

RESEARCH ARTICLE

# Adoption of multiple sustainable land management practices among irrigator rural farm households of Ethiopia

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## Abstract

Using a household and plot-level survey conducted in Ethiopia, this study analyses the difference in farmers' adoption of sustainable land management (SLM) practices between their rainfed and irrigated plots. The paper also investigates the varying influence of different types of irrigation water management systems and associated irrigation technologies on the adoption of SLM practices in irrigated plots. After controlling for heterogeneity among different irrigation water management systems and technologies, we found that access to irrigation play major role in enhancing farmers' motivation to adopt more SLM practices. Furthermore, the combined effect of irrigation water management system and irrigation technology on type and number of SLM practices adopted is quite varied and very significant. The evidence highlights that farmers adopt more SLM practices in their plots with pump irrigation compared with those plots where gravity irrigation is applied because pump irrigation systems enhance complementarities with SLM practices. Finally, the findings underscore that the type of irrigation water management and the irrigation technology applied play an important role in restoring degraded lands and maintaining soil fertility, even when farmers' adoption of irrigation was not explicitly triggered by concerns for soil health.

## KEYWORDS

Ethiopia, irrigation technologies, irrigation water management, soil and water conservation methods, sustainable land management

## 1 | INTRODUCTION

Sub-Saharan African countries are trying to improve the sustainability of agriculture and land management within the context of severe poverty and food insecurity (Gebremedhin & Swinton, 2003; Nkonya et al., 2008). Vicious circles of poverty and land degradation coupled with transmission effects from rural poverty and food insecurity to macro economies, crucially impede the development process (von Braun et al., 2013). It has been recognized that with the land frontier for further agricultural expansion shrinking, future growth in agriculture will increasingly have to come from improvements in productivity

and resource use efficiency rather than from area expansion (Eicher, 1995; FAO, 2017; Otsuka & Larson, 2012). Thus, innovative systems that protect and enhance the natural resource base, while increasing productivity have been fundamental requirements for sustainability (Von Braun, 2014).

Like most regions in sub-Saharan Africa, land degradation is a prevalent problem in Ethiopia. Over 85% of the land in Ethiopia is estimated to be moderately to very severely degraded, and approximately 75% is affected by desertification (The Global Mechanism, 2007). A study by Le et al. (2016) shows that land degradation occurred in approximately 23% of total land area between 1982 and 2006 in Ethiopia.

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Gebreselassie et al. (2016) reported that there was a decline in the total economic value of ecosystem services between 2001 and 2009, by about 5% due to land use and land cover changes in Ethiopia as a whole but reaching up to 30% of losses in ecosystems values in the Harari region. This environmental challenge has several adverse impacts that have threatened the sustainable production of agricultural goods. This has wider implications in Ethiopia, since agriculture accounts for 35% of the Country's GDP, employs 70% of the labour force, and provides a livelihood to 80% of the more than 100 million people (NBE, 2018).

The Government of Ethiopia has focused on the irrigation sector with the aim of ensuring poverty alleviation in the face of extreme weather conditions and population growth. According to the FAO (2016), between 2004 and 2015, the area under agricultural water management in Ethiopia increased from 510,000 hectares to 1.96 million hectares. Despite its high potential benefits, the use of irrigation water has caused adverse environmental conditions. Water management in medium- and large-scale irrigated areas is hampered by institutional, technological, capacity, and market constraints that lead to waterlogging, salinity, acidity, soil erosion, sedimentation, inadequate subsurface drainage, and related problems (Awulachew et al., 2010; Hordofa et al., 2008; Umali, 1993). In addition, since most of the irrigation schemes in the Country are in the arid and semiarid lowlands of major river basins (Ruffeis et al., 2008), the challenge of sustainable irrigation is more substantial in these regions (Wichelns & Qadir, 2015). In addition to soil quality degradation, Loiskandl et al. (2008) and Amdihun (2008) discussed the negative environmental impacts from land use change, including deforestation that results in high soil erosion and sediment transportation, which, in turn, affect irrigation canals. Siltation of canals has become severe in some schemes. If current irrigation practices do not improve, the emerging soil degradation problems may outweigh the benefits of irrigation projects. Thus, in order to combat land degradation due to poor irrigation management, the promotion of various kinds of sustainable land management (SLM) practices has been suggested (Nkonya et al., 2016), with additional benefits in terms of several other sustainable development goals (SDGs), such as poverty eradication, zero hunger, and attainment of climate and biodiversity protection targets.

Investment in SLM practices both to revert already degraded lands to productive uses and to proactively reduce future land degradation is important for sustainable irrigation development, management, and use. This is particularly true in Ethiopia, where the Government considers irrigated agriculture as a primary engine of economic growth and has made investments to increase the irrigated land through rainwater harvesting as well as small-, medium-, and large-scale irrigation schemes. Most available empirical studies regarding sustainable land management in Ethiopia have concentrated on the social, economic, institutional, and biophysical factors that affect the adoption of SLM technologies by small-scale farmers (Anley et al., 2007; Gebremedhin & Swinton, 2003; Gebreselassie et al., 2016; Holden et al., 2004; Kassie et al., 2009; Teklewold et al., 2013; Teshome et al., 2014); on the impacts of soil and water conservation (SWC) technologies on crop production in the Ethiopian Highlands (Pender et al., 2001; Pender & Gebremedhin, 2007; Kassie, Pender, et al., 2008; Kassie, Zikhali, et al., 2010; Schmidt &

Tadesse, 2019; Teklewold et al., 2013, 2019); on the contribution of SLM technologies to water security for both crop and livestock production (Kato et al., 2019); on the impacts of SWC technologies on agricultural production risk (Kassie et al., 2008; Kato et al., 2011; Yesuf et al., 2009), and on climate resilience (Teklewold et al., 2017). These earlier works are all focused on rainfed agriculture, with SLM issues in irrigated agriculture being given very limited attention so far.

This study contributes to the literature on SLM in irrigated systems, with two inter-related objectives. First, it investigates whether rural households make different decisions in adoption of SLM practices between their rainfed and irrigated plots and what factors play a role in their decisions about SLM adoption. Second, it analyzes if irrigation water management systems and associated irrigation technologies affect the adoption of SLM practices on the irrigated fields.

## 2 | CONCEPTUAL BASIS AND HYPOTHESES

There is ample evidence that mismanaged irrigated agriculture has adverse environmental impacts on natural resources (De Fraiture et al., 2010; Gebrehiwot, 2018; Hordofa et al., 2008; Ruffeis et al., 2008; Umali, 1993; Wichelns & Qadir, 2015) that include changes in soil quality such as waterlogging, soil salinity, and ecological damage, which have the potential to cause loss of soil fertility and productivity in irrigated agriculture (Rosegrant et al., 2009; The Malabo-Montpellier Panel, 2018). As a result, investment in SLM practices to restore already degraded lands to productive uses and to proactively reduce future land degradation becomes vital for sustainable irrigation development, management, and use.

The United Nations 1992 Rio Earth Summit defined sustainable land management (SLM) as "...the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions" (UN, 1993). It is expected that adoption of SLM practices to be affected by factors that influence farmers' awareness of different practices; the costs, benefits, and risks of the technologies; or the availability of productive factors used for the application of the practices.

Adoption of SLM practices and their comparative advantage depends on household-level factors, village-level characteristics (such as market access and other infrastructures), farm-level factors (such as land size and land tenure security), and biophysical factors (such as soil type and slope of the plot, rainfall, temperature, and vegetation covers). In addition, household-level factors such as access to training on natural resource management and experience of using irrigation are important factors that determine the adoption of SLM practices. The choice of explanatory variables that explain the adoption of SLM in this study is based on economic theory and findings from earlier studies (Anley et al., 2007; Kato et al., 2011; Pender et al., 2001; Pender & Gebremedhin, 2007; Pender & Kerr, 1999; Schmidt & Tadesse, 2019; Teklewold et al., 2019).

