation development is suitable. Perhaps a program in which public support is provided in creating and or supporting the enabling environment for farmer-led irrigation to thrive (e.g. improved credit access, market access, local capacity building etc.) may be needed. This would complement private sector investments in strengthening of the irrigation supply chain and services (e.g. financial or repair services) in areas with high irrigation suitability. In addition, marginal farmers' access to irrigation can be improved by designing a hybrid model where farmers receive additional government subsidies based on both biophysical suitability for irrigation and socio-economic status.

If investment decisions are made considering both spatial irrigation suitability as well as socio-economic characteristics and existing agricultural practices, and the programs are tailored to the needs of specific target groups, such investments can help increase agricultural productivity, reduce poverty and food insecurity without increasing social inequality. In addition, tailored investments in farmer-led irrigation that take account both biophysical and socio-economic factors can be helpful in both adaptations to climate change and mitigation of adverse impacts of climate change on agriculture in Ethiopia.

Figures

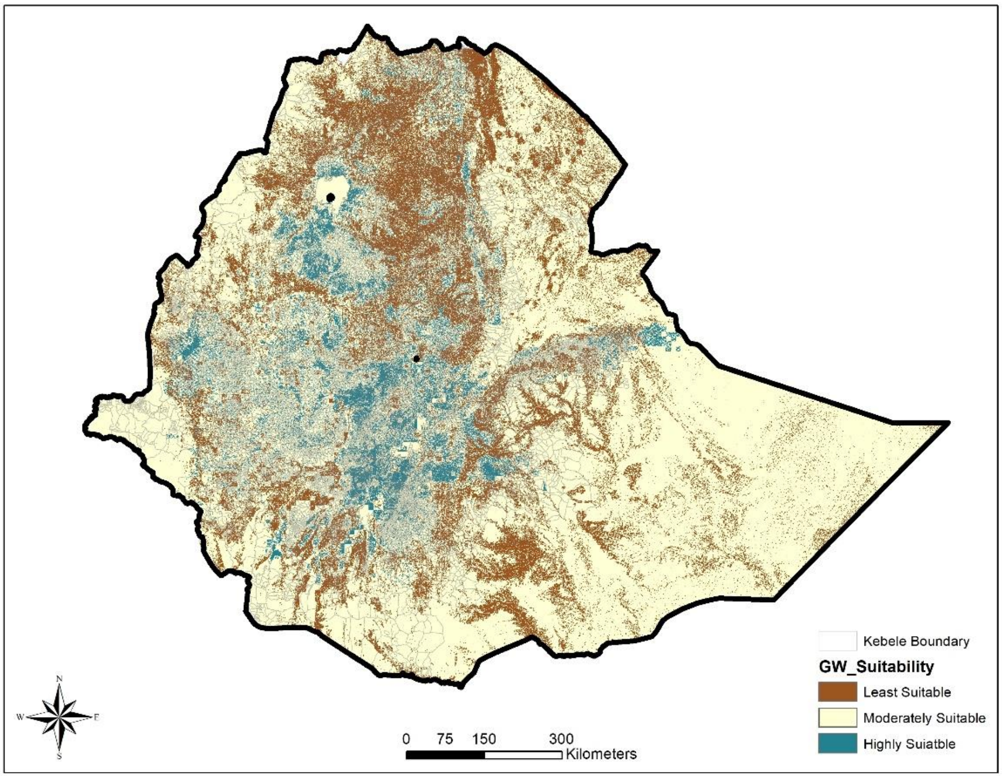

Figure 1. Mapping groundwater irrigation suitability in Ethiopia

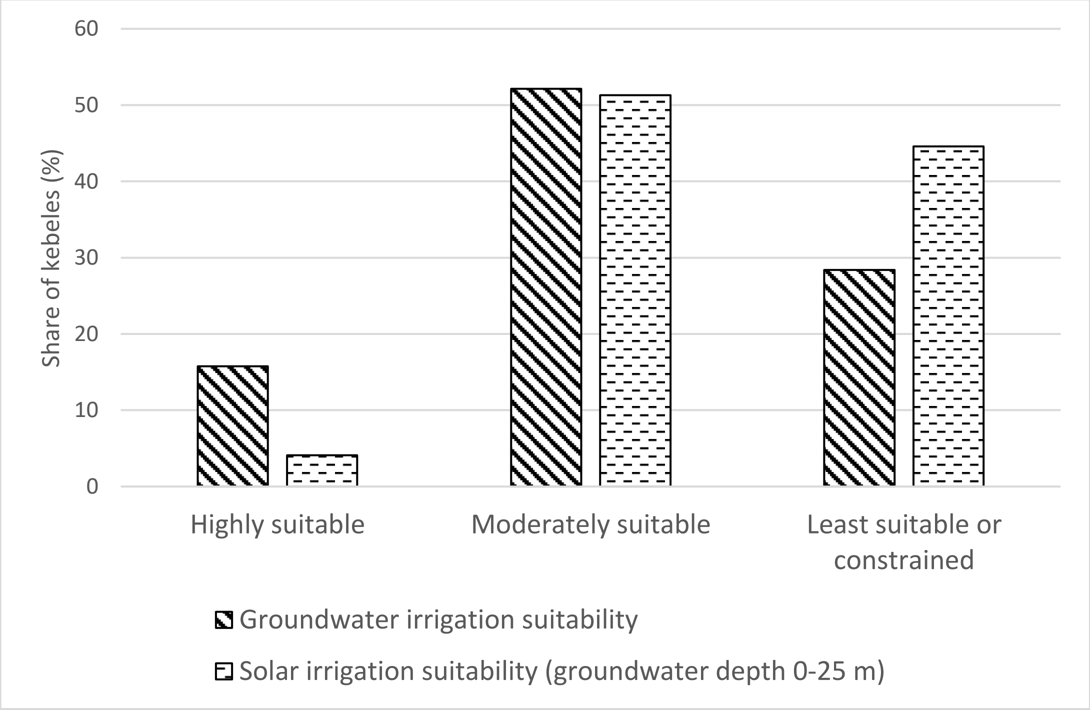

Figure 2. Share of kebeles (%) under different levels of irrigation suitability

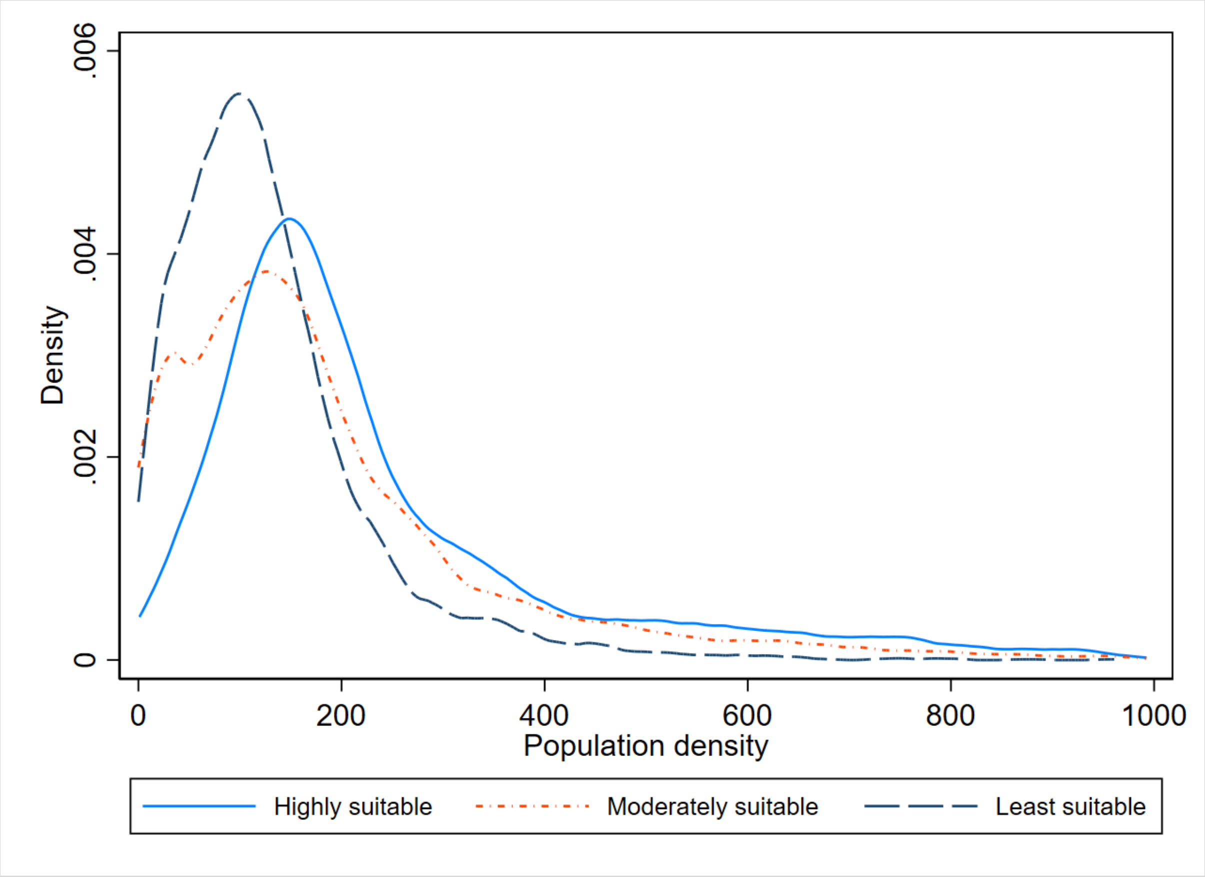

Figure 3. Distribution of population density across groundwater irrigation suitability areas

Tables

