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Impact of modern irrigation on household production and welfare outcomes

Evidence from the Participatory Small-Scale Irrigation Development Programme (PASIDP) project in Ethiopia

by
Alessandra Garbero
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Authors:
Alessandra Garbero, Tisorn Songsermsawas

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About the authors

Alessandra Garbero is a senior econometrician in the Research and Impact Assessment Division (RIA), IFAD. Her work focuses on impact assessment methodologies and applied econometrics. She supports RIA strategic management related to the impact assessment production cycle and she is in charge of the estimation and projection of corporate impacts. Her first degree is in economics, with specializations in demography and statistics. She also holds a PhD in epidemiology and population health from the London School of Hygiene & Tropical Medicine.

Tisorn Songsermsawas is an economic analyst in RIA, IFAD. His research focuses on IFAD's overarching goal and objectives related to economic mobility, production, marketing and resilience. He also supports the coordination of impact assessment activities of IFAD-supported projects in various countries in Asia and Africa. He holds a PhD in agricultural and applied economics from the University of Illinois, United States, with a focus on labour economics, development economics and social network analysis, and a BSc in mathematics and economics from Bucknell University, United States, with a focus on statistics and econometrics. He joined IFAD as an economic analyst in 2017 and before that was a consultant for IFAD in 2015. Before joining IFAD, Tisorn served as a graduate instructor at the University of Illinois. He was an intern at both the International Crops Research Institute for Semi-Arid Tropics in Hyderabad, India, and the Food and Agriculture Organization of the United Nations in Rome, Italy.

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Abstract

Irrigation systems have been shown to substantially improve farmers' productivity, and thus help alleviate poverty. Our study provides an example of such investment: the Participatory Small-Scale Irrigation Development Programme in Ethiopia. Combining a primary household survey with geographical data, we estimate the impact of the project on agricultural production and household expenditure using a novel identification strategy. Beneficiaries gain from the project through improved crop yields and greater diversity of crops cultivated, which raise revenues and enable a switch from relying mainly on consuming their own produce to purchasing more food from the market. The lessons learned from this work may help improve the design and implementation of future small-scale irrigation projects to focus on strengthening access to markets. Such focus on access to markets would provide greater opportunities for beneficiaries to take maximum advantage of their improved productive capacity.

1 Introduction

What are the returns to public investments in irrigation infrastructure systems? A number of studies have documented that public investments in agriculture, which have been designed and rolled out to suit local conditions and contexts, may help increase agricultural productivity and resilience capacity of the same group (Asfaw et al., 2012; Haile et al., 2017; Minde et al., 2008; Duflo and Pande, 2007). Investment in irrigation facilities illustrates a special example of improving the agricultural performance of farmers in the developing world by raising productivity (Hussain and Hanjra, 2004). Although the returns to investments in irrigation can potentially be high, the World Bank (2007) reports that irrigation coverage in sub-Saharan Africa (SSA) remains low. Given the low level of irrigation coverage in SSA, a strong case could be made for investing in the expansion of investment in irrigation projects across SSA as a means of improving agricultural productivity, and thereby contributing to rural poverty alleviation (You et al., 2011).

The goal of this study is to assess the impact of the Participatory Small-scale Irrigation Development Programme (PASIDP) in rural Ethiopia.[1] Within the context of irrigation systems in Ethiopia, previous studies have shown that irrigation increases agricultural productivity, improves food security levels, and reduces the dependency on food-for-work programme participation (Amacher et al., 2004; Esrado, 2005; Van Den Berg and Ruben, 2006; Tesfaye et al., 2008; Bacha et al., 2011; Aseyehegu, Yirga and Rajan, 2012; Yami, 2013). While finding positive impacts of irrigation is a desirable outcome, these studies present weak identification strategies, where the presence of a valid counterfactual to attribute the impact of the projects on the outcomes of interest is questionable. This study aims to fill this gap in the literature and investigates the impact of a locally adapted irrigation project (PASIDP), which was introduced in a participatory manner in Ethiopia, by using a rigorous counterfactual-based estimation approach.

PASIDP focused on developing modern small-scale irrigation schemes in drought-prone, food-deficit areas of Ethiopia. Between 2008 and 2015, the project was mainly responsible for building new and upgrading existing small-scale irrigation schemes in several locations in Ethiopian highland and lowland zones. Our analysis uses primary household-level survey data from PASIDP beneficiary and non-PASIDP beneficiary households across 20 *kebeles*[2] in four regions of Ethiopia. Specifically, the study investigated whether such public investments in small-scale irrigation schemes can generate impacts on production (as measured by agricultural yields and revenues) and welfare (as measured using household expenditure levels) of beneficiary households.