For the past three decades, the role of local rural communities and households in irrigation water management has been increasing.

The government and development partners have committed to the implementation of policy reforms that encourage irrigation management at lower level and adoption of irrigation technologies at micro and small scale to farm households. Apart from other benefits of using irrigation water, the study proposes irrigation may play a significant role in the adoption of SLM practices. Moreover, the type of water management system and complimentary irrigation technology in use influence the adoption and intensity of SLM practices applied on irrigated farms. The central hypothesis of this study is that using privately managed irrigation system may lead to increased mismanagement of natural resources and lower adoption of SLM practices due to differences in the private and social discount rates in resource use. On the other hand, irrigation schemes that are initiated and managed by groups of farmers can more easily adopt sustainable land management practices. It is also assumed that irrigation schemes jointly managed by farmers and public entities have a greater incentive to use and manage the resource efficiently and invest in land management technologies, since most of these systems are equipped with modern structures. However, it is noteworthy to mention that the performance of each agricultural activity in this kind of system highly depends on the relation between the agents that manage the scheme at higher level of the irrigation infrastructure and the farmers that use the irrigation water with the responsibility to manage the resource at a lower level.

### 3 | METHOD OF ANALYSIS

#### 3.1 | Data description

The dataset for this study comes from a unique cross-sectional survey customized for capturing various aspects of irrigation management and use in Ethiopia. The survey was conducted in 2016/17 in four regions of Ethiopia: Tigray, Amhara, Oromia, and Southern Nations, Nationalities, and Peoples (SNNPR) covering both irrigated and rainfed farmlands.

In order to enhance the validity and reliability of the findings, information was gathered from multiple sources for purposes of triangulation. The instruments used are the following:

**Household surveys:** Irrigation beneficiary farmers were interviewed using structured household-level questionnaires. The interviews were carried out using pen-and-paper (PAPI) as well as computer-assisted personal interviewing (CAPI) method. The data were collected using a multi-stage stratified random sampling method. In the first stage of the sample selection process, among the nine regions in the country, Tigray, Amhara, Oromia, and Southern Nations, Nationalities, and Peoples (SNNPR) regions were purposively selected due to the relatively higher irrigation coverage in these four regions. In the second stage, in consultation with irrigation experts at the federal and regional levels, *Woredas* (districts representing the third-level administrative divisions in Ethiopia), which fulfill the objective of the study (containing diversified irrigation practices and water management systems), were identified. The survey covered 10 districts in different agroecological zones of the Country. From each region, we

selected one to four *woredas*: Tigray (two *woredas*), Amhara (three *woredas*), Oromia (four *woredas*), SNNPR (one *woreda*). In the third stage, based on information from *woreda* office of agriculture and water resources, *kebele* (peasant associations or *tabias*) constituting different scales of irrigation (large, medium, small, and micro) were selected. *Kebele*, Peasant Association, or *Tabia* are the smallest administrative units in Ethiopia. Finally, based on the lists of irrigation water users provided at *kebele* level by Bureaus of Agriculture, Bureaus of Water Resources, Water User Associations, or Cooperatives (in different regions, different agencies are responsible for maintaining these lists), 464 irrigation water beneficiary households were randomly selected. In this study, 403 households with their 921 rainfed and 889 irrigated plots are included. Rainfed plots are plots that rely mainly on precipitation as a source of moisture to cultivate crops, however, irrigated plots are those plots that are equipped to provide irrigation water and cultivated in at least one irrigation season in a year. The salient features of irrigation schemes included in the study are presented in Table 1 and Figure 1.

**Satellite-based biophysical datasets:** The survey data were merged with climate variables for the period 1981–2016 based on geo-referenced plot-level latitude and longitude coordinates. The climate variables (temperature and precipitation) were obtained from two different sources. The dataset on temperature was 0.5° by 0.5-degree gridded time series data downloaded from Climate Research Unit, University of East Anglia (Harris & Jones, 2017). The dataset for precipitation was downloaded from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) that incorporate 0.05-degree resolution satellite imagery with in situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring (Funk et al., 2015). After downloading the datasets from the respective sources, the monthly temperature and precipitation data values for the study sample farms were extracted and interpolated from the gridded time series data to farm-level GPS coordinates measured during the survey. The thin-plate spline method of spatial interpolation was used to impute plot-specific rainfall and temperature values using geo-referenced information, following the approach proposed by Di Falco et al. (2012) and Teklewold et al. (2017). Furthermore, using geo-referenced points from the household and plot survey, LANDSAT images were extracted to compute a normalized difference vegetation index (NDVI). The Landsat series of images were acquired from NASA/US Geological Survey Earth Observation satellites space-based images of the Earth's land surface (US Geological Survey, 2016). Other climate and agroecological characteristics included in the analysis (by matching them to household GPS coordinates) included farming systems, altitude, and agroecological zones. We used the agroecological zone classification, applied in the Ethiopian Social Accounting Matrix developed by the Ethiopian Development Research Institute (EDRI), namely, (1) drought-prone lowland, (2) drought-prone highland, (3) humid lowland moisture reliable, and (4) moisture reliable-cereals, and moisture reliable-*enset*.

**Focus Group Discussions:** In addition, qualitative information was gathered through focus group discussions (FGDs) with open-ended questions to enhance the validity and reliability of the quantitative data and augment the econometric results. In-depth focus group discussions with 6–12 irrigation water beneficiaries in various

**TABLE 1** Salient features of irrigation schemes included in the study

Region	Zones included	Woredas <sup>a</sup> included	Agroecological zone <sup>b</sup>	No. of Kebeles <sup>c</sup>	Scale of irrigation	No. of household	No. of rainfed plots	No. of irrigated plots
Tigray	Eastern Tigray	Atsebi Wemberta	Drought-prone highland	2	Small, Micro <sup>d</sup>	51	122	66
	Southern Tigray	Raya Alamata	Drought-prone highland, drought-prone lowland	4	Small, <sup>e</sup> Micro	49	75	73
Amhara	North Wello	Raya Kobo	Drought-prone highland, drought-prone lowland	2	Large, Small, Micro	38	82	79
		Raya Town	Drought-prone highland, drought-prone lowland	2	Large, Small, Micro	27	62	45
	East Gojjam	Mecha	Moisture reliable, highland-cereal	2	Large, Small, Micro	66	161	175
Oromia	South West Shoa	Illu	Moisture reliable, highland-cereal	8	Small, Micro	60	223	11
		Wonchi	Moisture reliable, highland-cereal	2	Medium, <sup>f</sup> Small, Micro	50	188	86
	Arsi	Sire	Humid moisture reliable, lowland	1	Large <sup>g</sup>	12	10	36
		Jeju	Humid moisture reliable, lowland	1	Large	8	11	13
SNNPR	Sidama	Wondo Genet	Moisture reliable, highland – <i>enset</i> <sup>h</sup>	2	Small, Micro	103	207	305
4	7	10		26		464	1141	889

<sup>a</sup>Woredas means districts. They are the third-level administrative divisions of Ethiopia.

<sup>b</sup>The characterization of agroecological zone has been expanded to “5 Ethiopia's” (drought. Prone, humid lowland moisture reliable, moisture reliable – cereals, moisture reliable – *enset*, and pastoralist) for the Ethiopian Social Accounting Matrix developed by the Ethiopian Development Research Institute (EDRI). Previously, it was only ‘Three Ethiopias’: moisture reliable highlands, drought-prone highlands, and pastoral lowland areas.

