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Abstract

The climate change forecasts for Ethiopia predict higher temperature and rainfall and increased variability in rainfall with periodic severe droughts and floods. The increased weather variability poses a check on the extent of Ethiopia's agricultural transformation unless it is supported with improved agricultural water management such as irrigation to make smallholder farming resilient to adverse weather events. This study analyzes the role of irrigation on agricultural transformation in Ethiopia by systematically comparing households with irrigated and non-irrigated plots on key agricultural transformation and welfare indictors (i.e., intensification, commercialization, and consumption expenditures). The study used a representative data from the four main agriculturally important regions of the country and employed an endogenous switching regression approach that address potential biases from placement of irrigation schemes and the self-selection of farmers to adopt irrigation on their plots. The approach allows for counterfactual analysis on the effect of irrigation if it is adopted on plots or in households without current irrigation and the counterfactual realizations of outcome variables if irrigated plots were not irrigated or irrigating households were relying only on rainfed agriculture. The main results show a positive and significant effects of irrigation on intensification, commercialization, and household welfare. Specifically, the results show that farm households with irrigated plots: (i) use more fertilizer and agrochemicals; (ii) sold sizable share of their harvest; and (iii) spend more on food and non-food expenditures. The counterfactual analysis on what would have been the effect of irrigation on currently non-irrigated plots indicate a stronger result across our outcome indicators, suggesting further the importance of expanding irrigation in accelerating agricultural transformation and welfare improvement in Ethiopia.

Key words: *Irrigation, input intensification, commercialization, household expenditure, modern input uses, endogenous switching regression, Ethiopia*

1. Introduction

Ethiopia has experienced rapid economic growth in the last two decades, primarily driven by government investments in agriculture, infrastructure, and rural services, leading to substantial increases in cereal yields. Despite these gains, agricultural production is still predominantly characterized by traditional farming. It heavily relies on animal draft power with little mechanization, and under-application of productivity enhancing inputs like fertilizer, improved seed, and agrochemicals continues to be its main feature (Sheahan and Barrett 2017). Moreover, Ethiopia's agriculture is almost entirely dependent on rainfall, and exposed to frequent droughts and unreliable rain patterns, despite the country's potential to irrigate about 5.3 million hectares of land (Teshome and Zhang 2019; Suryabhagavan 2017; Fazzini et.al 2015; Awulachew 2010).

The last decade has seen significant momentum towards irrigation development in Ethiopia both in terms of policy focus and investment. Investment in irrigation was the major component of Government of Ethiopia's (GoE) second Growth and Transformation Plan (the five-year economic development plan between 2015 and 2020) and comprise the largest share (over one-third) of the total budget of US$582 million of the Ministry of Agriculture's Agricultural Growth Program (World Bank 2015, Passarelli et. al 2018, GoE 2015). Investment in irrigation continues to be GoE's priority after the 2018 political reform with greater emphasis on infrastructure, including water and irrigation schemes. For instance, In April 2018, the GoE has allowed duty-free imports of irrigation technologies (Ministry of Finance, 2018). Currently, there are at least 13 ongoing large-scale irrigation projects with a combined command area of more than 400,000 hectares.

Given these huge investments in irrigation and Ethiopia's efforts to transform its subsistence-based agriculture to high-input high-output agriculture with surplus production for markets, it is high time to analyze the role irrigation plays in agricultural transformation and welfare improvements in the country. Existing studies on the effect of irrigation so far have been limited to irrigation-specific surveys in three to five woredas/districts (Baye et. al 2019; Passarelli et al. 2018; Mekonnen et. al 2020). This study, therefore, aims to contribute to the incipient literature on the role of irrigation on agricultural transformation and household welfare using a large, representative, and longitudinal data from the four main agriculturally important regions of the country and with the following basic questions: (i) does irrigation increase the adoption of productivity enhancing inputs (i.e., fertilizer and agrochemicals)?; (ii) does irrigation increase smallholder farmers' market participation (as measured by share of marketed surplus)?; and (iii) does irrigation increase income (as measured by consumption expenditures)?

The results show a positive and significant effects of irrigation on intensification, commercialization, and household welfare. Specifically, the results show that farm households with irrigated plots: (i) use more fertilizer and agrochemicals; (ii) sold sizable share of their harvest; and (iii) spend more on food and non-food expenditures. The counterfactual analysis on what would have been the effect of irrigation on currently non-irrigated plots indicate a stronger result across our outcome indicators, suggesting further the importance of irrigation in accelerating agricultural transformation and welfare improvement in Ethiopia.

The remainder of the paper is organized as follows. Section 2 briefly reviews prior empirical evidence on the link between access to irrigation, agricultural transformation, and welfare. Section 3 presents data and descriptive statistics on the main outcome measures and all the variables accounted in the analysis. Section 4 discusses the empirical strategy (method) we used to identify/measure the direct effect of irrigation on agricultural intensification, commercialization, and welfare, followed by discussion of the results in Section 5. Section 6 briefly discuss the results, while section 7 concludes with the policy implications of the main findings.

2. Irrigation, agricultural transformation, and welfare

While the literature on the effects of irrigation on agricultural transformation and welfare gains is thin (based on small samples) in Ethiopian context, there is a strong evidence base on the role of irrigation on productivity growth and livelihood improvements from other counties. For instance, a study by Evenson et al. (1999) indicated public investment in irrigation as a key factor in agricultural productivity growth during the Indian Green Revolution. Song et al. (2018) also show that access to irrigation substantially improve crop yields by inducing greater use of complementary agricultural inputs in China. Small scale irrigation in particular is found to be a catalyst for agricultural intensification and productivity growth (Nakawuka et.al, 2018; Giordano and de Fraiture, 2014; Burney and Naylor, 2012; Burney et al., 2013; Dillon, 2011). Besides catalyzing intensification, irrigation also increase smallholder's productivity by extending production into dry season and by making smallholder farmers resilient to climate shocks or stressors and thereby ensure high crop yields (Bryan et al. 2019; Adamson et al., 2017).

The literature posits irrigation as a key farm-level factor that stimulate transition from subsistence to commercial farming through enabling farmers to participate in market-oriented production. For instance, a study from neighboring Kenya and Tanzania shows that more than three-quarters of crop grown in irrigated plots were commercialized (Nkonya et al.2011). Another study by Wickramasinghe (2015) found a positive and significant role of access to irrigation on maize farmers' market entry decision and on the volume of maize sales in Tanzania. Access to irrigation also facilitate participation to high value markets (Ola and Menapace, 2020; Ochieng et al., 2017).

The evidence on the impact of irrigation on welfare and income improvements is also compelling. For instance, a study by Dillon (2011) in Mali found that access to irrigation increases household consumption by about 30% relative to rainfed farmers and households with irrigation save more, are able to cope with shocks and risks, and engage in informal food sharing with non-irrigators. Studies also found that irrigation developments improve rural household income by increasing the frequency of harvest (production season) in a year and enlarging the land area allocated to high-value crops that are considered to be risky under rainfed conditions (Zaveri et al., 2020; Buisson and Balasubramanya, 2019; Singh, 2015; and Hagos et al., 2012). Several other studies that evaluate the introduction of treadle pump and small pump engines also found that adopters of irrigation technologies quickly transit out of poverty (Mangisoni, 2008; Barker et al. 1999; Shah et al. 2000; van Koppen and Mahmud 1996).

Irrigation is also seen as a viable adaptation strategy for agriculture to climate change and population pressure especially in Africa where food security is highly tenuous and easily disrupted (Adamson et al., 2017; Wiltshire et al., 2013; Maliwichi et al., 2012). All that said, the contribution of irrigation to productivity and income growth effectively materialize only when complementary inputs, rural extension services, and markets are available (You et al., 2011).

3. Data and descriptive statistics

3.1. Data description

The study uses data from the three household surveys conducted in 2012, 2016, and 2019 by Ethiopia Agricultural Transformation Agency (ATA) and the International Food Policy Research Institute (IFPRI). The total households interviewed in each survey round are 3000, 4991 and 5311, respectively. Table 1 presents the panel structure of the data: 1,899 households appeared in all the three rounds of the survey, 889 households were sampled in both the 2012 and 2016 rounds, 1,136 households in both the 2016 and 2019 rounds, and only 11 households were interviewed in both the 2012 and 2019 rounds. Over the three rounds of the survey, the number of household observations totals 13,302.

Table 1. Household panel structure of the data

Panel Structure	Survey year			
	2012	2016	2019	Total
Only in 2012	201	0	0	201
Only in 2016	0	1067	0	1067
Only in 2019	0	0	2265	2265
Only in 2012 & 2016	889	889	0	1778
Only in 2012 & 2019	11	0	11	22
Only in 2016 & 2019	0	1136	1136	2272
In all years (3-year panel)	1899	1899	1899	5697
Total	3000	4991	5311	13302

Source: Analysis of ATA datasets.

For the descriptive analysis we used the data from all the survey rounds, but the econometric analysis is based on the recent two survey rounds, since the 2012 round missed important plot level variables that are important for the irrigation analysis (e.g., slope of the plot, soil quality). Table 2 shows the share of households with irrigated plot and the main source of water. Close to 8% of sample households used irrigation in at least one of their parcels across the survey rounds. The source of water for irrigation is primarily surface water. Ground water use for irrigation purpose is very limited in the sampled households.

Table 2. Share of irrigating households over survey rounds

Survey rounds	Irrigating households?	Irrigation using surface water	Irrigation using ground water
2012	0.077	0.074	0.004
2016	0.084	0.076	0.009
2019	0.069	0.062	0.009
Total	0.077	0.070	0.008

Source: Analysis of ATA datasets.

3.2. Outcomes of interest

As indicated above, our main outcomes of interest include agricultural intensification, commercialization, and household welfare. We used fertilizer application and agrochemical intensities as measures of agricultural input intensification. Level of commercialization is measured as the share of harvest sold in the market. Household welfare is measured based on household's net crop income, daily food, and non-food expenditures.

Table 3 presents the descriptive statistics of our main outcome indicators by irrigation status. Input use indicators such as fertilizer, value of purchased seed and agrochemical applications indicate that there is a significant intensification of the inputs on irrigated plots than non-irrigated plots. On average, irrigators more than double fertilizer application per hectare, invest on purchased seeds 7.4 times higher per hectare, while the value of agrochemical application per hectare on irrigated plots is nearly thirteen-fold of those non-irrigated fields. These further translate into a significantly higher share of marketed crops (50% higher) of irrigators than non-irrigators.

Table 3. Descriptive statistics of outcome variables by irrigation status

Variables	N-non irrigators	N-Irrigators	Mean-Non-irrigators (a)	Mean-Irrigators (b)	Diff. (b-a)	Sign.
Plot level indicators						
Fertilizer (kg/ha)	45613	1714	71.20	175.69	104.49	***
Purchased seed (Birr/ha)	45613	1714	249.85	1856.61	1606.76	***
Agrochemicals (Birr/ha)	45613	1714	24.12	306.77	282.65	***
Household level indicators						
Share of crops sold (%)	10742	937	30.27	45.39	15.12	***
Net Crop Income (Birr)	10764	939	19492.54	32690.88	13200.00	***
Daily total food expenditure	10764	939	85.60	111.27	25.67	***
Daily total food and non-food expenditure	10764	939	108.71	141.53	32.83	***

Note: *** denotes statistical significance at 1% level.
Source: Analysis of ATA datasets.