Table 1. Shares of matched kebeles between 2007 Census and groundwater irrigation suitability dataƗ, by region

Regions	**Census data**		**Groundwater irrigation suitability data**	
	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: ƗGroundwater 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.

Table 2. 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.

Table 3. Distribution of households and population across different categories of solar irrigation suitability

Solar irrigation suitability	Number of kebeles	Households per kebele	Population per kebele (,000)	Kebele-population density (per Sq Km)
Groundwater depth 0-25m				
Moderately suitable	6,527	885	4.28	212.16
Highly suitable	532	774	3.76	161.04
Groundwater depth 0-7m				
Moderately suitable	2,471	901	4.32	176.43
Highly suitable	822	803	3.91	166.78
Surface water				
Least suitable	7,338	849	4.13	203.92
Moderately suitable	323	1064	4.99	141.80
Highly suitable	641	1035	4.85	143.17

Notes: Three scenarios are different in terms of groundwater depth. The first two scenarios consider groundwater depth up to 25 m and 7 m, respectively but scenario 3 is about surface water only.

Table 4. Share of households (%) likely to benefit from investment in solar irrigation

	Scenarios			
	Groundwater up to 25 m	Groundwater up to 7 m	Small reservoirs and rivers	Number of households
Ethiopia	55.65	25.63	9.26	10,728,390
Regions				
Afar	8.40	8.08	0.92	188,023
Amhara	60.39	22.29	7.50	2,909,926
Benishangul-Gumuz	26.12	4.36	0.50	134,973
Gambella	46.82	31.50	-	46,007
Harari	92.56	92.56	68.76	15,181
Oromiya	58.35	32.98	6.91	4,167,860
SNNP	58.20	20.58	2.14	2,572,273
Tigray	28.42	21.28	60.32	694,147
Number of kebeles	**8,468**	**3,892**	**10,075**	