<sup>c</sup>Kebele, Peasant Association, or Tabia are the smallest administrative units in Ethiopia.

<sup>d</sup>Micro-irrigation users – individualized household-level irrigation schemes of less than 1 ha.

<sup>e</sup>Small-scale irrigation systems – command area less than 200 ha.

<sup>f</sup>Medium-scale irrigation systems – command area 200–3000 ha.

<sup>g</sup>Large-scale irrigation systems – command area greater than 3000 ha.

<sup>h</sup>*Enset* is a root crop.

Source: Authors' compilation using survey data.

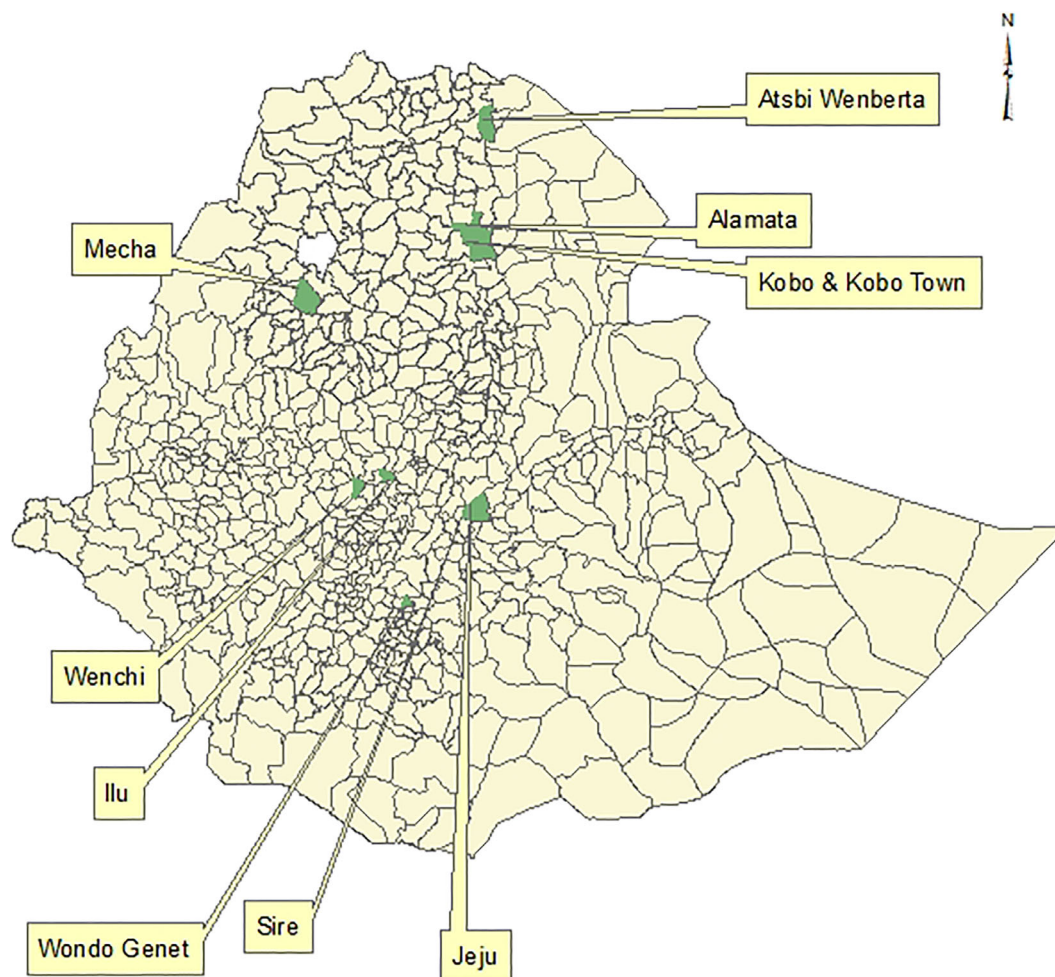
management systems and technologies were conducted in each sub-district included in the study. FGDs complemented the formal surveys and gave very nuanced and rich information about lived experiences of people about different irrigation types from their own perspectives. This questionnaire also helped to collect village-level general information such as access to services, irrigation water management, distribution and use, irrigation services, agriculture input and output (quantity and price), and perception towards use of irrigation on livelihood, decision-making power, participation, and perception on environmental change, weather and climate change, and variability.

### 3.2 | Typology of irrigation systems and technologies included in the study

Irrigation water management system for smallholder farmers in Ethiopia is diversified. It ranges from private access and use rights of an irrigation water source such as shallow well to full participation of group of farm

households in the inception, design, construction, and operation of an irrigation scheme, and to partial participation of farmers only at the low reaches of management level. In this section, we summarize the different irrigation systems included in this study as follows:

1. Privately managed irrigation system is a 'micro-scale private irrigation', which refers to individualized small-scale technologies for storing, lifting, conveying, and applying irrigation water. The main character of farmers in a privately accessed irrigation system is their reliance on drilled and hand dug wells or water harvesting ponds to store water for irrigation; treadle and motor pumps to lift water; and a variety of irrigation application technologies such as flooding, furrow, small buckets, and drip systems to apply water on a farm plot (Figure 2 and 3). Approximately 19% of the sample households and plots in the study fall in this category.
2. Users-managed irrigation system refers to irrigation schemes where farmers and water users' associations (WUA) have full control and responsibility from inception to the construction and



**FIGURE 1** Location of the study sites [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

implementation of the scheme, including the utilization and management of the irrigation water. Usually, this kind of system is characterized as small-scale and found in traditional irrigation schemes constructed using diversion weirs made from local materials and need annual maintenance (Figure 4 and 5). They may apply gravity or pump to lift irrigation water. Approximately 12.5% of the sample plots in the study apply pump to lift irrigation water and 22% of the sample plots use canal (gravity) to deliver irrigation water.

3. Jointly (users-agency) managed irrigation system refers to a system where farmers and a government agency manage irrigation schemes jointly. Since the schemes are usually medium- or large-scale irrigation systems, a government agency has control of the water to the delivery point and is responsible for operation and maintenance (O&M) at higher level; the use of water and O&M thereafter is under the control of the farmers and their association. As farmer-managed irrigation systems, they may use gravity or pump irrigation technology to withdraw water from a source. Approximately, 10% and 37% of the total samples in the study apply pressurized pump irrigation and canal irrigation systems to withdraw water from a source, respectively (Figures 6–9).



**FIGURE 2** Privately developed drilled well and motor pump [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

The combinations of alternative irrigation management schemes and irrigation technologies are provided in Table 2. There are no private irrigators that use gravity for water application, resulting in five water management-technology alternatives.