Moreover, irrigators earn 67.7% more income net of all input costs (except family labor cost) than non-irrigators and this, in turn, implies a higher consumption of food and non-food items in the irrigator households. Specifically, on average, both daily total food expenditure and daily total food and non-food expenditure in irrigating households are higher at least by 30% than those of non-irrigators.

3.3. *Sample household characteristics by irrigation status*

We present summary statistics of household characteristics by irrigation status in Table 4. Irrigator households have, on average, more household members, greater number of oxen, and more trees on their plots. Besides tree planting, irrigator households are more likely to undertake other natural resource management (NRM) on their farm plots than non-irrigators. Irrigators are also found to have more years of education for the household head and the spouse of the head with higher maximum level of education completed by household members, are more likely to own cellphones which might help them to adopt irrigation technologies and access information easily.

Table 4. Descriptive statistics of sample household characteristics by irrigation status

Variables	N-non irrigators	N-Irrigators	Mean-Non-irrigators (a)	Mean-Irrigators (b)	Diff. (b-a)	Sign.
Household size	10764	939	5.90	6.14	0.24	***
Sex of head (1=male)	10764	939	0.90	0.92	0.02	*
Age of head (year)	10764	939	47.06	47.46	0.40	
Head's education (year)	10764	939	3.41	4.08	0.67	***
Spouse's education (year)	10764	939	1.14	1.53	0.39	***
Maximum education in the household (year)	10764	939	7.13	7.86	0.74	***
Farm size owned (ha)	10764	939	1.79	1.72	-0.07	
Own cellphone (1=yes)	10764	939	0.55	0.66	0.11	***
Number of oxen owned	8312	804	2.26	2.45	0.19	***
Credit access (1=yes)	10764	939	0.27	0.27	0.01	
Distance from river (km)	8376	720	7.99	7.37	-0.62	**
Distance from stream (km)	8376	720	14.48	11.93	-2.55	***
Time to market (minutes)	10759	939	67.45	71.76	4.31	**
Time to all-weather road	10378	913	65.14	54.05	-11.09	***
Time to tarmac road	8020	706	93.02	85.94	-7.08	**
Time to Woreda Admin center	10721	937	135.64	132.73	-2.91	
Manure on plot (kg)	45627	1714	129.38	116.08	-13.30	
Number of trees on plot	45627	1714	2.96	11.85	8.89	***
Other NRM on plot (1=yes)	45619	1714	0.45	0.52	0.07	***

Note: ***significant at 1%, **significant at 5%, *significant at 10%
Source: Analysis of ATA datasets.

Household's distance from water sources such as rivers and streams are crucially determining irrigation adoption. Irrigator households are found in a better proximity to rivers and streams relative to non-irrigators. Irrigator households also appear to live in areas relatively closer to all-weather roads and tarmac roads compared to non-irrigators, while their distance from woreda administrative center on average does not differ. On the contrary, non-irrigators are closer to weekly markets than irrigators. There is no observed significant difference in age of the head, farm size owned, credit access, and manure applications between irrigators and non-irrigators.

3.4. *Characteristics of irrigators and irrigated plots*

The analysis also shows that irrigation farms are very small in scale. The average size of irrigated parcels is around 0.5 hectares in *Belg*, the dry season in Ethiopia between February to June which provides 5-10% of cereal output in the country while irrigated land size averaged 0.4 hectare in *Meher,* the main rainy season from June to October that provides 90-95% of cereal output. The average size of rainfed parcels is about 2.4 hectares in the *Meher* season and 1.3 hectares in the *Belg* (small showers) season (Table 5).

Table 5. Parcel size by irrigation status

	Mean	N
Land size - irrigated – *Belg*	0.5	920
Land size - irrigated – *Meher*	0.4	261
Land size - rainfed – *Belg*	1.3	6,314
Land size - rained – *Meher*	2.4	12,421

Source: Analysis of ATA datasets.

Irrigated plots (and households with irrigated plots) show a higher level of agricultural intensification across all main productivity enhancing modern inputs. For instance, farmers use more of saved and purchased seeds on their irrigated plots than non-irrigated plots though the marginal seedling rates significantly differs. The use of own saved seed from previous harvest is higher by 37% in irrigated plots than on rainfed plots (100 Kg/ha vs. 73Kg/ha), while the use of newly purchased seed (a proxy measure for improved seed) on irrigated plot is more than four times the amount used on rainfed fields (Table 6). In monetary terms, on average, farmers spend 1857 Birr per hectare for the purchase of seed on irrigated plots while the average expenditure on non-irrigated plots amount 250 Birr per hectare on purchased seed.

Table 6. Irrigation and agricultural intensification - seeds

Variables	Non-Irrigators (a)	Irrigators (b)	Diff. (b-a)	Sign.
Saved seed (Kg/Ha)	72.92	100.13	27.21	***
Purchased seed (Kg/Ha)	25.14	116.67	91.54	***
Value of purchased seed (Birr/ha)	249.85	1856.61	1606.76	***
Number of obs.	45613	1714		

Note: *** denotes statistical significance at 1% level.
Source: Analysis of ATA datasets.

Fertilizer use per hectare on irrigated plots is more than threefold that of on rainfed plots, particularly for the two most common types of fertilizers in Ethiopia – Urea and DAP. Use of Urea fertilizer per hectare is 98 Kgs on irrigated plots and 30 Kgs on non-irrigated plots while the use of DAP fertilizer per hectare is 23 Kgs on irrigated plots and 9 Kgs on rainfed plots (Table 7). On the other hand, rainfed plots get more of the recently introduced NPS fertilizer compared to irrigated plots.

Table 7. Irrigation and agricultural intensification – fertilizers

Variables	Non-Irrigators (a)	Irrigators (b)	Diff. (b-a)	Sign.
UREA Kg/ha	29.89	98.47	68.58	***
DAP Kg/ha	8.99	22.60	13.61	***
NPS Kg/ha	32.32	54.62	22.30	***
Fertilizer cost (Birr/ha)	1076.56	2515.83	1439.27	***
Number of obs.	45613	1714		

Note: *** denotes statistical significance at 1% level.
Source: Analysis of ATA datasets.

By far the biggest difference between irrigated and rainfed plots on input intensification is on the use of agrochemicals. This is expected because the moisture from irrigation in an otherwise dry season changes the local ecology of pests and requires active pest management. As a result, the value of agrochemicals and spraying services used per hectare on irrigated plots is 50 times higher for pesticides, 9 times higher for insecticides, and 3.5 times higher for fungicides compared to rainfed plots (Table 8). In addition, the use of herbicides and spraying services per hectare is 2 times higher on irrigated plots compared to rainfed plots. Overall, the value of pesticides, herbicides, insecticides, and fungicides per hectare is more than 10 times than that on rainfed plots.

Table 8. Irrigation and agricultural intensification – agrochemicals

Variables	Non-Irrigators (a)	Irrigators (b)	Diff. (b-a)	Sign.
Value of pesticides and spraying services per Ha	7.62	379.38	371.76	***
Value of herbicides and spraying services per Ha	47.36	85.95	38.60	***
Value of insecticides and spraying services per Ha	4.64	43.06	38.41	***
Value of fungicides and spraying services per Ha	17.45	61.24	43.79	***
Value of all agrochemicals, per Ha	24.12	306.77	282.65	***
Number of obs.	45613	1714		

Note: *** denotes statistical significance at 1% level.
Source: Analysis of ATA datasets.

Overall, the descriptive statistics shows significant levels of intensification of input use for seeds, fertilizers, and agrochemicals, that translates itself to higher shares of marketed surplus, and higher levels of net crop income on an irrigated land. However, we cannot make conclusion at this point, since the descriptive statistics does not consider potential social, economic, and contextual confounding factors on the link between irrigation and our main outcomes of interest, a point we will focus on in the following sections.

4. Method: estimation strategy

Identification of causal effects to examine the impact of irrigation on intensification, commercialization, and other farm household welfare indicators is complex because of the often-non-random placement of irrigation schemes and the self-selection of farmers to adopt irrigation on their plots. In this study, we address the self-selection and endogeneity problem by using an endogenous switching regression approach where a full-information maximum likelihood (FIML) method simultaneously fits a binary selection equation (irrigated vs non-irrigated plots or irrigating vs non-irrigating households) and a second continuous equation on the impact of irrigation on outcome variables with corrections for the selection equation. The endogenous switching regression (ESR) approach acknowledges that irrigators and non-irrigators could be inherently different in observed and unobserved characteristics and estimates different response functions by irrigation status. In addition, the approach allows for counterfactual analysis on the effect of irrigation if it is adopted on plots or in households without current irrigation and the counterfactual realizations of outcome variables if irrigated plots were not irrigated or irrigating households were relying only on rainfed agriculture. The approach requires factors that affect irrigation decisions but not the outcome variables where we used distance from rivers and streams to instrument for irrigation status. The ESR estimation in this study closely follows those used by Kassie et al. (2020), Khonje et al. (2015), Shiferaw et al. (2014), Di Falco and Veronesi (2013), Teklewold et al. (2013), Asfaw et al. (2012), and Di Falco et al. (2011).

Formally, farmers' decision to irrigate can be modelled using a random utility framework. Let I* denote the difference between the utility from irrigation adoption (U_{i1}) and the utility from non-irrigation (U_{i0}) as shown by Khonje et al. (2015) and Shiferaw et al. (2014) for adoption decisions of agricultural technologies. The household will adopt irrigation if I*>0. U_{i1} and U_{i0} (and hence I*) are unobservable but can be expressed as a function of observable variables in the following latent variable model:

$$I_i^* = Z_i\alpha + v_i \quad with\ I_i = \begin{cases} 1 & if I_i^* > 0 \\ 0 & otherwise \end{cases} \qquad (1)$$

where I is an indicator variable that gets a value of 1 when irrigation is adopted and zero otherwise. Z is a vector of variables that determine the decision to adopt irrigation such as distance from rivers and streams, distance from cities and district/*woreda* centers, size of the plot, size of total land ownership in other plots, slope and soil quality of the plot and its distance from the homestead, season and year indicators, age and education of the household head, education of the spouse of the household head, maximum level of education in the household, and village/*kebele* fixed effects that account for time invariant observed and unobserved local factors that influence the decision to irrigate. For the household level estimations, plot level characteristics such as slope, soil quality, and distance from the homestead are replaced by their average across the different plots of the household. α is a vector of parameters to be estimated and v_i is the error term of the first stage irrigation decision equation.