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. Households residing in kebeles that fall under the first three solar irrigation suitability categories – very highly suitable, highly suitable, and moderately suitable – are considered to likely benefit from investment in solar irrigation.

Table 5. Agricultural practices, irrigation status, and source of water by groundwater irrigation suitability

Variables	Full sample	*Groundwater irrigation suitability*		
		Highly suitable	Moderately suitable	Least suitable
Agricultural households and plots				
Share of agricultural households (%)	83.81	86.11	82.68	84.83
	(0.68)	(1.54)	(0.91)	(1.32)
Number of plots per household	9.30	10.69	9.05	8.93
	(0.14)	(0.36)	(0.18)	(0.26)
Plot size (Ha)	0.14	0.10	0.17	0.10
	(0.02)	(0.01)	(0.03)	(0.01)
Number of crops cultivated	6.08	6.55	6.24	5.39
	(0.07)	(0.18)	(0.10)	(0.13)
Primary crop type was high-value crops (%)	33.70	35.32	36.68	25.77
	(0.87)	(2.13)	(1.16)	(1.60)
Primary crop type was staple crops (%)	53.98	52.18	50.90	62.28
	(0.92)	(2.23)	(1.21)	(1.78)
Irrigation status				
Number of irrigated plots per household	0.19	0.21	0.18	0.19
	(0.02)	(0.04)	(0.02)	(0.04)
Households with at least one irrigated plot (%)	8.20	9.92	7.70	8.19
	(0.50)	(1.33)	(0.64)	(1.01)
Households with no irrigated plot (%)	91.80	90.08	92.30	91.81
	(0.50)	(1.33)	(0.64)	(1.01)
Number of households	**2,964**	**504**	**1,715**	**745**
Source of irrigation water				
River (%)	64.19	56.0	66.67	65.57
	(3.08)	(7.09)	(4.12)	(6.13)
Lake/pond (%)	6.17	10.0	3.03	9.84
	(1.55)	(4.29)	(1.49)	(3.84)
Rainwater harvest (%)	5.76	4.0	3.03	13.11
	(1.49)	(2.79)	(1.49)	(4.36)
Other/unspecified sourcesƚ (%)	24.0	30.0	27.27	11.48
	(2.77)	(6.66)	(3.92)	(4.11)
Number of households	**243**	**50**	**132**	**61**