**FIGURE 3** Treadle pump user in Atsebi Wemberta Woreda [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 4** Spring water source for traditional irrigation users [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 5** Traditional irrigation system which needs frequent maintenance [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 6** Koga Dam in Mecha Woreda [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## 4 | ECONOMETRIC ESTIMATION STRATEGY

### 4.1 | Ordered probit model

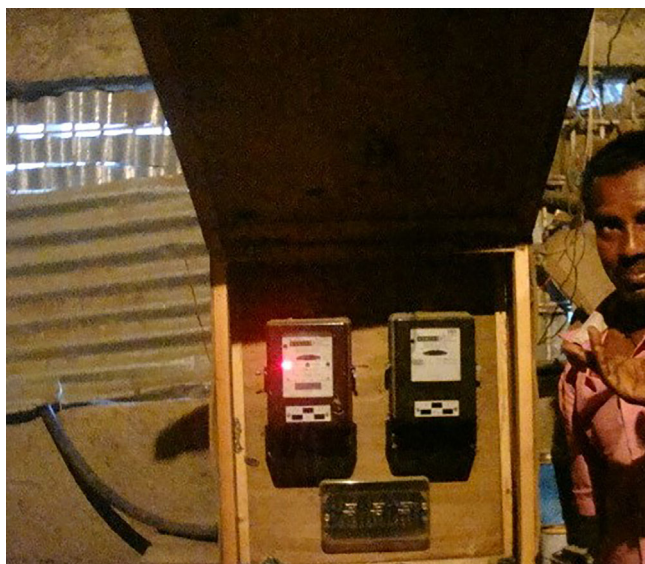
The ordered probit model allows us to analyze the factors that affect the number of SLM practices adopted. We use the number of SLM practices adopted in the plot as our dependent variable measuring the intensity of SLM adopted. The number of practices adopted could



**FIGURE 7** One of the canals in the Koga large-scale irrigation project with geomembrane canal liner sheet [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 9** Drip irrigation lateral extension in Kobo Woreda [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 8** Drip irrigation controller and operator in Kobo Woreda [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

have been considered as a count variable. Count data are usually analyzed using a Poisson regression model with a basic assumption that all practices have the same probability of being adopted (Wollni et al., 2010). However, in our application, the probability of adopting the first practice is not the same as the probability of adoption of the second and third practices, since in the latter cases, the farmers have gained experience and information. Hence, we treat the number of SLM practices adopted as an ordinal variable and use an ordered probit model in the estimation.

The dependent variable ( $E$ ) is a function of observed heterogeneity ( $X$ ) with unknown weights ( $\beta$ ) and other unobserved characteristics ( $u$ ):

$$E_{ip} = X_{ip}\beta + u_{ip},$$

**TABLE 2** Combined alternatives of water management systems and irrigation technologies included in the analysis

Choice	Alternatives	No of plots	%
1	Privately managed pump users	168	18.94
2	Users-managed pump users	111	12.51
3	Users-managed gravity users	195	21.98
4	Jointly managed pump irrigators	87	9.81
5	Jointly managed gravity irrigators	326	36.75
	Total	887	100.00

Source: the household survey, described in the data section.

represents the categorical outcome variable  $E_{ip} \in \{1, \dots, m\}$ , indicating the number of SLM practices adopted on plot  $p$ .

The estimation is implemented at the plot level to capture spatial heterogeneity across plots (both rainfed and irrigated) and to minimize omitted variables bias. Yet, we ran the analysis clustered at household level.

## 4.2 | Multivalued treatment effects approach

To estimate the impact of various combinations of irrigation water management systems and technologies on the number of SLM practices adopted, the multivalued treatment effects approach of Imbens (2000), Wooldridge (2007, 2010), and Cattaneo (2010) is applied. This method allows estimating the treatment effects when there are more than two treatments among the individuals in the sample. In our case, this includes private individual irrigators with pumps, users-managed pump systems, users-managed gravity systems, government and users jointly managed gravity systems, government and users jointly managed pump systems, and rainfed plots. The potential outcome means (POMs) of the number of SLM practices adopted in each alternative management and technology combination are

computed. Similar to the ordered probit model above, the analysis is implemented at the plot level to capture spatial heterogeneity across irrigated plots and to minimize omitted variable bias. Since the choice of irrigation technology may be endogenous with unobserved household characteristics, if they are not properly controlled for, the obtained results may be biased. The plot-level analysis in this study enables us to control for unobserved household characteristics through household fixed effects.

As the first step to estimate the impact of adopting various combinations of water management systems and irrigation technologies on SLM, a conditional probability model is constructed to estimate the likelihood that each plot would be in each alternative combination (see Figure S1–S5). In the second step, the conditional means (the average potential outcome for the specified alternatives) of the number of SLM practices applied are estimated using inverse probability weighted regression adjustment (IPWRA) estimators (refer to section S1 for details). IPWRA is used to account for non-random nature of irrigation technology and irrigation management system adoption. This econometric estimation method helps to remove the known and explicitly modeled sources of self-selection and endogeneity. In our specification, the full list of covariates to predict alternative (treatment) status includes age and education level of the household head, household size, number of trainings attended, access to extension service, assets as proxies for wealth (Tropical Livestock Unit), land tenure, distance to the nearest *woreda* (district) market, whether adverse weather conditions occurred, average *Meher* (the main rainy season) precipitation, and annual temperature and NDVI. Multinomial logit model is used to predict treatment status as a function of the covariates and then use Poisson and Probit models to estimate the outcome variables (number of SLM technologies applied). Three kinds of SLM systems are used in the analysis: (i) sustainable cropping systems such as rotation, fallowing and legume planting, (ii) fertilizer use (chemical fertilizer with combination of manure [green] or compost), and (iii) soil and water conservation methods (physical land investments) such as contour plowing, planting trees/bushes in rows (agroforestry), terraces, trenches, cover cropping, and strip cropping.

### 4.3 | Estimation of average treatment effect on the treated

The challenge in impact evaluation using observational data is to estimate the counterfactual outcome; the outcome of a particular alternative could have been adopted had they were in a different alternative. A point worth mentioning is this analysis compares different combinations of water management and lifting technologies to each other, in addition to the number of SLM practices adopted in rainfed plots. The ATT indicates how the mean outcome of SLM would change if everyone who received one particular alternative (treatment) had instead received another particular alternative (treatment).

The ATT is the average effect among those subjects that receive treatment level  $\hat{k}$  of giving each subject treatment  $k^*$  instead of another treatment (in our case other treatment alternatives, the

outcome the irrigators in a particular alternative could have adopted had they different alternatives):

$$ATT_{\hat{k}k} = E[(y_k - y_0) / k = \hat{k}], \quad (2)$$

Where:  $y_{ki}$  is the realization of the random variable  $y_k$ . Let  $y_0$  denote the potential outcome of a subject that receive any other alternative (in our case other treatment alternatives, the outcome the irrigators who adopt a particular alternative could have adopted had they were in different alternatives) and  $i$  subscripts denote realizations of the corresponding unsubscripted random variables. To handle the case of multivalued treatments, we extend the definition of the unobservable, individual-level treatment effects to be  $y_k - y_0$  for  $k \in \{1, \dots, K\}$ . Defining the ATT in the multivalued treatment case needs three different treatment statuses:  $\hat{k}$  defines the treatment level of the treated potential outcome (a particular alternative); another alternative potential outcome (1, ..., 5); and  $k = \hat{k}$  restricts the expectation to include only those individuals who actually receive treatment level =  $\hat{k}$ .

## 5 | RESULTS

### 5.1 | Descriptive results

#### 5.1.1 | Descriptive statistics of relevant variables

Summary statistics of relevant variables by the five combinations of water management and irrigation technology alternatives is provided in Table 3. Household heads who are in privately managed pump irrigation systems are more likely to be younger and to have more years of formal education compared with household heads in the other alternatives. Gravity irrigators have more years of experience in using irrigation water (12 years) than the other alternatives (around 5–9 years). While access to credit is very limited for households in privately managed pump and jointly managed gravity irrigation, approximately 82% and 92% farmers managed and jointly (farmers and agency) managed pump irrigators have access to credit, respectively.