Conditional on adoption of irrigation, the endogenous switching regression model estimates two different response functions as follows:

$$\text{Regime 1 (irrigation): } Y_{1i} = X_{1i}\beta_1 + \varepsilon_{1i} \quad if\ I_i = 1 \qquad (2a)$$

$$\text{Regime 0 (no-irrigation): } Y_{0i} = X_{0i}\beta_0 + \varepsilon_{0i} \quad if\ I_i = 0 \qquad (2b)$$

where Y_{1i} and Y_{0i} are values of the outcome variables for irrigated plots/households and non-irrigated pltos/households; X_{1i} and X_{0i} are vectors of explanatory variables that affect the outcome variables and include the explanatory variables *Z* in equation (1); β_1 and β_0 are parameters to be estimated showing different response functions in observations with and without irrigation; and ε_{1i} and ε_{0i} are the corresponding error terms of the equations.

Following Di Falco et al. (2011), Khonje et al. (2015), Shiferaw et al. (2014), and Asfaw et al. (2012), v_i, ε_{1i}, and ε_{0i} are assumed to have a trivariate normal distribution with zero mean and covariance **Ω**, where

$$\Omega = \begin{vmatrix} \sigma_v^2 & \rho_{v1} & \rho_{v0} \\ \rho_{1v} & \sigma_1^2 & \\ \rho_{0v} & & \sigma_0^2 \end{vmatrix} \qquad (3)$$

and σ_v^2 is the variance of the equation on irrigation status (equation 1); σ_1^2 and σ_0^2 are the variances of regime 1 and regime 0 in equation (2a) and (2b); $\rho_{v1} = \rho_{1v}$ is the covariance of v_i and ε_{1i}; $\rho_{v0} = \rho_{0v}$ is the covariance of v_i and ε_{0i}; and the covariances of ε_{1i} and ε_{0i} are empty since the same plot cannot be irrigated and non-irrigated at the same time. As shown in Di Falco (2011) and Khonje (2015), the error structure in Ω implies that the expected values of ε_{1i} and ε_{0i} conditional on sample selection (irrigation status) are non-zero. That is,

$$E(\varepsilon_{1i} | I_i = 1) = \rho_{1v} \frac{\phi(Z_i\alpha)}{\Phi(Z_i\alpha)} = \rho_{1v}\lambda_{1i} \quad \text{and} \qquad (5)$$

$$E(\varepsilon_{0i} | I_i = 0) = -\rho_{0v} \frac{\phi(Z_i\alpha)}{1 - \Phi(Z_i\alpha)} = \rho_{0v}\lambda_{0i}, \qquad (6)$$

where $\phi(.)$ and $\Phi(.)$ are the standard normal probability density function and the standard normal cumulative density function; and $\lambda_{1i} = \frac{\phi(Z_i\alpha)}{\Phi(Z_i\alpha)}$ and $\lambda_{0i} = -\frac{\phi(Z_i\alpha)}{1 - \Phi(Z_i\alpha)}$ are the inverse mills ratios calculated from the selection equation and will be included in (2a) and (2b) to correct for selection bias (Khonje et al. 2017). As Di Falco et al. (2011) showed, if the estimated $\widehat{\rho_{1v}}$ and $\widehat{\rho_{0v}}$ are statistically significant, then the decision to irrigate is correlated with the outcome variables on intensification, commercialization, income, and expenditure, which is an evidence for endogenous switching and rejection of the null hypothesis of the absence of sample selection bias. The log likelihood function to estimate the ESR using a full information maximum likelihood (FIML) method is provided in Di Falco et al. (2011).

The ESR estimation above provides four actual and counterfactual average treatment effects on the actual impact of irrigation on plots or households with irrigation, the counterfactual treatment effect if non-irrigated plots or households were to have irrigation, the counterfactual case where irrigated plots or households were to have no access to irrigation, and the actual case of non-irrigators without irrigation (Kassie et al. (2020), Khonje et al. (2015), Shiferaw et al. (2014), Di Falco and Veronesi (2013), Teklewold et al. (2013), Asfaw et al. (2012), and Di Falco et al. (2011)). These average treatment effects are further described below:

Effect of irrigation on irrigated plots or households (actual sample of irrigators with irrigation):

$$E(y_{1i}|\ I_i = 1; x) = X_{1i}\beta_1 + \rho_{1v}\lambda_{1i} \qquad \text{(7a)}$$

Average treatment effect on the untreated households (actual non-irrigators without irrigation):

$$E(y_{0i}|\ I_i = 0; x) = X_{0i}\beta_0 + \rho_{0v}\lambda_{0i} \qquad \text{(7b)}$$

Irrigators if they were not to irrigate (counterfactual):

$$E(y_{0i}|\ I_i = 1; x) = X_{1i}\beta_0 + \rho_{0v}\lambda_{1i} \qquad \text{(7c)}$$

Non-irrigators if they were to irrigate (counterfactual):

$$E(y_{1i}|\ I_i = 0; x) = X_{0i}\beta_1 + \rho_{1v}\lambda_{0i} \qquad \text{(7d)}$$

The average treatment effect on the treated (ATT) is the difference between (7a) and (7c):

$$\text{ATT} = E(y_{1i}|\ I_i = 1; x) - E(y_{0i}|\ I_i = 1; x)$$

$$= X_{1i}(\beta_1 - \beta_0) + \lambda_{1i}(\rho_{1v} - \rho_{0v}) \qquad \text{(8)}$$

The average treatment effect on the treated (ATU) is the difference between (7d) and (7b):

$$\text{ATU} = E(y_{1i}|\ I_i = 0; x) - E(y_{0i}|\ I_i = 0; x)$$

$$= X_{0i}(\beta_1 - \beta_0) + \lambda_{0i}(\rho_{1v} - \rho_{0v}) \qquad \text{(9)}$$

Following Kassie et al. (2020), Khonje et al. (2015), Shiferaw et al. (2014), Di Falco and Veronesi (2013), Teklewold et al. (2013), Asfaw et al. (2012), and Di Falco et al. (2011), we also compute base and transitional heterogeneities. The base heterogeneity for irrigation (BH1) shows whether irrigation would have differential impact on current irrigators compared to the counterfactual case that the current non-irrigators were to have access to irrigation. BH1 is computed as the difference between (7a) and (7d):

$$\text{BH1}= E(y_{1i}|\ I_i = 1; x) - E(y_{1i}|\ I_i = 0; x)$$

$$= (X_{1i} - X_{0i})\ \beta_1 + \rho_{1v}(\lambda_{1i} - \lambda_{0i}) \qquad (10)$$

Similarly, the other base heterogeneity (BH2) shows who would be better without irrigation if current irrigators and non-irrigators both were to be non-irrigators, and this is computed as the difference between (7c) and (7b):

$$\text{BH2}= E(y_{0i}|\ I_i = 1; x) - E(y_{0i}|\ I_i = 0; x)$$

$$= (X_{1i} - X_{0i})\beta_0 + \rho_{0v}(\lambda_{1i} - \lambda_{0i}) \qquad (11)$$

The transitional heterogeneity (TH) shows whether irrigation would have a higher impact on current irrigators compared to the counterfactual case that the current non-irrigators have access to irrigation. This is computed as the difference between ATT (equation 8) and ATU (equation 9).

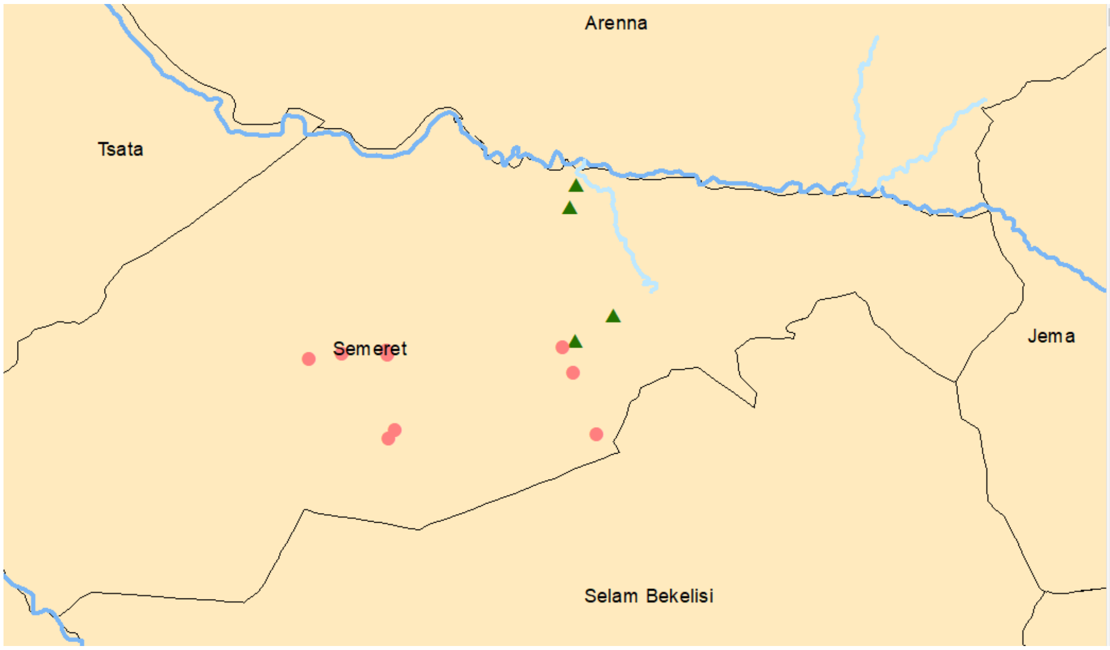
The ESR approach requires variables that affect the decision to irrigate (equation 1) but not the outcome variables in equations (2a) and (2b). We used households' distance from rivers and distance from streams (Figure 1), which are computed from Remote Sensing using the GIS coordinates of sampled households, as exogenous variables that influence adoption of irrigation but not the outcome variables of fertilizer and agrochemical intensification, share of crops sold, average daily food expenditure, average total food and non-food expenditure, and net crop income. A higher resolution images at local levels also indicate that irrigators tend to be located closer to rivers and streams. See Figure 2 for an example of

We argue that distance to rivers and streams affect the outcome only through their effect on irrigation but not directly by themselves once the irrigation decision is considered. Following (Kassie et al. (2020), Khonje et al. (2015), Shiferaw et al. (2014), Di Falco and Veronesi (2013), Teklewold et al. (2013), Asfaw et al. (2012), and Di Falco et al. (2011), we also did a simple falsification test on the validity of the distance to rivers and distance to streams variables as instruments for irrigation. If distance to rivers and streams affect the outcome variables only through their effect on irrigation, then the inclusion of these two variables in the irrigation (selection) equation should be statistically significant (i.e., they are important determinants of irrigation access) but these variables should not be statistically significant in the outcome variables once the irrigation variable is included as an explanatory variable in the regression of the outcome variables.

Figure 1. Distance from rivers and streams of sampled households in 2019

Note: Darker blue are rivers and lighter blue are streams.

Figure 2. Relative locations of irrigators and non-irrigators for sample enumeration area in Amhara region



Note: Darker blue are rivers and lighter blue are streams. The green tringles represent irrigators, and the red circles represent non-irrigators.