Notes: Point estimates are weighted means; standard errors are in parentheses. ƚOther sources include boreholes, piped water, spring water, etc.

Table 6. Relationship between groundwater irrigation suitability and household wealth status (Panel random effects)

	(1)	(2)	(3)
	Log(consumption expenditure)	Asset index	Land size (Ha)
Groundwater irrigation suitability	0.15^{**}	0.067	0.21^{***}
	(0.074)	(0.24)	(0.057)
Current irrigation			
Access to irrigation	0.070^{*}	0.027	0.15^{***}
	(0.036)	(0.088)	(0.022)
Share of irrigated plots	0.055	0.26	-0.55^{***}
	(0.12)	(0.27)	(0.059)
Household characteristics			
Household size	-0.26^{***}	0.086^{***}	0.042^{***}
	(0.0044)	(0.013)	(0.0029)
Access to loan	-0.020	-0.088^{**}	0.013
	(0.015)	(0.035)	(0.0097)
Has one or more migrants	-0.044^{**}	0.056	0.0054
	(0.017)	(0.047)	(0.011)
Household head characteristics			
Age (years)	0.0023^{***}	0.0054^{***}	-0.00046
	(0.00060)	(0.0016)	(0.00038)
Female head	0.042	0.39^{***}	-0.13^{***}
	(0.027)	(0.082)	(0.015)
Married	-0.067^{**}	0.11	0.020
	(0.026)	(0.078)	(0.014)
Head can read or write	0.065^{***}	0.064	0.021
	(0.020)	(0.052)	(0.013)
Education level (grade)	0.035^{***}	0.19^{***}	-0.013^{***}
	(0.0027)	(0.012)	(0.0018)
Regional dummies	Yes	Yes	Yes
Constant	8.27^{***}	-1.07^{***}	-0.11^{**}
	(0.072)	(0.22)	(0.051)
Observations	**8,435**	**8,782**	**8,787**

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.

Table 7. Relationship between groundwater irrigation suitability and crop choices (Panel random effects)

	(1) Number of crops cultivated	(2) High-value crops	(3) Staple crops
Groundwater irrigation suitability	2.68***	0.12**	-0.14**
	(0.47)	(0.046)	(0.044)
Current irrigation			
Access to irrigation	1.22***	0.0034	-0.064**
	(0.18)	(0.029)	(0.029)
Share of irrigated plots	-0.80	0.16*	-0.17*
	(0.57)	(0.091)	(0.090)
Household characteristics			
Household size	0.14***	0.0093***	-0.0004
	(0.022)	(0.0024)	(0.0023)
Access to loan	0.14**	-0.030**	0.025**
	(0.068)	(0.011)	(0.010)
Has one or more migrants	0.14*	-0.039***	-0.0016
	(0.076)	(0.011)	(0.012)
Household head characteristics			
Age (years)	0.0054	0.0005	-0.0006*
	(0.0034)	(0.0004)	(0.0003)
Female head	-0.73***	0.024	-0.027*
	(0.14)	(0.016)	(0.014)
Married	0.26**	0.012	0.010
	(0.13)	(0.016)	(0.015)
Head can read or write	0.35***	-0.0018	-0.019
	(0.10)	(0.013)	(0.013)
Education level (grade)	-0.11***	0.011***	-0.0037**
	(0.018)	(0.0016)	(0.0015)
Regional dummies	Yes	Yes	Yes
Constant	1.38**	-0.18***	0.31***
	(0.69)	(0.042)	(0.040)
Observations	**7,015**	**8,787**	**8,787**

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.