There are differences between the alternatives with respect to average travel time to the nearest *woreda* market and all weather roads. Gravity irrigators in farmers and jointly managed systems travel, on average, more than 40 min to the nearest *woreda* market. However, irrigated farms are similar in terms of plot characteristics such as soil type and slope across all groups. Even if most of the farmers operate on registered lands, only around 17% of irrigated plots that are in privately managed system are allocated by the local government. Farmer-led irrigators are located at higher elevation than farms that are located in the other alternatives. Farmer-managed pump irrigators receive lower precipitation than irrigators in the other groups. Overall, most of the normalized difference vegetation index (NDVI) reported in the study areas are very small that represents land cover with shrubs and grasslands. Irrigated farmlands that are located in privately managed systems have slightly higher NDVI values than in the other alternatives.

**TABLE 3** Summary statistics of relevant variables by the five combinations of water management and technology alternatives sub-groups

Variable name	Private + pump	Farmer + pump	Farmer + gravity	Jointly + pump	Jointly + gravity
Household human capital					
Age of the household head (in years)	42.11 (11.7)	44.83 (12.5)	46.67 (12.3)	44.40 (12.1)	45.54 (11.9)
Education level of the household head (in years)	6.25 (4.32)	4.18 (4.07)	4.51 (5.25)	3.99 (4.95)	4.99 (5.23)
Family size, (in number)	6.92 (2.77)	5.93 (1.93)	6.01 (1.86)	5.71 (1.82)	6.06 (1.95)
Number of training attended in 2015/16	0.67 (1.24)	1.13 (2.32)	1.32 (2.46)	0.71 (1.22)	1.36 (2.33)
Frequency of contact to extension worker in 2015/16, (in number)	18.39 (41.02)	19.23 (57.98)	16.80 (33.18)	13.6 (29.85)	16.89 (35.95)
Household physical capital					
Livestock ownership (TLU)	4.02 (3.91)	3.30 (2.32)	4.80 (3.97)	3.30 (3.08)	5.96 (7.48)
Village-level characteristics					
Distance to the woreda market in min, one way	28.89 (24.41)	33.98 (33.40)	44.97 (42.54)	19.67 (15.19)	40.58 (37.43)
1 = if there was adverse weather condition in 2015/16	0.35 (0.47)	0.72 (0.44)	0.35 (0.47)	0.78 (0.41)	0.24 (0.42)
Plot characteristics					
Irrigation plot size (in ha)	0.23 (0.23)	0.30 (0.22)	0.19 (0.13)	0.37 (0.29)	0.33 (0.35)
1 = if the soil type loamy	0.79 (0.41)	0.59 (0.49)	0.51 (0.50)	0.67 (0.47)	0.57 (0.49)
1 = if the plot is flat	0.98 (0.13)	0.97 (0.18)	0.96 (0.20)	0.94 (0.23)	0.87 (0.33)
1 = if the plot is allocated by the government	0.17 (0.37)	0.54 (0.50)	0.49 (0.50)	0.69 (0.46)	0.44 (0.49)
1 = if the plot is certified	0.97 (0.18)	0.98 (0.15)	0.81 (0.39)	0.92 (0.27)	0.74 (0.43)
Biophysical variables					
Mean annual temperature	17.4 (0.75)	18.7 (0.82)	17.1 (1.18)	19.1 (0.26)	17.0 (0.76)
Meher mean total precipitation	528 (100.73)	445 (49.26)	726 (294.12)	439 (22.80)	781 (336.01)
Belg Mean total precipitation	366 (91.47)	220 (85.56)	254 (97.47)	189 (16.42)	243 (99.37)
Normalized difference vegetation index (NDVI)	0.34 (0.11)	0.18 (0.11)	0.21 (0.12)	0.14 (0.06)	0.23 (0.16)
Agroecological zones					
Moisture reliable, highland, cereal	0.09 (0.28)	0.13 (0.34)	0.60 (0.48)	0.06 (0.23)	0.51 (0.50)
Drought-prone lowlands	0.09 (0.29)	0.28 (0.45)	0.11 (0.31)	0.41 (0.49)	0.01 (0.13)
Drought-prone highland	0.005 (0.07)	0.41 (0.49)	0.05 (0.22)	0.52 (0.50)	0.01 (0.10)
Humid moisture reliable, lowland	0	0	0	0	0.15 (0.36)
	0	0	0	0	
Moisture reliable, highland, enset	0.80 (0.39)	0.16 (0.36)	0.22 (0.42)	0	0.29 (0.45)
				0	

Source: Author's computation using own survey data.

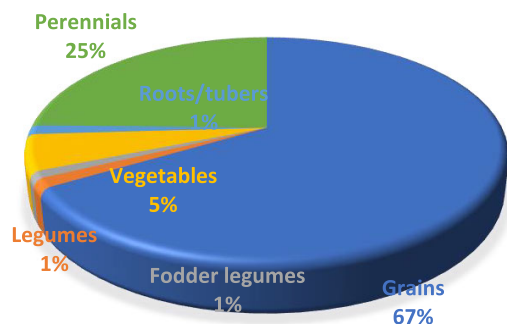
### 5.1.2 | General overview of crop pattern and diversity

Figures 10 and 11 show crop types grown in the study areas during the rainy (*Meher*) and irrigation seasons in 2015/16. During the rainy season, the main crop category was grains, which took approximately 67% of the total cultivated plots. From the grain category, white teff, a staple food in the country, took the lion's share (22.2%), followed by maize (13%), wheat (7.51%), and sorghum (7%). Perennials were also grown on 25% of the rainfed plots such as *enset*<sup>1</sup> (6.45%), *chat*<sup>2</sup> (4.9%), coffee (3.5%), banana (2.7%), and avocado (1.5%). In rare cases, roots/tubers and vegetables such as onion, potato, tomato, and cabbage were grown on rainfed plots. However, during the irrigation season of 2015/16, plots in the irrigation sites were covered with different crops (see Figure 11). The major types of irrigated crops

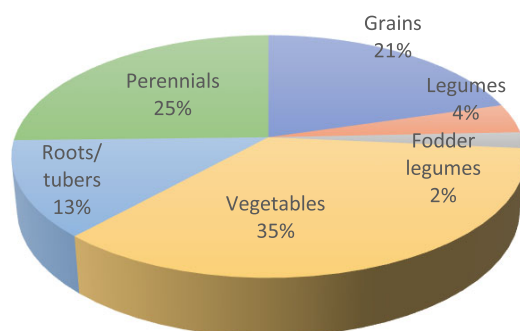
were vegetables, such as onion, tomato, cabbage, and pepper, which accounted for 35% of the plots included in the study. The lion's share was taken by onion (18.4%) and tomato (10.9%). The second most frequently grown crop group in the irrigation seasons were perennials (26%). *chat* (10.3%), *enset* (3.7%), banana (2.66%), and coffee (2.4%) were among the major perennial crops in the plots included in the study sites. Roots and tubers were the third most frequently grown crop group (13%), with potato covering 8% of the plots.

### 5.1.3 | Qualitative assessment of environmental impacts of irrigation and SLM practices

Focus group discussions with irrigators in our sample indicate that the most frequent environmental impacts of irrigation are waterlogging,



**FIGURE 10** Crops grown during *Meher* season [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 11** Crops grown during irrigation season [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

soil salinity, soil fertility, and soil erosion. Approximately 27% of irrigators reported that their soil fertility level has been deteriorating since they started to use irrigation. Similarly, approximately 18% of the irrigated plots face waterlogging problem, while soil salinity is observed in 27% of the plots, according to farmers' perceptions. The occurrence of erosion due to irrigation was observed in only 5% of the plots. However, the figure is much higher (21%) when farm households were asked about their perception toward soil erosion as a general environmental threat including their rainfed plots.