Table A1 in the appendix shows the results of this falsification test for plot level analysis. Distance to river and distance to streams are both statistically significant in the irrigation equation (column 2 of Table A1) while both are not statistically significantly different from zero in the estimations for fertilizer use per hectare, agrochemical use per hectare, and share of crops sold from the plot (columns 2, 3, and 4 in Table A1). Similarly, the two instruments are statically significantly different from zero in the household level irrigation estimation (where a household is defined as an irrigator if it has at least one irrigated plot) (column 2 of Table A2), but they are not statistically significant in the estimations for daily food expenditure, total food and non-food expenditure, and net crop income (columns 2, 3, and 4 in Table A2). The ESR model is estimated using the *movestay* command developed by Lokshin and Sajaia (2004). We pooled the data set of plots and households across the 2016 and 2019 survey rounds, control for several plot and household specific variables, and kebele fixed effects. Observations within a household are likely to be correlated with each other and hence we clustered standard errors at the household level.

5. Results

Table A3 and A4 in the appendix show the full set of results from the plot-level endogenous switching regression estimation for fertilizer use per hectare, agrochemical use per hectare, and share of harvest sold. Tables A5 and A6 in the appendix show results from the household level ESR estimations. Overall, the results show that farms further away from rivers and streams, with steep plots, further away from the homestead, and very fertile lands are less likely to be irrigated. In addition, plots in households whose head is aged and who have a greater number of oxen are less likely to be irrigated. Not surprisingly, a smaller number of plots are irrigated in the rainy season compared to the dry season. On the other hand, farm plots further away from the woreda center, are relatively bigger in size, and households with higher spousal education or bigger overall land ownership are more likely to be irrigated.

5.1. Irrigation and fertilizer use

The average treatment effects of irrigation use on fertilizer intensification are summarized in Table 9 below. The results show that irrigated plots use about 13Kgs per hectare more fertilizer because of irrigation. That is, out of the 29Kg difference in fertilizer use per hectare between irrigated and non-irrigated plots, about 45 percent can be ascribed to differences in irrigation use. In other words, irrigated plots are predicted to use about 114 Kg per hectare with irrigation and 101 Kgs per hectare if they were not irrigated, with an increase of 13Kgs per hectare due to irrigation. In the counterfactual case that currently non-irrigated plots were to be irrigated, then fertilizer use per hectare is expected to increase by about 51 Kgs on those plots. The heterogenous effect of irrigation on currently irrigated and non-irrigated plots (in the event the later were to be irrigated) amounts to about 37Kgs and is statistically significantly different from zero. On the other hand, if the currently irrigated plots were not to be irrigated, they would still use about 16 Kgs per hectare more than the currently non-irrigated plots. Similarly, if the currently non-irrigated plots were to be irrigated, they would have used about 22 Kgs more fertilizer per hectare compared to currently irrigated plots.

Table 9. Fertilizer use in Kg/ha at the plot level, predictions from ESR estimation

Subsamples	Regimes and counterfactuals		
	Irrigated	Non-irrigated	Treatment Effects
Irrigated plots	114.6***	101.3***	TT=13.3***
	(2.96)	(2.53)	(2.68)
Non-irrigated plots	136.3***	85.5***	TU=50.8***
	(1.35)	(0.82)	(1.12)
Heterogeneity effects	BH1= -21.7***	BH2= 15.9***	TH= -37.5***
	(3.26)	(2.66)	(2.90)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

5.2. Irrigation and use of agrochemicals

The average treatment effects of irrigation on agrochemical use per hectare are summarized in Table 10. The results show that farmers spend about 430 Birr more on agrochemicals per hectare on irrigated plots because of irrigation. The current cost of agrochemicals on non-irrigated plots (about 210 Birr per hectare) would have increased by about 956 Birr in the counterfactual case that these plots were irrigated. These results indicate that irrigation would lead to an even higher agrochemical use per hectare in currently non-irrigated plots compared to currently irrigated plots by about 526 Birr per hectare if the former were to be irrigated. The effect of irrigation on agrochemical uses in currently non-irrigated plots compared to the currently irrigated plots would have been higher by about 466 Birr per hectare if the former were to have irrigation. On the other hand, irrigated plots would have higher cost on agrochemicals (by about 59 Birr per hectare) even if they were not irrigated compared to the currently non-irrigated plots.

Table 10. Cost of agrochemicals (in Birr/ha) at the plot level, predictions from ESR estimation

Subsamples	Regimes and counterfactuals		
	Irrigated	Non-irrigated	Treatment Effects
Irrigated plots	699.3***	269.2***	TT=430.1***
	(44.96)	(9.27)	(42.50)
Non-irrigated plots	1165.8***	210***	TU=955.8***
	(19.29)	(3.29)	(18.91)
Heterogeneity effects	BH1= - 466.5***	BH2=59.2***	TH= - 525.8***
	(48.93)	(9.84)	(46.52)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

5.3. *Irrigation and purchased seed*

The average treatment effects of irrigation on cost of purchased seeds per hectare is provided in Table 11. The ESR estimation for cost of seeds per hectare did not converge in levels. Thus, the results in Table 11 are logarithmic transformations which helped the model to converge. The results are consistent with the findings for intensification of fertilizer and agro-chemicals. Farmers spend more per hectare on purchased seeds on irrigated plots compared to the counterfactual case that the plots were not irrigated. The current cost of purchased seed on non-irrigated plots would have increased significantly in the counterfactual case that those plots were irrigated. The result also indicates heterogenous treatment effects where the induced change on purchased seed because of irrigation would have been higher on currently non-irrigated plots (if they were to be irrigated) than the currently irrigated plots (compared to the case where they were not irrigated). The cost per hectare for purchased seed would have been higher on currently non-irrigated plots in the counterfactual case that those plots were irrigated compared to the currently irrigated plots. In addition, the non-irrigated plots would still have higher cost of purchased seed even if they were not irrigated compared the currently non-irrigated plots.

Table 11. Cost of purchased seed (in Birr/ha) at the plot level, predictions from ESR estimation in logarithmic transformations

Subsamples	Regimes and counterfactuals		
	Irrigated	Non-irrigated	Treatment Effects
Irrigated plots	3.0***	2.0***	TT=1.0***
	(0.07)	(0.05)	(0.07)
Non-irrigated plots	3.7***	1.6***	TU=2.1***
	(0.03)	(0.02)	(0.03)
Heterogeneity effects	BH1= - 0.7***	BH2=0.4***	TH= - 1.1***
	(0.07)	(0.05)	(0.07)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

5.4. *Irrigation and commercialization (share of crop sold)*

The average treatment effects of irrigation on commercialization (defined as the share of harvest sold from the amount produced on the plot) are summarized in Table 12. The results show that irrigation increases the share of crops sold on irrigated plots by 39 percentage points compared to what would have been sold on that plot from a harvest without irrigation. On currently non-irrigated plots, irrigation would have increased the share of produce sold by 27 percentage points if those plots were to be irrigated. The effect of irrigation on commercialization is higher on currently irrigated plots than currently non-irrigated plots (by about 12 percentage points) in the counterfactual case where the later had access to irrigation. If currently non-irrigated plots were to have irrigation, a higher share of produce would be sold from those plots compared to the currently irrigated plots (by about 8 percentage points). On the other hand, if the currently irrigated plots were not irrigated, they would have a lower share of produce sold to the market compared to the currently non-irrigated plots (by about 19 percentage points).

Table 12. Share of crops sold at the plot level, predictions from ESR estimation

Subsamples	Regimes and counterfactuals		
	Irrigated	Non-Irrigated	Treatment Effects
Irrigated plots	0.45***	0.07***	TT=0.39***
	(0.01)	(0.01)	(0.01)
Non-irrigated plots	0.53***	0.26***	TU=0.27***
	(0.00)	(0.00)	(0.00)
Heterogeneity effects	BH1= - 0.08***	BH2= -0.19***	TH= 0.12***
	(0.01)	(0.01)	(0.01)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

5.5. Irrigation and household welfare

We estimate the effect of irrigation on household welfare through its impact on household's daily food and total (food and non-food) expenditures and net crop income.

The average treatment effects of irrigation on daily food expenditure are summarized in Table 13. The results show that the effect of irrigation on average daily food expenditure is not statistically significantly different from zero compared to the counterfactual case that the household was not irrigating. On the other hand, the daily food expenditure of current non-irrigators would have increased by 136 Birr if they were to have irrigation, indicating heterogenous effects of irrigation on food expenditure on current irrigators and non-irrigators. If current non-irrigators were to become irrigators, their daily food expenditure would have been higher than current irrigators (by about 113 Birr). On the other hand, if current irrigators were to become non-irrigators, they would still have higher food expenditure compared to current non-irrigators (by about 20 Birr).

Table 13. Daily total food expenditure, predictions from ESR estimation

Subsamples	Regimes and counterfactuals		
	Irrigating	Non-Irrigating	Treatment Effects
Irrigators	140.9***	138.1***	TT=2.8
	(4.63)	(3.87)	(3.50)
Non-irrigators	254.1***	118.0***	TU=136.2***
	(3.04)	(2.2)	(2.51)
Heterogeneity effects	BH1= -113.2***	BH2= 20.2***	TH= -133.4***
	(5.54)	(4.45)	(4.31)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

The average treatment effects of irrigation on daily total (food and non-food) expenditure are summarized in Table 14. The results show that irrigation leads to an increase on total daily food and non-food expenditure (by about 9 Birr) compared to the counterfactual case that these households were non-irrigators. On the other hand, the daily total food and non-food expenditure of current non-irrigators would have increased by 147 Birr if they were to have irrigation. The effect of irrigation on total food and non-food expenditure is higher for current non-irrigators than current irrigators (by about 138 Birr) in the counterfactual case that the former became irrigators. If current non-irrigators were to become irrigators, their daily total food and non-food expenditure would have been higher than current irrigators (by about 116 Birr). On the other hand, if current irrigators were to become non-irrigators, they would still have higher food and non-food expenditure compared to current non-irrigators (by about 22 Birr).

Table 14. Daily total food and non-food expenditure, predictions from ESR estimation

Subsamples	Regimes and counterfactuals		
	Irrigating	Non-Irrigating	Treatment Effects
Irrigators	177.0***	167.9***	TT=9.2**
	(5.10)	(4.15)	(3.90)
Non-irrigators	293.0***	146.1***	TU=146.9***
	(3.36)	(2.38)	(2.82)
Heterogeneity effects	BH1= -116.0***	BH2= 21.8***	TH= -137.8***
	(6.11)	(4.78)	(4.82)

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

6. Discussions

Five general trends emerge in the econometric findings presented in the preceding section. First, irrigation leads to higher levels of input intensification for fertilizers, agro-chemicals, and purchased seeds compared to the level of intensification that would have been possible in the same plots without irrigation. This is presumably due to the strong complementarity between water and other production inputs.