Table 8. Relationship between groundwater irrigation suitability and choice of specific crops (Panel random effects)

	High value crops			Staple crops			
	Fruits	Vegetables	Cash crops	Cereals	Legumes	Oilseeds	Root crops
Groundwater irrigation suitability	0.073**	0.038	-0.021	-0.11**	0.081**	-0.027	-0.11***
	(0.031)	(0.034)	(0.041)	(0.053)	(0.029)	(0.018)	(0.033)
Current irrigation							
Access to irrigation	0.075***	-0.0072	0.012	-0.0051	-0.046***	-0.014	-0.028**
	(0.021)	(0.017)	(0.022)	(0.029)	(0.012)	(0.0091)	(0.013)
Share of irrigated plots	-0.042	0.038	0.13	-0.16*	-0.013	-0.0014	-0.031
	(0.063)	(0.056)	(0.087)	(0.088)	(0.031)	(0.021)	(0.044)
Household characteristics							
Household size	0.0054**	0.00005	-0.0006	-0.0011	0.00076	0.00019	-0.0026
	(0.0018)	(0.0019)	(0.0021)	(0.0028)	(0.0015)	(0.00091)	(0.0018)
Access to loan	-0.0095	-0.0023	-0.0009	-0.0058	0.019**	-0.0039	0.0059
	(0.0073)	(0.0085)	(0.0095)	(0.012)	(0.0079)	(0.0044)	(0.0081)
Has one or more migrants	-0.0021	0.0055	-0.0031	-0.027*	0.0084	0.017**	0.0024
	(0.0087)	(0.0098)	(0.011)	(0.015)	(0.0095)	(0.0062)	(0.0092)
Household head characteristics							
Age (years)	0.0008**	0.00014	0.0003	-0.0006	0.00014	-0.0002	-0.0002
	(0.0003)	(0.0003)	(0.0003)	(0.0004)	(0.00024)	(0.00014)	(0.0003)
Female head	-0.0052	0.040**	-0.020	0.0059	0.012	-0.017**	-0.0098
	(0.014)	(0.015)	(0.017)	(0.020)	(0.011)	(0.0070)	(0.015)
Married	-0.019	0.019	-0.0078	0.021	0.0017	-0.012	-0.0070
	(0.015)	(0.015)	(0.017)	(0.021)	(0.012)	(0.0076)	(0.015)
Head can read or write	0.0086	0.0074	0.0048	-0.0013	-0.0075	-0.0061	-0.00028
	(0.0097)	(0.010)	(0.012)	(0.015)	(0.0089)	(0.0054)	(0.0093)
Education level (grade)	0.0024	-0.0006	0.0069***	-0.006**	0.0009	0.000004	-0.0009
	(0.0016)	(0.0017)	(0.002)	(0.0023)	(0.0014)	(0.0008)	(0.0015)
Regional dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.025	0.035	0.15**	0.57***	0.045	0.088***	0.19***
	(0.035)	(0.036)	(0.045)	(0.063)	(0.032)	(0.023)	(0.040)
Observations	**4,847**	**4,847**	**4,847**	**4,847**	**4,847**	**4,847**	**4,847**

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.