Table 4 presents SLM practices applied on irrigated and rainfed plots in the study areas. In line with previous studies by Bekele and Drake (2003) and Gebreselassie et al. (2016), crop rotation, fallowing, and chemical fertilizers are the most common practices adopted by most farmers in both irrigated and rainfed systems. Compared to irrigated plots, fallowing, crop rotation, and legume planting are more common in rainfed plots. This is partly due to larger land size holdings as well as higher number of rainfed plots than irrigated plots. Farm households use more chemical fertilizers on their irrigated plots (by 25 percentage points) than their rainfed plots. However, it is noteworthy to mention that the use of chemical fertilizer alone is not counted as SLM practice. It should be combined with manure or compost. In this case, households applied chemical fertilizer with manure (green) or compost in only 8% and 19% of rainfed and irrigated plots, respectively. There is a significant difference in the use of compost between the irrigated plots (13%) and rainfed plots (7%).

The level of physical land management practices is comparable between irrigated and rainfed plots. Overall, physical land conservation investments such as construction of trenches, strip cropping, and cover cropping are the least adopted SLM measures by farm households. This is possibly because these land management practices could remove land out of agricultural production. Nonetheless, trenches and strip cropping are more common in rainfed plots than irrigated plots. On the other hand, contour ploughing, terraces, and tree planting are common soil erosion mitigating practices. Planting trees is more common in irrigated plots, while there is no statistically significant difference in contour plowing and terraces between rainfed and irrigated plots (Table 4). This result is consistent with previous studies in Ethiopia. Farm households with access to irrigation water are more likely to implement agroforestry practices, showing that farmers are more encouraged to grow multipurpose trees, which are perennial on their plots with the available water for irrigation (Etsay et al., 2019).

Even if significant differences are observed between many of the practices applied individually among plots in irrigated and rainfed plots, the difference in the total number of SLM technologies applied on representative rainfed and irrigated plots is very small. The average number of SLM practices adopted in irrigated and rainfed plots stands at 2.22 and 2.08, respectively, out of 13 possible SLM practices that information is collected on. In the next section, we examine econometrically first whether access to irrigation affects the number of SLM practices adopted and then if there is a difference in the number and type of SLM practices and investments among plots benefiting from different combinations of water management systems and irrigation technologies.

## 5.2 | Quantitative results: Number of SLM practices adopted

### 5.2.1 | Ordered probit results

Table 5 presents an estimation of the ordered probit result of the number of SLM practices adopted. The major reason for the estimation of determinant of intensity of SLM adoption is to find out whether irrigated plots have a greater number of adopted practices. The findings did not show that irrigated plots have higher number of SLM practices than rainfed plots. The results rather indicate that most of the household, village, and biophysical variables are statistically significant in explaining the number of SLM practices adopted. For comparison, Poisson model is estimated for rainfed and irrigated agriculture, and the results are presented in Table S1.

Among the household-level characteristics, the age of household head increases the intensity of SLM adoption, whereas the education level of household heads has a negative and significant effect. This is likely due to higher opportunity cost of labor for better educated households. Household wealth indicator variable-livestock ownership of the household, proxied by Tropical Livestock Unit (TLU), has significant and positive effect on the number of SLM technologies, since livestock is vital input for producing manure and compost (Kassie et al., 2009).

**TABLE 4** Mean separation tests of sustainable agriculture practices applied in plots with and without access to irrigation

Sustainable agricultural practices	Rainfed		Irrigated		Rainfed versus irrigated (diff)	
	Mean	SE	Mean	SE	Mean	SE
<b>Sustainable cropping system</b>						
Crop rotation	0.65	0.01	0.56	0.02	0.09***	0.02
Fallowing	0.30	0.01	0.21	0.01	0.09***	0.02
Legume planting	0.11	0.01	0.03	0.01	0.08***	0.01
Any one of the sustainable cropping systems are adopted	0.73	0.01	0.63	0.02	0.10***	0.02
Number of sustainable cropping system	1.06	0.02	0.80	0.02	0.26***	0.03
<b>Fertilizer use</b>						
Manure	0.14	0.01	0.19	0.01	−0.05***	0.02
Compost	0.07	0.01	0.13	0.01	−0.06***	0.01
Green manure	0.00	0.00	0.02	0.00	−0.02***	0.00
Chemical fertilizer (DAP, urea, NPS)	0.50	0.01	0.75	0.01	−0.24***	0.02
Combining use of chemical fertilizer and manure or compost	0.08	0.01	0.19	0.01	−0.11***	0.01
<b>Soil erosion control practices</b>						
Contour plowing	0.17	0.01	0.15	0.01	0.02	0.02
Planting trees/bushes/ in rows (agroforestry)	0.11	0.01	0.16	0.01	−0.05***	0.01
Terraces or bunds	0.33	0.01	0.30	0.02	0.03	0.02
Trenches	0.09	0.01	0.04	0.01	0.05***	0.01
Cover cropping	0.09	0.01	0.09	0.01	0.00	0.01
Strip cropping	0.05	0.01	0.03	0.01	0.02***	0.01
Any of the S&W conservation practices used	0.52	0.01	0.50	0.02	0.02	0.02
Average number of soil erosion control practices adopted	0.52	0.01	0.50	0.02	0.02	0.02
Number of SLM technologies applied	2.22	0.05	2.08	0.06	0.14*	0.07
No of observation	1141		889			

Note: Statistical significance at \* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ . Use of chemical fertilizer is presented for additional information but not included as SLM practice alone.

Source: Author's computation using own survey data.

The village-level characteristics have mixed effect on the number of practices adopted. Distance to district market influences the intensity of SLM practices positively. In villages that were more distant from markets, the number of SLM practiced was significantly higher. As distance increases from the district market, off-farm employment opportunities are very limited in rural Ethiopia (Gebremedhin & Swinton, 2003). On-the- other-hand, distance to all weather roads is also a significant determinant of the number of SLM technologies. The farther away from the road, the less the number of SLM technologies adopted. There is a positive effect of extreme weather events on the number of practices adopted, implying occurrence of extreme weather events such as flooding, drought, hailstorm, and disease pressures have a direct biophysical effect on diversification of adoption of SLM practices as a risk management strategy (Teklewold et al., 2019).

Regarding farm-level characteristics, the evidence also depicts that there is lower number of SLM practices in plots that have loamy soil type. This result is similar to Kassie et al. (2009); the likelihood of adopting these practices is less likely on plots with predominantly black soil. Tenure security also affects the number of practices

adopted, with a greater number of practices on certified plots. This result is in line with previous works on technology adoption in Ethiopia by Gebremedhin & Swinton (2003), Teklewold et al. (2013, 2019), and Gebreselassie et al. (2016).

Lower number of SLM practices are adopted in households that have highly fragmented plots, due to high travel cost to plots (Gebremedhin & Swinton, 2003). Distance of plots from residence positively and significantly influence the adoption of SLM practices. This reflects the fact that plots that are farther away from the residence are less likely to be accessed easily. The result also shows that there is higher adoption of SLM practices in more arid agroecological zones.