Second, if the currently non-irrigated plots were to be irrigated, the level of input intensification would be much higher than even the currently irrigated plots, because of differences in the characteristics of currently irrigated and non-irrigated plots. These results indicate a central role irrigation can play in improving agricultural intensification and break the low-input low-output vicious circle in Ethiopia's agriculture. Though the mechanisms as to how irrigation leads to higher intensification of inputs are beyond the scope of this study, potential reasons include irrigation's ability to reduce risks from failed rains, its ability to facilitate the use of complementary inputs that can lead to better yields, its ability to expand the crop calendar into the dry season, and its provisions of moisture in an otherwise dry season that change the local ecology of pests and hence require active pest management.

Third, though currently irrigated plots have higher levels of intensification than currently non-irrigated plots, it is misleading to ascribe the entire difference in the levels of intensification to irrigation. That is, irrigated plots would have higher level of intensification even without irrigation compared to currently non-irrigated plots. For instance, there is a predicted difference of 29 Kg per hectare in fertilizer intensification between irrigated and non-irrigated plots, while irrigation is responsible for only about 13Kgs per hectare increase in fertilizer intensification on irrigated plots. Thus, studies that do not consider the inherent differences in irrigated and non-irrigated plots or irrigating and non-irrigating households are likely to overestimate the impact of irrigation on agricultural intensification.

Fourth, irrigation significantly increases commercialization of agricultural production in rural Ethiopia – a 39 percentage point increase in the share of crops sold compared to what would have been produced on those plots without irrigation. The higher levels of input use in irrigation, as well as the ability to supply the markets in dry seasons where prices are higher and competition from rain-fed farmers is less severe, appears to increase the market orientation of irrigators, both in terms of what is produced and how much of it is sold to the market. As such, irrigation holds the key in the transformation from subsistence to market-oriented production in Ethiopia.

Fifth, the increased intensification and commercialization of agriculture because of irrigation is shown to improve household welfare as measured by household expenditure. However, the impact of irrigation on household expenditure is found to be statistically significantly different from zero only when we include total non-food expenditure on food expenditure. The lack of statistically significant impact of irrigation on households' food expenditure is possibly because irrigation, with year-round production, reduces households' reliance on purchased food compared to non-irrigators.

Overall, the results provide the evidence base that irrigation is an important piece of the puzzle to bring about improved agricultural intensification, commercialization, and welfare improvements in Africa's agriculture. The role irrigation plays in transforming agriculture in Sub-Saharan Africa, in general, is getting a new traction after being neglected for about two decades in the 1990s and early 2000s. For instance, the Malabo Declaration and the Comprehensive Africa Agriculture Development Program (CAADP) recognize irrigation as one of the major pillars to end hunger and transform agriculture in Africa (Ringler et al. 2020). Investments in irrigation, however, do not seem to grow commensurate with this evidence or expressed interests of African governments and regional organizations. For instance, the annual World Bank lending for irrigation that reached more than 2 billion dollars in the late 1970 and early 1980s, has hovered around 200 million dollars in the early 2000s (both in 1990 constant prices) (Turral et al. 2011). Annual lending has increased a bit to about 700 million dollars and donors appear to be re-engaging in irrigation in recent years.

Governments and development partners can play a big role in making smart investments in irrigation, which will have at least the following four pillars. First, it needs to be inclusive of all scales of operation such as large-scale irrigation, community managed systems, small-scale irrigation, and farmer-led irrigation as they all have different implications for food security, foreign exchange earnings, nutritional improvements, and environmental impacts. Second, it needs to change the build-neglect-rebuild modes operandi of past investments in irrigation to one that builds, maintains, and sustains irrigation infrastructures. Third, investments in physical irrigation infrastructures such as dams and canals need to be accompanied by investments in the institutional and governance aspects of the systems to improve sustainability of the infrastructures. Fourth, investments in irrigation need to involve the private sector in a manner that builds on the appropriate roles and strengths of both the public and private actors.

7. Conclusions

Despite its huge potential, the contribution of irrigation to Ethiopia's agricultural development has been very limited. While the number of smallholder farmers with access to irrigation are estimated at 1.3 million, the current share of irrigated crop area (a widely used measure of irrigation development) within private smallholders is limited to 1.4% (CSA, 2020). This represents only about 4% of the country's estimated 5.3 million hectares of potentially irrigable land.

The startling divergence between irrigation potential and utilization has been the subject of policy discussions in the recent decade, which results in a significant impetus towards irrigation development in the country both in expressed commitment and actual investment. For instance, the current 10 years development plan of the country placed irrigation as a main catalyst for accelerated agricultural transformation. In terms of investment, there are at least 13 ongoing large-scale irrigation development projects with a combined command area of more than 400,000 hectares (close to twice the current size of irrigated area by smallholder farmers). The government has also recently allowed duty-free imports of irrigation technologies to encourage small-scale irrigation development.

Given the renewed interest on irrigation development, it is high time to rigorously assess and quantify the contribution of irrigation to agricultural transformation and welfare improvements based on the realized gains on irrigated plots (by irrigators). This study generated empirical evidence along this line through systematically comparing irrigator and non-irrigator households on key agricultural transformation and welfare indictors using representative and longitudinal household data from the four main agriculturally important regions of Ethiopia.

Overall, the results from our analysis strongly corroborated the existing evidence that shows a positive role of irrigation on agricultural intensification, commercialization, and welfare (in neighboring and Asian countries). Specifically, our results clearly show that farm households with irrigated plots are more likely to use complementary Green Revolution technologies (i.e., fertilizer, improved seed, and agrochemicals), sale large share of their production, and generate relatively higher income (as measured by their food and non-food consumption expenditure). The counterfactual analysis on what would have been the effect of irrigation on currently non-irrigated plots also indicate a positive and statistically significant results across our intensification, commercialization, and welfare indicators.

The positive effect of irrigation on intensification indeed indicates its catalytic role in agricultural transformation through its influence on: (i) the scope for using inputs like fertilizer and improved seed due to the strong complementarity between water and other inputs; and (ii) the effectiveness/efficacy with which different inputs of production are used. Similarly, the relatively high level of commercialization among irrigators indicates the role irrigation can play in accelerating the transition from subsistence farming to commercial farming through increasing frequency of production (and thereby increasing surplus production) and creating opportunities for cultivating high value crops that can be risky under rainfed conditions. The positive effect of irrigation on total (food and non-food) consumption expenditure also indicates the overall income gains from more intensified and commercialized farming.

Altogether the results from this study imply that the economic and welfare gains from utilizing irrigation potentials through planned irrigation development is enormous in Ethiopia. That said, it is worth mentioning that different scales of irrigation development such as large-scale irrigation, community-managed systems, small scale irrigation, and farmer-led irrigations have different implications on food and nutrition security, foreign exchange earnings, staple vs cash crop production, and environmental health that require careful considerations in investment decisions on irrigation development.

References

Adamson, D., Loch, A. and Schwabe, K., 2017. Adaptation responses to increasing drought frequency. Australian Journal of Agricultural and Resource Economics, 61(3), pp.385-403.

Asfaw, S., Shiferaw, B., Simtowe, F., Lipper, L., 2012. Impact of modern agricultural technologies on smallholder welfare: Evidence from Tanzania and Ethiopia, Food Policy, Volume 37, Issue 3.

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

Baiphethi, M. N., & Jacobs, P. T. (2009). The contribution of subsistence farming to food security in South Africa. *Agrekon*, *48*(4), 459-482.

Barker, R., & Kappen, B. C. (1999). *Water scarcity and poverty*. Colombo, Sri Lanka: International Water Management Institute.

Baye, K., J. Choufani, D. K. Mekonnen, E. Bryan, C. Ringler, J. K. Griffiths, and E. Davies. 2019. Irrigation and women's diet in Ethiopia: A longitudinal study. IFPRI Discussion Paper, 1864. Washington, DC: International Food Policy Research Institute (IFPRI).

Bryan, E.; Chase, C.; Schulte, M. 2019. Nutrition-sensitive irrigation and water management. World Bank, Washington, DC. 34p.

Buisson, M.C. and Balasubramanya, S., 2019. The effect of irrigation service delivery and training in agronomy on crop choice in Tajikistan. *Land Use Policy*, *81*, pp.175-184.

Burney, J.A., Naylor, R.L. (2012). Smallholder irrigation as a poverty alleviation tool in Sub-Saharan Africa. World Dev. 40 (1), 110–123.

Burney, J.A., Naylor, R.L., Postel, L.S. (2013). The case for distributed irrigation as a development Priority in sub-Saharan Africa. Proc. Natl. Acad. Sci. USA 110 (31), 12513–12517.

Central Statistical Agency (CSA). 2020. Report on Farm Management Practices (Private Peasant Holding). Statistical Bulletin, Addis Ababa.

Chenery, H. B., Robinson, S., Syrquin, M., & Feder, S. (1986). *Industrialization and growth* (p. 175). New York: Oxford University Press.

De Fraiture, C., & Giordano, M. (2014). Small private irrigation: A thriving but overlooked sector. *Agricultural Water Management*, *131*, 167-174.

Di Falco, S., Veronesi, M. and Yesuf, M., 2011. Does Adaptation to Climate Change Provide Food Security? A Micro-Perspective from Ethiopia. Amer. J of Ag. Econ., 93: 829-846.

Di Falco, S., & Veronesi, M., 2013. How Can African Agriculture Adapt to Climate Change? A Counterfactual Analysis from Ethiopia. *Land Economics, 89*(4), 743-766.

Dillon, A., 2011. Do differences in the scale of irrigation projects generate different impacts on poverty and production?. *Journal of Agricultural Economics*, *62*(2), pp.474-492.

Dillon, A., 2011. The effect of irrigation on poverty reduction, asset accumulation, and informal insurance: Evidence from Northern Mali. *World Development*, *39*(12), pp.2165-2175.

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. Global Food Security, 6, 24–33.

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: A review. *Global Food Security*, *6*, 24-33.

Evenson, R.E., Pray, C., Rosegrant, M., 1999. Agricultural research and productivity growth in India. Research Report Number 109, International Food Policy Research Institute, Washington, DC.

Fazzini, M., Bisci, C., & Billi, P. (2015). The climate of Ethiopia. In *Landscapes and landforms of Ethiopia* (pp. 65-87). Springer, Dordrecht.

Fuglie, K.O., 2008. Is a slowdown in agricultural productivity growth contributing to the rise in commodity prices? Agric. Econ. 39, 431–441.

Fuglie, K.O., Rada, N.E., 2013. Resources, Policies, and Agricultural Productivity in Sub-Saharan Africa Economic Research Report Number 145. Economic Research Service, United States Department of Agriculture, Washington, DC.

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

Government of Ethiopia (GoE), 2015. Growth and Transformation Plan II (GTP II). 2015/16 – 2019/20. National Planning Commission.

Hagos, F., Jayasinghe, G., Awulachew, S.B., Loulseged, M. and Yilma, A.D., 2012. Agricultural water management and poverty in Ethiopia. *Agricultural Economics*, *43*, pp.99-111.