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APPENDIX

Figures

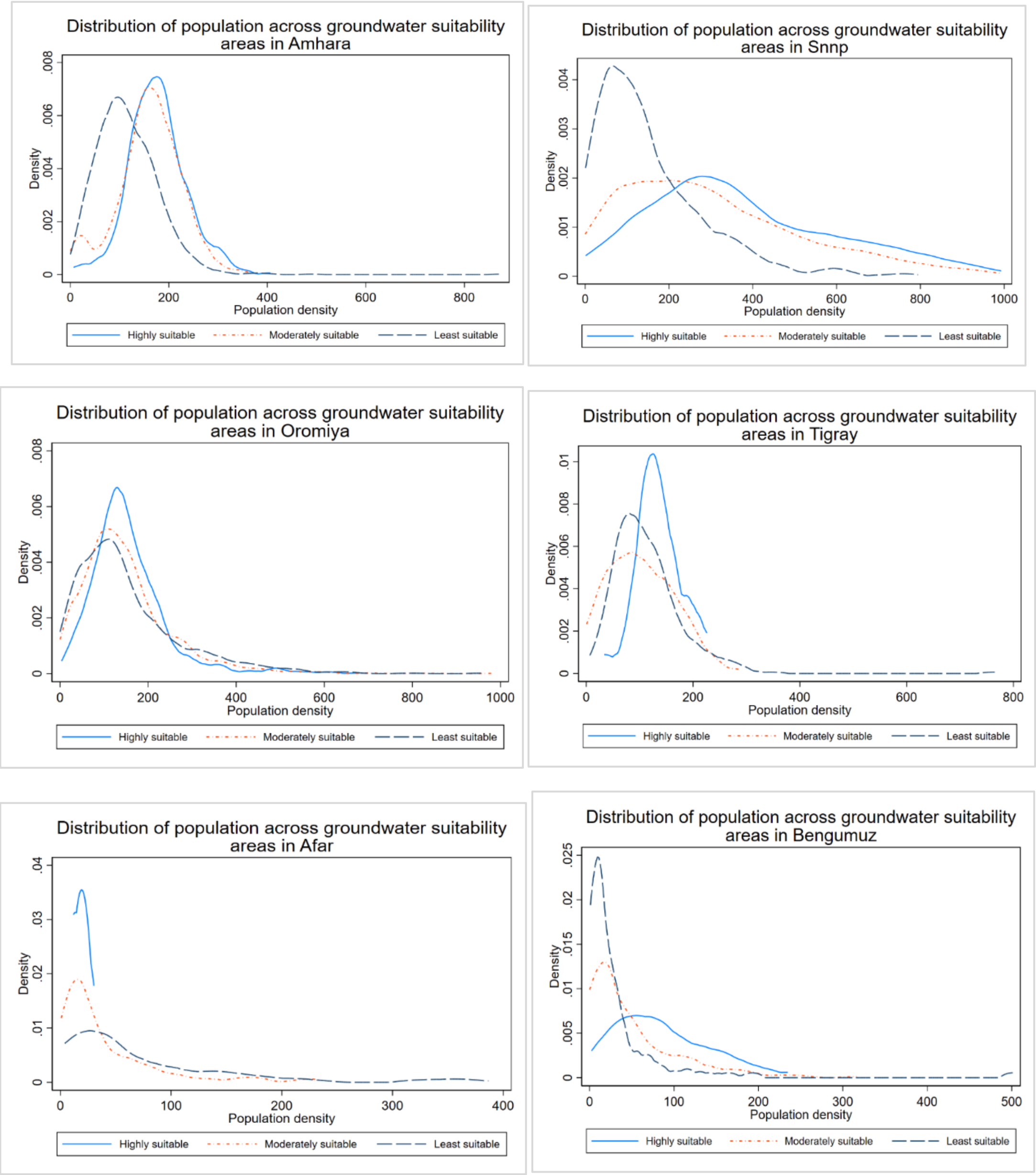

Figure A1. Distribution of population across groundwater irrigation suitability areas in Ethiopia, by regions