## 5.2.2 | Multivalued treatment effect results

This section examines how differences in irrigation water management and technology choice affect the adoption of SLM practices, comparing each other and to rainfed plots. The section presents the

**TABLE 5** Coefficient estimates of the ordered probit model-determinants of number of SLM practices adopted (clustered at household level)

Variable name	Coeff	SE
Household human capital		
Age of the household head (in years)	0.0041**	0.002
Education level of the household head (in years)	−0.018***	0.0052
Family size, (in number)	0.0003	0.0076
Number of training attended in 2015/16	−0.0063	0.0124
Frequency of contact to extension worker in 2015/16, (in number)	0	0.0006
Exchange labour participation	−0.1153*	0.0589
Household physical capital		
Livestock ownership (TLU)	0.0178***	0.0058
Total size	−0.0047	0.006
Village-level characteristics		
Distance to the <i>woreda</i> market	0.004***	0.0008
Distance to the all weather roads	−0.010***	0.0013
1 = if there was adverse weather condition in 2015/16	0.094*	0.0572
Plot characteristics		
1 = Irrigated plot	−0.022	0.0491
1 = if the soil type loamy	−0.161***	0.0525
1 = if the plot is flat	0.0427	0.0827
Fragmented (no of plots/household)	−0.072***	0.0102
Distance from home	−0.003***	0.0012
1 = if the plot is certified	0.4588***	0.0719
Agroecological zones, cf, dummy moisture reliable, highland-enset		
Moisture reliable, highland, cereal	0.6484***	0.0728
Drought-prone lowlands	0.3503***	0.1079
Drought-prone highland	0.2387**	0.1037
Humid moisture reliable, lowland	0.1005	0.1993
No of observation	2030 plots	

Note: Statistical significance at \* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .

Source: Author's computation using own survey data.

conditional means (the potential outcomes means – POM) of the most widely applied SLM technologies in the irrigation sites by water management system and complementary irrigation technology, after controlling for other characteristics of each plot. The descriptive statistics of the number and type of land management practices among plots benefiting from different combinations of water management systems and irrigation technologies is presented in Table S2. The simple comparison based on the result from unconditional means of number of SLM practices in different categories along the alternatives may be misleading because it does not account for other factors that may influence the outcome variables. The multivalued treatment estimation controls for such confounding factors and is appropriate when there are more than two treatments. We also estimated multivariate

probit, probit, Poisson and ordered probit estimation as robustness checks and found similar results with the multivalued treatment effect using inverse probability weighted regression adjustment (IPWRA) estimation. The multivariate probit, probit, Poisson, and ordered probit estimation results are presented in Tables S3 and S4.

Table 6 presents the multivalued treatment effect results of potential mean outcome (SLM practices applied) of each combination of water management and technology alternatives, including rainfed plots. The multivalued treatment effect results depict that there are significant differences in the number and type of land management practices among irrigated plots benefiting from different combinations of water management systems and irrigation technologies (see Table 6). Unlike the results from ordered probit estimation, the result from multivalued treatment effect analysis reveals that there is statistically significant difference in the number of SLM practices adopted between rainfed plots and irrigated plots in various irrigation water management system and technologies. Adoption of sustainable cropping systems such as crop rotation, fallowing, and legume planting is higher among pump irrigators in any of the management systems (private, users-managed, and jointly managed systems) than gravity-irrigated plots in users-managed and jointly managed systems. Approximately 1.75, 1.53, and 1.02 average number of sustainable cropping practices are adopted in jointly managed, privately managed, and farmer-managed irrigated plots with pump irrigation, respectively, compared with 0.55 and 0.49 sustainable cropping practices in users-managed and jointly managed gravity systems. Farm households also adopt approximately 0.86 average number of sustainable cropping practices in their rainfed plot. Irrigated areas affected by different salinity levels can be restored by introducing improved irrigation and crop management practices. Planting salt-tolerant foregate grasses and legume crops result in remarkable improvement in soil quality. These integrated crop and forage-livestock feeding systems have a capacity to increase resilience of smallholders in Ethiopia (Qureshi et al., 2018).

The use of organic fertilizer (alone or in combination with chemical fertilizers) is the lowest in jointly managed pump irrigation systems compared with other combination of pump and gravity irrigation in open-access, users-managed, and jointly managed systems, including plots in rainfed system (Table 6). Physical soil and water investments are the lowest in user-managed systems (both gravity and pump-based irrigation) compared with private and jointly managed irrigation systems.

The results show a greater number of SLM practices in jointly managed pump irrigated plots (3.08) compared with any of the management systems. On the other hand, plots that are in privately managed pump irrigation systems have a higher number of SLM practices than gravity irrigators in users-managed and jointly managed irrigation plots.

Plots in gravity irrigation systems have adopted lower number of total SLM practices compared with pump applied irrigators. In particular, gravity irrigators in user-managed system have adopted on average only 1.75 number of SLM practices. Specifically, the least numbers of sustainable cropping practices and physical soil and water

**TABLE 6** Estimated average potential number of sustainable management technologies adopted in plots with various combinations of water management and water lifting technologies

Potential outcome means	Privately accessed + pump (1)	Users-managed + pump (2)	Users-managed + gravity (3)	Jointly managed + pump (4)	Jointly managed + gravity (5)	Rainfed
Sustainable cropping system (out of three practices)	1.53** (0.67)	1.02*** (0.22)	0.55*** (0.07)	1.75** (0.70)	0.49*** (0.05)	0.86*** (0.05)
Fertilizer use (compost/manure/green manure alone or with chemical fertilizer) (=1 if organic fertilizer or organic fertilizer with chemical fertilizer is applied)	0.28*** (0.06)	0.30*** (0.08)	0.43*** (0.07)	0.14** (0.07)	0.30*** (0.05)	0.40*** (0.04)
Physical soil and water conservation (out of six practices)	1.40 (0.93)	0.72*** (0.11)	0.43*** (0.07)	1.19 (1.08)	0.80*** (0.10)	0.93*** (0.08)
Total number of SLM practices adopted (out of 10 practices)	2.66*** (0.38)	2.26*** (0.34)	1.75*** (0.17)	3.07* (1.56)	1.84*** (0.15)	2.23*** (0.09)

Note: Standard errors in parenthesis. Statistical significance at \* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .

investments were reported in this alternative. These results suggest that there is a complementary between using pump irrigation and adopting SLM practices.

Table 7 reports the estimated treatment effect on the treated (ATT) by alternatives among different SLM practices. Even if most of the treatment effects are not statistically significant, an important point worth mentioning is applying pump irrigation in any of the water management systems plays a great role in the adoption of SLM practices compared with plots using gravity irrigation and depending on rainfall as a main source of moisture. The estimated ATT of changing the decision from depending on rainfall to adopting privately managed pump irrigation, users-managed pump irrigation and jointly managed pump irrigation led to more 0.63, 0.48, and 0.40 average number of SLM practices, respectively.

Generally, the significant difference between the number of SLM adopted on a plot across different alternatives implies that besides whether to irrigate or not, the type of irrigation water management and the technology applied play a role in restoring degraded soils and maintaining the current condition of the irrigated land, considering that improving and maintaining the soil condition of irrigating plots was not the explicit reason why farmers adopt irrigation.

## 6 | CONCLUSIONS AND POLICY IMPLICATIONS

The government of Ethiopia has made irrigation a pivotal part of its rural development strategy as explained in current and previous development plans such as the previous first and second 5-year growth and transformation plans as well as the current 10-year development plan from 2021 to 2030. This strategy is also supported with actual budget as irrigation comprise the largest share (over one-third) of the total budget of US\$582 million of the Ministry of Agriculture's

Agricultural Growth Program (Passarelli et al., 2018; World Bank, 2015). Given this increased focus in expanding irrigation in the country, this study provides the much needed and so far less explored insights on the linkages between irrigation and SLM and what types of institutional and technological typologies for irrigation enhance adoption of SLM, such that future irrigation investments are designed in a manner that can enhance sustainable land and water management. Six major takeaways emerge from the econometric as well as descriptive analysis of the study.

First, the findings of this study underscore that a considerable part of surveyed farming households in Ethiopia who had adopted irrigation observed some negative soil quality changes such as water-logging, soil salinity, decline in soil fertility, and soil erosion after the development of irrigation on their plots. Long-term sustainability of irrigation development in Ethiopia thus critically depends on the more rapid and wider adoption of SLM technologies in irrigated plots.