Hussain, I. (Ed.) (2004). Poverty in irrigated agriculture in developing Asia: Issues, linkages, options and pro-poor interventions, Indonesia. Colombo, Sri Lanka: IWMI. 231p. (Country report Indonesia)

IFAD ((International Fund for Agricultural Development) (2015). Rural poverty in Africa. http://www.ruralpovertyportal.org/region/home/ tags/africa.

IFAD (International Fund for Agricultural Development) (2011). Rural Poverty Portal. http://www.ruralpovertyportal.org/web/guest/region/home/tags/africa.

Kassie, M., Fisher, M., Muricho, G., Diiro, G., 2020. Women's empowerment boosts the gains in dietary diversity from agricultural technology adoption in rural Kenya, Food Policy, Volume 95, 2020,

Khonje, M., Manda, J., Alene, A. D., Kassie, M., 2015. Analysis of Adoption and Impacts of Improved Maize Varieties in Eastern Zambia, World Development, Volume 66, Pages 695-706.

Koppen, B. V., & Mahmud, S. (1996). *Women and water pumps in Bangladesh: the impact of participation in irrigation groups on women's status*. Intermediate Technology Publications Ltd (ITP).

Kuznets, S., 1973. Modern economic growth: findings and reflections. Am. Econ. Rev. 63 (3), 247_258.

Lewis, A.W., 1954. Economic development with unlimited supplies of labor. Manchester Sch. 22 (2), 139_191.

Lewis, A.W., 1954. Economic development with unlimited supplies of labor. Manchester Sch. 22 (2), 139_191.

Lokshin, M., and Sajaia, Z., 2004. Maximum likelihood estimation of endogenous switching regression models. The Stata Journal 4(3), 282-289.

Maliwichi LL, Oni SA, Obadire OS (2012). “An investigation into the factors affecting food availability, choices and nutritional adequacy of smallholder farming households under irrigation and dryland farming in Vhembe district of Limpopo, province, South Africa”. Afr. J. Agric. Res. 7(25):3653-3664.

Mangisoni, J. H. (2008). Impact of treadle pump irrigation technology on smallholder poverty and food security in Malawi: a case study of Blantyre and Mchinji districts. *International Journal of Agricultural Sustainability*, *6*(4), 248-266.

Mekonnen, D., J. Choufani, E. Bryan, C. Ringler, and B. Haile (2020). Unpublished. Irrigation improves WHZ-scores of children under five, WDDS, and HDDS in Ethiopia and Tanzania, with stronger effects in households who reported drought shocks.

Nakawuka et al (2018). A review of trends, constraints, and opportunities of smallholder irrigation in East Africa.

Ochieng, D.O., Veettil, P.C., Qaim, M. (2017). Farmers’ preferences for supermarket contracts in Kenya. Food Policy 68, 100–111.

Ola, O., & Menapace, L. (2020). A meta-analysis understanding smallholder entry into high-value markets. *World Development*, *135*, 105079.

Ola, O., & Menapace, L. (2020). Smallholders' perceptions and preferences for market attributes promoting sustained participation in modern agricultural value chains. *Food Policy*, *97*, 101962.

Passarelli, S., D. Mekonnen, E. Bryan, and C. Ringler. 2018. Evaluating the Pathways from Small-Scale Irrigation to Dietary Diversity: Evidence from Ethiopia and Tanzania. Food Security, 10 (4): 981–97.

Pingali, P. L., & Rosegrant, M. W. (1995). Agricultural commercialization and diversification: processes and policies. *Food policy*, *20*(3), 171-185.

Rao, E. J., & Qaim, M. (2011). Supermarkets, farm household income, and poverty: insights from Kenya. *World Development*, *39*(5), 784-796.

Rao, E. J., Brümmer, B., & Qaim, M. (2012). Farmer participation in supermarket channels, production technology, and efficiency: the case of vegetables in Kenya. *American Journal of Agricultural Economics*, *94*(4), 891-912.

Rao, E.J.O., Brümmer, B., Qaim, M. (2012). Farmer participation in supermarket channels, production technology, and efficiency: the case of vegetables in Kenya. Am. J. Agric. Econ. 94 (4), 891–912.

Ringler, C.; Mekonnen, D. K.; Xie, H., and Uhunamure, A. M. 2020. Irrigation to transform agriculture and food systems in Africa South of the Sahara. In 2020 Annual trends and outlook report: Sustaining Africa's agrifood system transformation: The role of public policies. Resnick, Danielle; Diao, Xinshen; and Tadesse, Getaw (Eds). Chapter 6, Pp. 57-70. Washington, DC, and Kigali: International Food Policy Research Institute (IFPRI) and AKADEMIYA2063.

Romer, P. M. (1994). The origins of endogenous growth. *Journal of Economic perspectives*, *8*(1), 3-22.

Shah, T., Alam, M., Kumar, M. D., Nagar, R. K., & Singh, M. (2000). Pedal Pump and the Poor: Social impact of a manual irrigation technology in South Asia.

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, *67*, 12-25.

Shiferaw, B., Kassie, M., Jaleta, M., Yirga, C., 2014. Adoption of improved wheat varieties and impacts on household food security in Ethiopia, Food Policy, Volume 44, Pages 272-284.

Signorelli, S., Haile, B., and Kotu, B. (2017). Exploring the agriculture-nutrition linkage in northern Ghana. IFPRI Discussion Paper 1697. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Singh, A., 2015. Land and water management planning for increasing farm income in irrigated dry areas. *Land Use Policy*, *42*, pp.244-250.

Song, C., Liu, R., Oxley, L. and Ma, H., 2018. The adoption and impact of engineering-type measures to address climate change: evidence from the major grain-producing areas in China. *Australian Journal of Agricultural and Resource Economics*, *62*(4), pp.608-635.

Suryabhagavan, K. V. (2017). GIS-based climate variability and drought characterization in Ethiopia over three decades. *Weather and climate extremes*, *15*, 11-23.

Teshome, A., & Zhang, J. (2019). Increase of extreme drought over Ethiopia under climate warming. *Advances in Meteorology*, *2019*.

Teklewold, H., Kassie, M. and Shiferaw, B., 2013. Adoption of Multiple Sustainable Agricultural Practices in Rural Ethiopia. Journal of Agricultural Economics, 64: 597-623.

Timmer, C. Peter. "Agriculture and Pro-Poor Growth: An Asian Perspective." *Asian Journal of Agriculture and Development* 5, no. 1362-2016-107692 (2008): 1-29.

Tittonell, P., Giller, K.E. (2012). When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res.143, 76–90.

Turral, H., Burke, J. J., & Faurès, J. M. (2011). Climate change, water, and food security. Rome, Italy: Food and Agriculture Organization of the United Nations.

Wickramasinghe, U. (2015). Production specialization and market participation of smallholder agricultural households in developing countries. In *Sustainable Economic Development* (pp. 349-367). Academic Press.

Wiggins, S., 2009. Can the smallholder model deliver poverty reduction and food security for a rapidly growing population in Africa? In: Proceedings of the Expert Meeting on How to feed the World in 2050. Food and Agriculture Organization of the United Nations, Economic and Social Development Department. http://m.rrojasdatabank.info/ak982e00.pdf.

Wiltshire AJ Kay G, Gornall JL, Betts RA (2013). The Impact of Climate, CO2 and Population on Regional Food and Water Resources in the 2050s. Sustainability 5:2129-2151.

World Bank. (2015). International development association project appraisal document to the Federal Democratic Republic of Ethiopia for a second agricultural growth project.

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.

Zaveri, E.D., Wrenn, D.H. and Fisher-Vanden, K., 2020. The impact of water access on short-term migration in rural India. Australian Journal of Agricultural and Resource Economics, 64(2), pp.505-532.

Appendix: Supplementary tables

Table A1. Plot level of estimation with instruments as regressors for all outcome variables

Variables	(2) parcel irrigated	(3) fertilizer	(4) agrochemicals	(5) share of crop sold
Parcel irrigated		1.013***	0.797***	0.122***
		(0.153)	(0.266)	(0.024)
Distance from a river (km)	-0.021**	0.058	-0.090	-0.018*
	(0.011)	(0.064)	(0.115)	(0.011)
Distance from a stream (km)	-0.016*	-0.055	0.028	-0.006
	(0.010)	(0.070)	(0.117)	(0.011)
Distance from a small city (km)	-0.004	0.028	-0.049	-0.019*
	(0.008)	(0.084)	(0.099)	(0.011)
Distance from a 20K population city	0.025	0.019	0.292	0.021
	(0.026)	(0.205)	(0.275)	(0.028)
Distance from woreda center (km)	0.001	-0.119***	-0.150***	-0.014***
	(0.003)	(0.037)	(0.048)	(0.005)
Plot size (ha)	0.006			0.021***
	(0.004)			(0.004)
Land size less the plot (ha)	0.002**	0.004	0.038***	0.010***
	(0.001)	(0.008)	(0.011)	(0.001)
Household size	-0.004	0.165**	0.008	-0.035***
	(0.008)	(0.076)	(0.091)	(0.010)
Age of the head	0.005	-0.413***	-0.403***	-0.007
	(0.012)	(0.112)	(0.139)	(0.013)
Number of oxen	-0.019**	0.157***	0.199**	0.031***
	(0.009)	(0.060)	(0.078)	(0.008)
2019 survey round	-0.005	-0.104*	0.771***	0.013*
	(0.005)	(0.061)	(0.067)	(0.007)
Meher season	-0.221***	0.250***	-0.137	-0.070***
	(0.020)	(0.079)	(0.108)	(0.018)
Slope (medium)	-0.013**	-0.057	0.057	-0.007
	(0.006)	(0.054)	(0.068)	(0.007)
Slope (steep)	-0.023***	-0.068	0.034	-0.005
	(0.005)	(0.084)	(0.097)	(0.011)
Sex of head of household	0.002	-0.044	-0.184	-0.022*
	(0.010)	(0.098)	(0.129)	(0.011)
Education of head	-0.000	-0.007	0.015	0.003***
	(0.001)	(0.008)	(0.011)	(0.001)
Maximum education in household	0.002*	0.008	-0.006	
	(0.001)	(0.009)	(0.013)	
Education of spouse	0.001	0.007	0.007	0.003**
	(0.001)	(0.011)	(0.012)	(0.001)
Household owns cell phone	-0.005	0.093	0.128	0.008
	(0.007)	(0.064)	(0.081)	(0.008)
Parcel distance (quantile 2)	-0.024**	0.387***	0.427***	0.027***
	(0.010)	(0.068)	(0.086)	(0.008)
Parcel distance (quantile 3)	-0.016*	0.499***	0.599***	0.055***
	(0.009)	(0.068)	(0.088)	(0.009)
Parcel distance (quantile 4)	-0.029***	0.441***	0.437***	0.048***
	(0.010)	(0.072)	(0.094)	(0.009)
Parcel distance (quantile 5)	-0.046***	0.472***	0.609***	0.060***
	(0.010)	(0.086)	(0.109)	(0.011)
Soil quality (average)	-0.018***	-0.082	-0.054	-0.005
	(0.005)	(0.066)	(0.078)	(0.008)
Soil quality (good)	0.008	-0.089	-0.165**	0.014**
	(0.008)	(0.055)	(0.067)	(0.007)
Constant	0.213**	2.537***	1.573	0.562***
	(0.106)	(0.853)	(1.086)	(0.124)
Kebele fixed effects	Yes	Yes	Yes	Yes
Observations	29,529	29,529	29,529	29,529
R-squared	0.284	0.307	0.393	0.196