1. In this paper, we use the terms “PASIDP irrigation” and “modern irrigation” interchangeably to refer to the small-scale irrigation infrastructure systems supported by PASIDP.
2. A *“kebele”* (historically known as a peasant association) is a local administration unit in Ethiopia, similar to a ward or a subdistrict.

One key challenge of evaluating the impact of an irrigation project is the estimation bias due to the non-random placement of the project, and the self-selection of beneficiaries into receiving the project. The location of an irrigation scheme is likely to be correlated with geographical suitability, village or community characteristics, and pre-existing local conditions such as access to markets or roads. For instance, projects may be implemented in areas that are expected to perform strongly, such as in villages with good access to markets and roads, or may have targeted beneficiaries based on factors that indicate the greatest need, such as villages or communities with high prevalence of poverty or drought. Self-selection into treatment is another common empirical problem when a project is introduced in a participatory manner. Specifically, PASIDP used a participatory approach to promote community involvement and ownership, and required the formation of water user associations (WUAs) and the payment of subscription fees by group members. In this context, a household's participation in the project may be correlated with some underlying unobserved characteristic(s) such as perceived expected returns of modern irrigation, which may be linked with expected outcomes such as yields or revenues.

Our data come from a primary household survey conducted in 2015, commissioned by the International Fund for Agricultural Development (IFAD) and collected by the Ethiopian Institute for Agricultural Research (EIAR). We supplement the household survey with observational data on geographical attributes. In the absence of a valid instrument (Duflo and Pande, 2007), or a regression discontinuity design (Lee and Lemieux, 2010) to assign households into each treatment status, we use a non-experimental design. We control directly for observable household-level characteristics and geographical attributes that might be correlated with the project's targeting strategy or the household's decision to participate in the project. To ensure that the treatment and the control groups in our sample are comparable, the identification strategy foresaw an extensive beneficiary mapping exercise of the households in all kebeles in our sample to establish a sampling frame and determine which households were using different forms of irrigation sources, and allocate them into mutually exclusive treatment and control groups.[3]

In our setting, there are one treatment group and two control groups. The treatment group received access to modern small-scale irrigation schemes, developed by PASIDP, because their plots are located inside the irrigation command area; they also received complementary interventions focused on best practices of agricultural production through farmer research groups and experimental trials. Farmers in one control group did not benefit from the modern irrigation schemes because their plots are located outside the irrigation command area, but they did have access to irrigation water from traditional irrigation methods. The other control group consists of those whose plots are also located outside the irrigation command area, and who rely on seasonal rainfall alone for their agricultural production.

We follow the multivalued treatment effects approach to estimate the impact of PASIDP on its beneficiaries (Cattaneo, 2010). This approach allows us to provide pairwise comparisons among the outcomes of PASIDP beneficiaries, those who use traditional irrigation and those who rely mainly on rainfall. Moreover, it allows us to quantify the additional benefit of having access to modern irrigation relative to traditional forms. We supplement the multivalued treatment effects approach by using an instrumental variable (IV) estimator to account for the potentially endogenous nature of programme placement.

3. The beneficiary mapping exercise was conducted in the form of a reconnaissance survey. More details about the beneficiary mapping exercise are provided in section 3.

We observed significant and positive effects on crop revenues, yields and number of crops grown among PASIDP beneficiaries and households using traditional irrigation compared with the rainfed control group.

Results provide evidence of positive effects of both modern and traditional irrigation schemes on crop yields, crop diversity and revenues, with estimated effects proving consistently positive across all crop yield, crop diversity and revenue quartiles. Households receiving benefits from the project and households using traditional irrigation also had lower values of crop consumption from their own production, with higher levels of food expenditures compared with those of the households using rainfed agriculture. However, we found no significant impact on expenditures on non-food items. The IV results exhibit qualitatively similar findings. Further, we perform a number of robustness checks to validate the estimates.