Second, in our hypothesis, we stated that access to irrigation water may play a significant role in the adoption of SLM practices. Using ordered probit model, our finding did not show that irrigated plots have higher number of SLM practices than rainfed plots. However, after controlling for heterogeneity among different irrigation water management systems and technologies, indeed, we found that those irrigators who have adopted pump irrigation are with greater number of SLM practices. This result implies that access to irrigation may not only help to increase productivity and food security, but it also plays a major role to motivate farmers to invest in complementary SLM practices. This suggests that the Government of Ethiopia's policy to support groundwater exploitation and, as of April 2019, to allow importing of pump irrigation technologies free of duty is likely to foster adoption of SLM compared with the now common gravity-based irrigation.

Third, physical soil and water investments are the lowest in user-managed systems (both gravity and pump-based irrigation) compared

**TABLE 7** Estimated average treatment effect on the treated (ATT) by alternatives among different SLM categories

Alternatives	Sustainable cropping system		Fertilizer use		Physical S&W conservation		Total SLM	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Private + Pump (1)								
2 versus 1	−0.48	0.68	−0.09	0.07	−0.42	0.93	−0.24	0.42
3 versus 1	−0.52	0.69	0.03	0.07	−0.52	0.95	0.04	0.44
4 versus 1	−0.26	0.69	−0.04	0.08	0.03	1.02	0.68	0.71
5 versus 1	−0.66	0.68	−0.05	0.07	−0.46	0.94	−0.45	0.5
6 versus 1	−0.51	0.67	−0.06	0.06	−0.39	0.93	−0.17	0.39
Farmer + Pump (2)								
1 versus 2	−0.37*	0.23	−0.05	0.09	−0.21*	0.12	−0.66*	0.35
3 versus 2	−0.47	0.23	0.13	0.1	−0.29**	0.13	−0.51	0.38
4 versus 2	0.73	0.73	−0.16	0.11	0.47	1.09	0.81	1.6
5 versus 2	−0.53	0.22	0	0.09	0.08	0.15	−0.43	0.37
6 versus 2	−0.17	0.22	0.1	0.09	0.21	0.14	−0.03***	0.35
Farmer + Gravity (3)								
1 versus 3	0.1	0.08	−0.18**	0.07	0.08	0.08	−0.14	0.19
2 versus 3	0.47	0.23	−0.13	0.1	0.29**	0.13	0.51	0.38
4 versus 3	1.2	0.71	−0.29**	0.1	0.76	1.09	1.32	1.57
5 versus 3	−0.06	0.08	−0.13	0.08	0.37***	0.12	0.09	0.22
6 versus 3	0.30***	0.08	−0.03	0.08	0.50***	0.1	0.48	0.19
Joint + Pump (4)								
1 versus 4	−1.1	0.7	0.1	0.08	−0.68	1.09	−1.47	1.57
2 versus 4	−0.73	0.73	0.16	0.11	−0.47	1.09	−0.81	1.6
3 versus 4	−1.2	0.71	0.29***	0.1	−0.76	1.09	−1.32	1.57
5 versus 4	−1.26	0.7	0.16*	0.08	−0.39	1.09	−1.24	1.57
6 versus 4	−0.9	0.7	0.25***	0.08	−0.26	1.09	−0.84	1.57
Joint + Gravity (5)								
1 versus 5	0.17	0.07	−0.06	0.06	−0.29***	0.11	−0.23	0.18
2 versus 5	0.53	0.22	0	0.09	−0.08	0.15	0.43	0.37
3 versus 5	0.06	0.08	0.13	0.08	−0.37***	0.12	−0.09	0.22
4 versus 5	1.26	0.7	−0.16*	0.08	0.39	1.09	1.24	1.57
6 versus 5	0.36**	0.07	0.1	0.06	0.13	0.13	0.40**	0.17
Rainfed (6)								
1 versus 6	−0.20***	0.07	−0.15***	0.05	−0.41***	0.09	−0.63***	0.13
2 versus 6	0.17	0.22	−0.1	0.09	−0.21	0.14	0.03	0.35
3 versus 6	−0.30***	0.08	0.03	0.08	−0.50***	0.1	−0.48***	0.19
4 versus 6	0.9	0.7	−0.25***	0.08	0.26	1.09	0.84	1.57
5 versus 6	−0.36***	0.07	−0.1	0.06	−0.13	0.13	−0.40***	0.17

with private and jointly managed irrigation systems. In addition, physical soil and water investments are the highest in privately managed pump systems. The results suggest that privately accessed irrigation systems may not suffer from collective action issues in their decision to practice or invest in SLM – a problem that is likely to be a constraint in users – and jointly managed irrigation systems. Thus, promoting SLM practices in users-managed and jointly managed systems needs to be accompanied by interventions that deliberately address collective action issues.

Fourth, the total number of SLM practices adopted is the highest in jointly managed pump systems than any of the four systems. Most of this difference is coming from high number of adoptions of sustainable cropping systems such as rotation, fallowing, and legume planting in jointly managed pump systems. Usually, this kind of system uses pressurized irrigation with high cost on diesel and electricity to pump water from the ground. It appears that the high cost of water extraction is forcing farmers in such irrigation systems to adopt cropping systems that would ensure higher productivity of irrigation water.

Fifth, the use of organic fertilizer (alone or in combination with chemical fertilizers) is the lowest in jointly managed pump irrigation systems compared with other combination of pump and gravity irrigation in users-managed and jointly managed systems. As mentioned above, high energy cost of jointly managed pump systems appears to push farmers' orientation toward high yield inputs such as chemical fertilizers instead of organic fertilizers. The generally limited availability of farmyard manure (FYM) due to its demand for energy within and outside of farm households may also play a role as it shifts FYM allocation away from improving soil fertility toward its use as source of energy (Mekonnen et al., 2017; Mekonnen & Kohlin, 2008; Teklewold, 2012).

Sixth, gravity irrigators in users-managed systems have adopted the least number of total SLM practices. This kind of irrigation system is mostly characterized as traditional irrigation system constructed using local materials, which generally leads to large seepage losses and a deterioration of the water volume to be distributed. This result is contrary to our hypothesis that states irrigation schemes that are initiated and managed by groups of farmers can more easily adopt SLM practices rather than plots that apply privately managed irrigation system that may lead to increased mismanagement of natural resources and lower adoption of SLM practices due to differences in the private and social discount rates in resource use. The fact that SLM practices and investments are the least common in this type of irrigation system is a worrying sign for the sustainability of such systems and requires the attention of stakeholders and institutions.

Generally, the type of irrigation water management and the irrigation technology applied impacts significantly farmers' SLM adoption decisions. Therefore, ongoing irrigation expansion efforts by the government also need to incentivize SLM practices suitable for each combination of irrigation water management system and the irrigation technologies.

## AUTHORS' CONTRIBUTION

All the authors have contributed sufficiently. Rahel Deribe Bekele has made the conception and design of the research, data collection, analysis, and interpretation of data and write-up; Alisher Mirzabaev has contributed substantially to the conception of the research questions and revising the study critically for important intellectual content; Dawit Kelemwork has contributed substantially in providing continuous critical feedback to the intellectual content as well as in helping to shape the research analysis and manuscript as a whole.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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## ENDNOTES

- <sup>1</sup> *Enset (ensete ventricosum)* is an African crop that currently provides the staple food for approximately 20 million Ethiopians (Borrell et al., 2019).
- <sup>2</sup> *Chat (catha edulis)* is a perennial crop and its leaves are chewed for a stimulating effect.

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