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

Table A2. Household level estimation with instruments as regressors for all outcome variables

Variables	(2) Irrigation	(3) food expenditure	(4) Total food and non-food expenditure	(5) Net crop income
Household irrigating		1.494	12.543*	0.406***
		(1.555)	(6.608)	(0.070)
Distance from a river (km)	-0.031***	-0.205	-1.435	0.012
	(0.008)	(1.073)	(4.412)	(0.046)
Distance from a stream (km)	-0.019*	-0.864	-4.160	0.076
	(0.010)	(1.310)	(5.379)	(0.056)
Distance from a small city (km)	0.021*	1.352	-0.659	-0.010
	(0.011)	(1.478)	(6.076)	(0.063)
Distance from a 20K population city	-0.036	4.938	-3.013	-0.160
	(0.025)	(3.211)	(13.213)	(0.137)
Distance from woreda center (km)	-0.004	-1.577***	-4.431*	-0.003
	(0.004)	(0.567)	(2.419)	(0.026)
Size of land owned (ha)	0.024***	2.770***	5.572**	0.745***
	(0.004)	(0.566)	(2.412)	(0.026)
Household size	0.011	10.011***	54.253***	0.043
	(0.008)	(1.087)	(4.556)	(0.048)
Age of the head	0.014	4.908***	14.200**	-0.102
	(0.012)	(1.561)	(6.521)	(0.068)
Number of oxen	0.001	3.652***	19.970***	0.353***
	(0.006)	(0.831)	(3.519)	(0.037)
2019 survey round	-0.005	9.856***	95.644***	0.893***
	(0.006)	(0.827)	(3.668)	(0.040)
Sex of head of household	0.002	-3.650***	0.501	0.193***
	(0.011)	(1.398)	(5.836)	(0.061)
Education of head	0.002**	0.292**	0.261	0.006
	(0.001)	(0.128)	(0.542)	(0.006)
Education of spouse	0.003***	0.485***	0.590	0.007
	(0.001)	(0.163)	(0.686)	(0.007)
Maximum education in household	0.001	0.655***	1.595***	0.000
	(0.001)	(0.136)	(0.576)	(0.006)
Household owns cell phone	0.010	6.679***	13.452***	0.099**
	(0.007)	(0.870)	(3.695)	(0.039)
Average slope	-0.013**	-1.959**	-6.416*	-0.069*
	(0.006)	(0.789)	(3.362)	(0.036)
Average soil quality	0.006	-0.309	8.949***	0.076***
	(0.004)	(0.493)	(2.109)	(0.022)
Average distance of plots	0.001	0.003	1.522	-0.018
	(0.002)	(0.289)	(1.231)	(0.013)
Cost of seed		0.220	-0.815	-0.032***
		(0.148)	(0.631)	(0.007)
Cost of fertilizer		0.006	0.687	-0.013*
		(0.173)	(0.737)	(0.008)
Cost of hired labor		0.752***	2.744***	0.007
		(0.123)	(0.527)	(0.006)
Cost of agrochemicals		0.732***	2.880***	0.010
		(0.176)	(0.751)	(0.008)
Constant	0.058	-29.228**	-121.986**	6.526***
	(0.103)	(13.517)	(55.797)	(0.581)
Kebele fixed effects	Yes	Yes	Yes	Yes
Observations	7,268	7,268	7,268	7,268
Number of hhs	4,868	4,868	4,868	4,868

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

Table A3. Endogenous switching regression for fertilizer and agrochemical intensification

VARIABLES	Fertilizer use per hectare			Agrochemical use per hectare		
	Irrigated plot	Non-irrigated plots	Irrigation status	Irrigated plot	Non-irrigated plots	Irrigation status
Distance from a small city (km)	-0.168	14.503*	0.234	35.262	-72.734	0.231
	(34.179)	(8.157)	(0.201)	(534.532)	(56.973)	(0.200)
Land size less the plot (ha)	-2.229	-20.351***	0.004	-1,103.732***	-41.842	0.003
	(11.247)	(5.506)	(0.082)	(335.197)	(31.458)	(0.082)
Number of oxen	-5.084	13.720**	-0.258**	752.242*	35.585	-0.263**
	(15.143)	(5.627)	(0.117)	(399.091)	(29.423)	(0.117)
2019 survey round	36.682	10.357*	-0.005	396.234	210.149***	0.008
	(24.125)	(5.522)	(0.080)	(439.188)	(54.421)	(0.079)
season==Meher	11.756	40.076**	-1.608***	318.663	-69.263	-1.604***
	(39.148)	(16.340)	(0.117)	(306.278)	(126.906)	(0.117)
Sex of head of household	25.651	16.761*	-0.013	1,853.682	64.411	-0.010
	(39.288)	(9.068)	(0.208)	(1,336.766)	(42.470)	(0.209)
Education of head	0.681	-0.602	-0.002	-68.770	-2.552	-0.003
	(2.175)	(1.091)	(0.017)	(43.171)	(6.841)	(0.017)
Education of spouse	0.560	0.860	0.039**	-25.036	-9.332	0.038*
	(3.446)	(1.321)	(0.020)	(59.300)	(8.738)	(0.020)
Maximum education in household	-3.576	0.786	0.016	75.135	8.037	0.017
	(3.037)	(1.503)	(0.019)	(66.922)	(11.326)	(0.019)
Household owns cell phone	-36.634	11.482	-0.112	-168.365	40.532	-0.114
	(26.838)	(7.006)	(0.121)	(418.273)	(46.602)	(0.121)
Parcel distance (quantile 2)	3.703	-13.442	-0.466***	852.541**	-37.541	-0.465***
	(26.266)	(9.304)	(0.152)	(413.609)	(39.051)	(0.153)
Parcel distance (quantile 3)	38.527*	-2.963	-0.417***	23.636	-41.307	-0.418***
	(20.649)	(8.458)	(0.128)	(239.628)	(48.446)	(0.129)
Parcel distance (quantile 4)	12.663	-7.144	-0.664***	493.476	50.373	-0.653***
	(28.499)	(9.874)	(0.141)	(392.563)	(53.004)	(0.141)
Parcel distance (quantile 5)	62.663	1.265	-0.999***	1,450.278*	150.524	-0.980***
	(41.181)	(12.934)	(0.162)	(764.312)	(102.672)	(0.161)
Soil quality = average	14.193	-3.492	-0.532***	-582.736	-46.236	-0.530***
	(44.552)	(9.304)	(0.166)	(553.625)	(43.156)	(0.166)
Soil quality=good	21.818	0.794	0.118	-564.426	-92.030**	0.116
	(29.256)	(7.523)	(0.121)	(396.614)	(46.348)	(0.122)
Distance from a 20K population	-31.164	25.414	0.426	-1,702.821*	-1.837	0.439
city	(82.432)	(33.279)	(0.472)	(996.086)	(113.892)	(0.470)
Distance from woreda center (km)	24.678	-11.650	0.114	508.401	-47.169*	0.108
	(17.943)	(9.857)	(0.073)	(595.895)	(24.137)	(0.074)
Household size	10.662	-11.298	0.022	-1,065.290	-62.073	0.019
	(32.492)	(13.827)	(0.153)	(1,266.880)	(57.970)	(0.154)
Age of the head	-71.632	-29.209	0.305	-1,059.558	-233.725**	0.293
	(46.110)	(21.151)	(0.232)	(1,384.564)	(92.240)	(0.233)
slope==Medium	43.642*	-10.473*	-0.192	-361.686	-50.351	-0.190
	(26.067)	(5.965)	(0.121)	(242.310)	(41.090)	(0.122)
slope==Steep	39.727	-20.097**	-0.848***	689.334	-100.934**	-0.851***
	(40.764)	(8.646)	(0.181)	(554.272)	(43.767)	(0.181)
Distance from a river (km)			-0.157**			-0.150**
			(0.075)			(0.076)
Distance from a stream (km)			-0.232			-0.241
			(0.149)			(0.148)
Constant	232.728	64.172	-1.365	5,945.825*	1,369.915**	-1.328
	(292.604)	(111.609)	(1.865)	(3,575.832)	(657.118)	(1.860)
Kebele fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
lns1			5.026***			7.777***
			(0.017)			(0.010)
lns2			4.928***			6.782***
			(0.001)			(0.000)
r1			-0.120			-0.078
			(0.236)			(0.220)
r2			0.121**			0.006
			(0.058)			(0.029)
Observations	8,132	8,132	8,132	8,122	8,122	8,122

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level. Source: Analysis of ATA datasets.