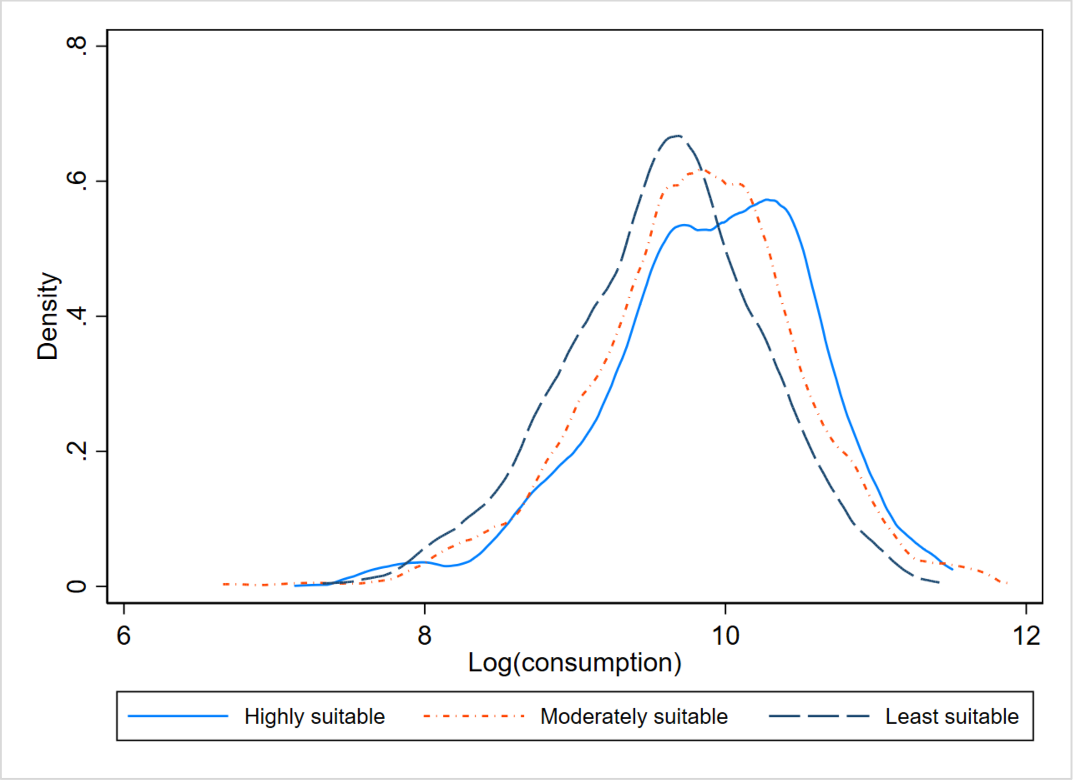

Figure A2. Distribution of household consumption by groundwater irrigation suitability

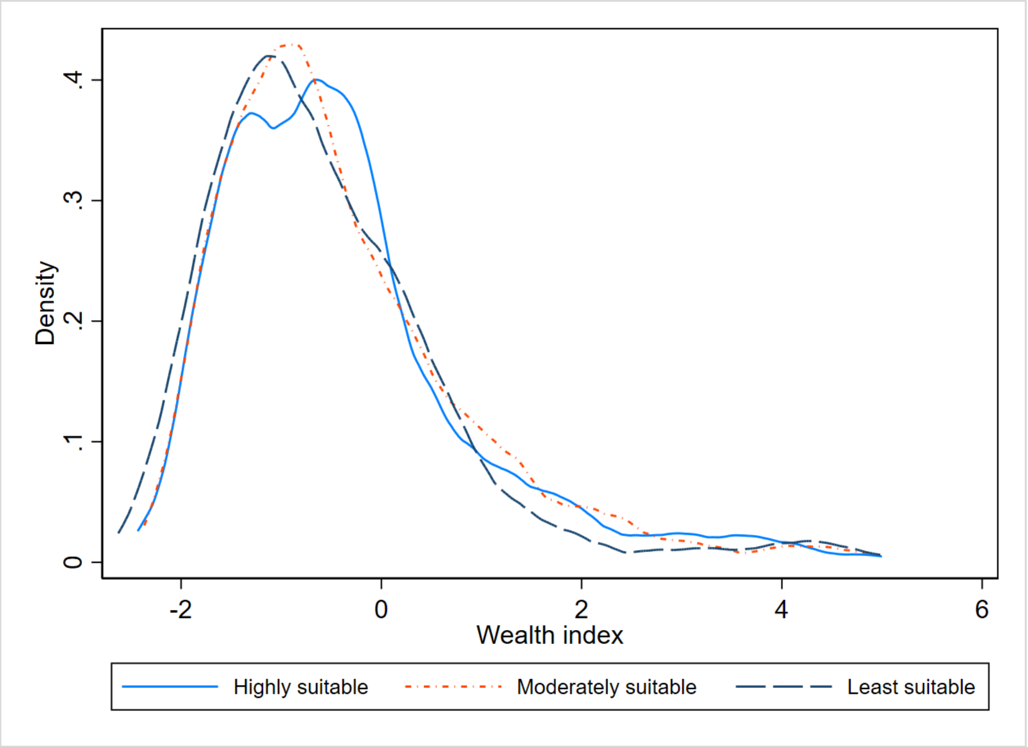

Figure A3. Distribution of household asset index by groundwater irrigation suitability

Tables

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 1km 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	**Scenario 1**	**Scenario 2**	**Scenario 3**
Solar irradiation (KWh/m2)	×	×	×
Slope (%)	×	×	×
Groundwater depth (0-7 m)	-	×	-
Groundwater depth (0-25 m)	×		-
Aquifer productivity (l/s)	×	×	-
Groundwater storage (mm)	×	×	-
Proximity to river (m)	-	-	×
Proximity to small reservoirs (m)	-	-	×
Proximity to roads (m)	×	×	×
Proximity to town (m)	×	×	×

Source: Schmitter et al. 2018

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

Data	Survey year		
	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, socioeconomic status, education, employment, consumption as well as detailed agriculture data.