Table A4. Endogenous switching regression for commercialization of production

	(1)	(2)	(3)	(4)	(5)	(6)
	Cost of purchased seed (Birr/hectare)				Crop share sold	
VARIABLES	Irrigated plot	Non-irrigated plots	Irrigation status	Irrigated plot	Non-irrigated plots	Irrigation status
Distance from a small city (km)	-0.241	0.404**	0.323	-0.056	-0.013	0.280
	(0.936)	(0.181)	(0.231)	(0.094)	(0.020)	(0.204)
Distance from a 20K population city	-0.655	-1.138**	0.463	0.039	-0.028	0.345
	(2.526)	(0.525)	(0.566)	(0.140)	(0.058)	(0.498)
Distance from woreda center (km)	-0.447	-0.079	0.186**	-0.035	-0.012	0.140*
	(0.537)	(0.089)	(0.080)	(0.039)	(0.009)	(0.074)
Land size less the plot (ha)	-0.574**	-0.104	0.057	-0.008	0.017*	-0.001
	(0.284)	(0.077)	(0.080)	(0.016)	(0.010)	(0.081)
Household size	0.197	0.386**	0.015	-0.124***	-0.049***	0.059
	(0.649)	(0.188)	(0.152)	(0.041)	(0.018)	(0.140)
Age of the head	-2.002**	-0.251	0.298	-0.157**	0.001	0.197
	(0.840)	(0.242)	(0.250)	(0.073)	(0.028)	(0.255)
Number of oxen	0.239	-0.208	-0.225*	0.017	0.028*	-0.276**
	(0.503)	(0.132)	(0.117)	(0.063)	(0.017)	(0.116)
2019 survey round	0.231	0.285***	0.024	0.043	0.023*	0.025
	(0.573)	(0.109)	(0.084)	(0.034)	(0.012)	(0.074)
Meher season	0.354	-1.044**	-1.462***	0.121	0.047	-1.355***
	(0.488)	(0.485)	(0.120)	(0.239)	(0.077)	(0.183)
Medium slope	-0.400	0.008	-0.114	0.033	0.002	-0.128
	(0.456)	(0.151)	(0.122)	(0.069)	(0.014)	(0.104)
Steep slope	-0.021	-0.127	-0.833***	-0.043	0.037*	-0.829***
	(0.740)	(0.205)	(0.212)	(0.193)	(0.022)	(0.240)
Sex of head of household	1.332	-0.169	0.040	0.064	-0.023	0.148
	(0.848)	(0.205)	(0.220)	(0.058)	(0.018)	(0.225)
Education of head	0.027	0.032*	-0.001	-0.009**	0.002	-0.005
	(0.059)	(0.019)	(0.018)	(0.004)	(0.002)	(0.016)
Education of spouse	0.035	0.040	0.049**	-0.009	-0.001	0.033
	(0.073)	(0.029)	(0.022)	(0.008)	(0.003)	(0.027)
Maximum education in household	-0.023	-0.039**	0.012	0.010*	0.002	0.009
	(0.072)	(0.020)	(0.020)	(0.006)	(0.002)	(0.017)
Household owns cell phone	-0.782	0.161	-0.162	0.005	0.009	-0.093
	(0.479)	(0.136)	(0.127)	(0.038)	(0.014)	(0.117)
Parcel distance (quantile 2)	0.473	-0.485**	-0.455***	0.116*	0.037	-0.403*
	(0.598)	(0.190)	(0.168)	(0.060)	(0.023)	(0.207)
Parcel distance (quantile 3)	-0.613	-0.515***	-0.291**	0.051	0.089***	-0.384***
	(0.469)	(0.175)	(0.138)	(0.066)	(0.020)	(0.141)
Parcel distance (quantile 4)	-0.558	-0.707***	-0.645***	0.025	0.105***	-0.563***
	(0.663)	(0.193)	(0.158)	(0.088)	(0.024)	(0.209)
Parcel distance (quantile 5)	0.557	-0.754***	-0.859***	0.100	0.096***	-0.920***
	(0.742)	(0.225)	(0.164)	(0.158)	(0.029)	(0.236)
Soil quality = average	-0.569	-0.322**	-0.590***	0.083	0.026	-0.486**
	(0.849)	(0.151)	(0.193)	(0.158)	(0.019)	(0.200)
Soil quality=good	0.327	-0.161	0.132	0.000	0.018	0.051
	(0.381)	(0.131)	(0.129)	(0.026)	(0.013)	(0.139)
Crop group = Pulses	-0.867**	-0.518***	-0.631***	0.155	0.103***	-0.614***
	(0.441)	(0.194)	(0.149)	(0.213)	(0.027)	(0.194)
Crop group = Oilseeds	-0.665	-0.016	-0.538***	0.607**	0.450***	-0.916*
	(1.283)	(0.411)	(0.175)	(0.247)	(0.043)	(0.499)
Crop group = Vegetables	0.183	-0.843**	0.953***	0.501**	0.314***	1.251***
	(0.499)	(0.402)	(0.138)	(0.217)	(0.067)	(0.308)
Crop group = Root crops	-0.726	0.062	0.179	0.267**	0.120**	0.409
	(0.735)	(0.527)	(0.237)	(0.127)	(0.047)	(0.250)
Crop group = Fruits	-4.513***	-2.735***	0.619**	0.476**	0.325***	0.953**
	(0.649)	(0.346)	(0.269)	(0.227)	(0.071)	(0.390)

Plot size (ha)				0.028	0.037***	0.255***
				(0.049)	(0.011)	(0.069)
Distance from a river (km)			-0.048			-0.005
			(0.074)			(0.106)
Distance from a stream (km)			-0.282*			-0.247*
			(0.161)			(0.138)
Constant	12.587	6.787***	-2.491	1.088	0.197	-1.560
	(9.295)	(2.100)	(2.070)	(0.720)	(0.222)	(1.985)
Kebele fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
lns1			0.894***			-1.369***
			(0.022)			(0.440)
lns2			0.951***			-1.362***
			(0.007)			(0.107)
r1			-0.104			-0.393
			(0.240)			(1.298)
r2			0.113			-0.957
			(0.210)			(0.787)
Observations	7,752	7,752	7,752	8,122	8,122	8,122

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

Table A5. Endogenous switching regression for household welfare indicators

Variables	daily food expenditure			daily food and non-food expenditure		
	(1) Irrigators	(2) Non-irrigators	(3) Irrigation status	(4) Irrigators	(5) Non-irrigators	(6) Irrigation status
Distance from a small city (km)	64.058*	-24.899*	0.259	63.148*	-22.728	0.261
	(34.281)	(15.077)	(0.193)	(32.296)	(16.426)	(0.195)
Distance from a 20K population city	0.524	-12.015	-0.067	25.922	-6.493	-0.078
	(68.550)	(39.025)	(0.495)	(71.778)	(41.468)	(0.489)
Distance from woreda center (km)	-27.319**	-7.771	0.001	-42.103***	-8.645	0.005
	(10.895)	(8.844)	(0.111)	(10.154)	(9.292)	(0.110)
Size of land owned (ha)	-9.128	-1.408	0.223**	-19.238	0.732	0.229***
	(16.996)	(5.615)	(0.090)	(15.587)	(5.785)	(0.088)
Household size	81.378***	43.250***	0.092	110.231***	49.832***	0.089
	(30.206)	(10.062)	(0.157)	(31.989)	(10.640)	(0.157)
Age of the head	9.528	-20.840*	0.089	5.169	-18.600	0.094
	(27.810)	(12.650)	(0.219)	(26.983)	(13.229)	(0.219)
Education of head	-3.623*	-0.189	-0.001	-2.240	0.154	-0.002
	(1.938)	(1.297)	(0.016)	(2.046)	(1.312)	(0.016)
Education of spouse	-7.322	-3.237**	0.082***	-7.718	-3.459**	0.084***
	(6.226)	(1.330)	(0.022)	(6.481)	(1.427)	(0.022)
Maximum education in household	2.874	2.478*	0.014	3.822*	3.122**	0.013
	(2.185)	(1.351)	(0.019)	(2.239)	(1.395)	(0.019)
Average slope	-2.993	-5.695	-0.106	-7.851	-8.104	-0.104
	(23.245)	(8.200)	(0.112)	(25.658)	(8.550)	(0.112)
Average distance of plots	-12.524**	0.641	0.060	-8.884	1.597	0.059
	(5.754)	(2.494)	(0.044)	(5.674)	(2.619)	(0.043)
Cost of seed	-5.978*	2.710*	0.059***	-5.665*	2.845*	0.058***
	(3.250)	(1.580)	(0.020)	(3.438)	(1.635)	(0.020)
Cost of fertilizer	0.932	0.044	0.039	1.774	0.044	0.039
	(4.658)	(1.221)	(0.029)	(4.769)	(1.278)	(0.029)
Cost of hired labor	2.310	0.596	-0.021	4.891**	1.074	-0.022
	(2.337)	(1.357)	(0.019)	(2.485)	(1.401)	(0.019)
Cost of agrochemicals	6.031	3.458***	0.034	5.804	4.245***	0.034
	(4.313)	(1.322)	(0.024)	(4.773)	(1.402)	(0.024)
Number of oxen	-15.792	20.482***	-0.228*	-22.712	25.285***	-0.224*
	(30.068)	(7.237)	(0.129)	(31.489)	(7.648)	(0.131)
round== 3.0000	111.692***	113.204***	-0.210**	126.389***	121.582***	-0.215**
	(21.944)	(8.607)	(0.103)	(21.290)	(8.741)	(0.103)
Sex of head of household	-71.335*	11.823	0.057	-110.048***	9.990	0.062
	(37.234)	(10.620)	(0.207)	(35.864)	(11.047)	(0.205)
Household owns cell phone	4.782	0.196	-0.005	19.277	6.991	-0.009
	(17.281)	(6.958)	(0.126)	(17.590)	(7.378)	(0.126)
Average soil quality	5.785	21.743***	0.145*	4.989	19.504***	0.147*
	(13.006)	(5.562)	(0.085)	(13.206)	(5.798)	(0.083)
Distance from a river (km)			-0.340***			-0.344***
			(0.121)			(0.119)
Distance from a stream (km)			-0.617***			-0.618***
			(0.184)			(0.177)
Constant	-16.802	103.374	1.039	-2.238	68.469	1.048
	(306.128)	(135.575)	(1.877)	(317.307)	(143.766)	(1.869)
Kebele fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
lns1	4.840***					4.871***
	(0.252)					(0.282)
lns2	4.650***					4.697***
	(0.001)					(0.001)
r1	-0.518					-0.563
	(0.907)					(0.961)
r2	0.058					0.039
	(0.067)					(0.074)
Observations	2,277	2,277	2,277	2,277	2,277	2,277

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.

Table A6. Endogenous switching regression for household welfare indicators: Net crop income

Variables	(1) Irrigators	(2) Non-irrigators	(3) Irrigation status
Distance from a small city (km)	0.242	0.086	0.114
	(0.260)	(0.106)	(0.217)
Distance from a 20K population city	-0.654	-0.285	-0.132
	(0.530)	(0.273)	(0.500)
Distance from woreda center (km)	-0.091*	-0.020	0.007
	(0.049)	(0.050)	(0.108)
Size of land owned (ha)	0.647***	0.743***	0.336***
	(0.150)	(0.046)	(0.086)
Number of oxen	0.292***	0.244***	-0.151
	(0.099)	(0.068)	(0.118)
2019 survey round	0.654***	0.587***	-0.074
	(0.091)	(0.053)	(0.088)
Sex of head of household	0.113	0.075	0.045
	(0.152)	(0.082)	(0.196)
Education of head	-0.016	0.001	0.005
	(0.015)	(0.009)	(0.016)
Education of spouse	-0.008	0.034*	0.079***
	(0.037)	(0.018)	(0.027)
Maximum education in household	0.030	0.004	0.021
	(0.018)	(0.010)	(0.018)
Household owns cell phone	0.003	0.086	-0.033
	(0.083)	(0.064)	(0.110)
Average slope	-0.169	-0.113**	-0.182
	(0.138)	(0.053)	(0.112)
Average distance of plots	-0.024	0.033	0.064
	(0.042)	(0.022)	(0.042)
Household size	-0.186	0.119	0.080
	(0.125)	(0.098)	(0.187)
Age of the head	-0.328	-0.270**	-0.074
	(0.231)	(0.110)	(0.237)
Average soil quality	0.206***	0.123***	0.072
	(0.071)	(0.042)	(0.082)
Distance from a river (km)			-0.200
			(0.166)
Distance from a stream (km)			-0.478***
			(0.160)
Constant	12.526***	9.941***	1.614
	(1.839)	(1.060)	(1.986)
Kebele fixed effects	Yes	Yes	Yes
lns1			-0.482***
			(0.114)
lns2			-0.257*
			(0.143)
r1			-0.064
			(0.938)
r2			1.379
			(1.247)
Observations	2,229	2,229	2,229

Note: Standard errors are in parenthesis. *** refers to statistical significance at 1% level.
Source: Analysis of ATA datasets.