Table A4. Shares of matched kebeles between 2007 census and solar irrigation suitability data, by region

Region	*Areas included in solar irrigation suitability mapping*			*Constrained area*	
	Matched (%)	Unmatched (%)	Number of kebeles	Number of kebeles	Share of total kebeles
Scenario 1					
Afar	86.84	13.16	38	296	88.62
Amhara	93.45	6.55	1,802	1,342	42.68
Bengumuz	91.79	8.21	134	287	68.17
Gambella	97.73	2.27	88	121	57.89
Harari	100	0	16	1	5.88
Oromiya	89.57	10.43	4,075	2,687	39.74
SNNP	90.57	9.43	2,141	1,647	43.48
Tigray	94.25	5.75	174	436	71.48
All regions	**90.87**	**9.13**	**8,468**	**6,817**	**44.60**
Scenario 2					

Afar	91.18	8.82	34	298	89.76
Amhara	95.09	4.91	631	2,426	79.36
Bengumuz	75	25	20	395	95.18
Gambella	96.43	3.57	56	153	73.21
Harari	100	0	16	1	5.88
Oromiya	89.9	10.1	2,207	4,353	66.36
SNNP	89.86	10.14	799	2,868	78.21
Tigray	93.8	6.2	129	479	78.78
All regions	**90.93**	**9.07**	**3,892**	**10,973**	**73.82**
Scenario 3					
Afar	83.72	16.28	43	293	87.20
Amhara	93.4	6.6	2,014	1,145	36.25
Bengumuz	93.63	6.37	267	160	37.47
Gambella	97.73	2.27	88	121	57.89
Harari	88.89	11.11	18	1	5.26
Oromiya	89.1	10.9	4,956	1,921	27.93
SNNP	91.02	8.98	2,249	1,539	40.63
Tigray	92.94	7.06	439	192	30.43
All regions	**90.72**	**9.28**	**10,075**	**5,372**	**34.78**

Notes: Three scenarios are different in terms of groundwater depth. Scenario 1 and scenario 2 consider groundwater depth up to 25 m and 7 m, respectively but scenario 3 is about surface water only. Schmitter et al. (2018) considers a large chunk of area as ‘constrained’ for solar irrigation and hence did not include in the study. The constrained area consists of 6,817 kebeles (44.6% of census kebeles) in scenario 1; 10,953 kebeles (73.8% of census kebeles) in scenario 2; and 5,372 kebeles (34.8% of census kebeles) in scenario 3.

Table A5. 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 (0-7 m)	0-7	NA	NA	NA	NA	>7
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 A6. Crop diversification and major crops grown in areas with different groundwater suitability

	Highly suitable	**Moderately suitable**	**Least suitable**	**Full sample**
Number of crops grown	6.55	6.23	5.35	6.06
	(3.71)	(3.79)	(3.19)	(3.65)
Crops types (%)				
Cereals	48.24	38.69	57.97	45.33
	(50.03)	(48.72)	(49.40)	(49.79)
Legumes	4.92	8.18	4.53	6.67
	(21.65)	(27.41)	(20.82)	(24.96)
Oilseed	1.41	1.28	2.34	1.58
	(11.78)	(11.25)	(15.14)	(12.46)
Spices	1.87	2.42	2.66	2.39
	(13.57)	(15.37)	(16.09)	(15.26)
Fruits	13.11	13.51	6.56	11.65
	(33.80)	(34.20)	(24.78)	(32.08)
Vegetables	12.88	10.81	7.66	10.35
	(33.54)	(31.06)	(26.61)	(30.47)
Cash crops	15.93	20.77	15.94	18.68
	(36.63)	(40.58)	(36.63)	(38.98)
Root and tubers	7.26	14.86	10.47	12.41
	(25.98)	(35.59)	(30.64)	(32.98)
Households	**427**	**1406**	**640**	**2473**

Notes: Point estimates are means. Standard deviations are in parentheses.