There are at least two contributions of this study to the literature on rural agricultural development. First, it complements a large body of empirical work aimed at estimating the impact of agricultural projects (e.g. Winters, Maffioli and Salazar, 2011; Cameron, Mishra and Brown, 2016). This is of particular importance for policy purposes, as there is a continued demand from international organizations and donors alike to quantify the impact of agricultural projects. Thus, any empirical contributions to this literature would be beneficial both to address an accountability goal and to support future designs of rural development policies (IDB, 2010; World Bank, 2010). Previous studies have evaluated agricultural projects with different interventions – namely marketing linkages (Cavatassi et al., 2011; González-Flores et al., 2014), agricultural extension (Dercon et al., 2009; Davis et al., 2012; Kondylis, Mueller and Zhu, 2017), research and technology adoption (Hotz et al., 2012; Emerick et al., 2016; Verkaart et al., 2017), microcredit programmes (Li, Gan and Hu, 2011; Karlan et al., 2014; Tarozzi, Desai and Johnson, 2015) and rural infrastructures (Duflo and Pande, 2007; Jensen, 2007; van de Walle, 2009; Del Carpio, Loayza and Datar, 2011; Dillon, 2011b; Gonzalez-Navarro and Quintana-Domeque, 2016). Our study complements the body of studies that adopt a rigorous counterfactual-based approach to evaluate the impact of agricultural projects, specifically the ones focusing on rural infrastructure development.

Second, our findings supplement existing evidence on the impact of rural infrastructure on economic and welfare outcomes in an agricultural setting. Our study relates to a growing number of papers that adopt non-experimental approaches to quantify the impacts of rural infrastructure development. Recent studies have documented the impact of construction or improvements in rural infrastructures, including dams (Duflo and Pande, 2007), roads (Jacoby and Minten, 2009; Khandker, Bakht and Koolwal, 2009; van de Walle, 2009; Gonzalez-Navarro and Quintana-Domeque, 2016), railways (Donaldson, 2018; Donaldson and Hornbeck, 2016), electrification (Dinkelman, 2011; Bernard, 2012), agricultural markets (Renkow, Hallstrom and Karanja, 2004; Fafchamps and Hill, 2005; Shilpi and Umali-Deininger, 2008), mobile-phone services (Jensen, 2007; Muto and Yamano, 2009; Aker, 2010) and irrigation systems (Del Carpio, Loayza and Datar, 2011; Dillon, 2011a,b; Nkhata, 2014; Zeweld et al., 2015; Alaofè et al., 2016).

Specifically, previous studies show that there can be significant economic effects from building or upgrading irrigation infrastructure on agricultural production (Hussain and Hanjra, 2004; Smith, 2004; Van Den Berg and Ruben, 2006; Del Carpio, Loayza and Datar, 2011; Dillon, 2011a,b) and agricultural marketing outcomes (Dorward et al., 2004). Del Carpio, Loayza and Datar (2011) evaluate the impact of an irrigation rehabilitation project in Peru.

They find that large landowners benefit from the project due to higher income from land ownership. For small landowners, the benefit also includes increased agricultural production. Dillon (2011b) finds that households with access to irrigation have higher household expenditures than those of households without access to irrigation in Mali. Moreover, irrigation beneficiaries accumulate more assets in the form of livestock, and are more likely to share food with non-beneficiaries. However, existing studies in this literature provide limited evidence of the mechanisms through which having access to irrigation generates benefits to beneficiaries. Dorward et al. (2004) document that improved marketing outcomes of households with access to irrigated farming systems across different countries in Asia and sub-Saharan Africa include more stabilized crop prices and guaranteed market demand for crops.

The growing intensity of exogenous weather-related shocks due to climate change have direct implications on farmers' agricultural production and, subsequently, on their household income. Thus, the findings of this study will provide insights on how the development of rural infrastructure helps smallholder farmers improve their agricultural outcomes and has direct implications for designing policy aimed at improving the livelihoods of smallholder farmers.

Our study contributes to the literature by directly testing the channels through which irrigation can help households increase the total value of their agricultural production and household consumption. Specifically, we test whether PASIDP beneficiaries have higher crop yields, use higher levels of cash inputs, have larger cultivation areas, or increase the number of crops grown per season. The empirical results from the analysis provide lessons on the project's implementation, which will serve as the basis for scaling up the project to similar geographical settings and targeted beneficiaries in the future.[4] This is particularly important in terms of policy, especially if the project is projected to be scaled up. However, if there is evidence of systematic targeting of projects, then the lessons drawn from this analysis may suffer from not having external validity, which may limit the potential to inform the scalability of the project in the future.

The rest of this paper is organized as follows. In the next section, we outline the details of PASIDP, along with the conceptual framework related to the project's impact on agricultural production and household welfare. In the third section, we present descriptive statistics of the households in our sample. In the fourth section, we describe the identification strategy used to estimate the impact of PASIDP on household production and welfare outcomes. The fifth section presents the estimation results from the multivalued treatment effects approach. The sixth section reports the outcomes from a number of robustness checks, conducted to test the stability of the results. The final section concludes the paper.

4. The project has been scaled up as the Participatory Small-scale Irrigation Development Programme phase II (PASIDP II) starting from late 2016.

2 The PASIDP project

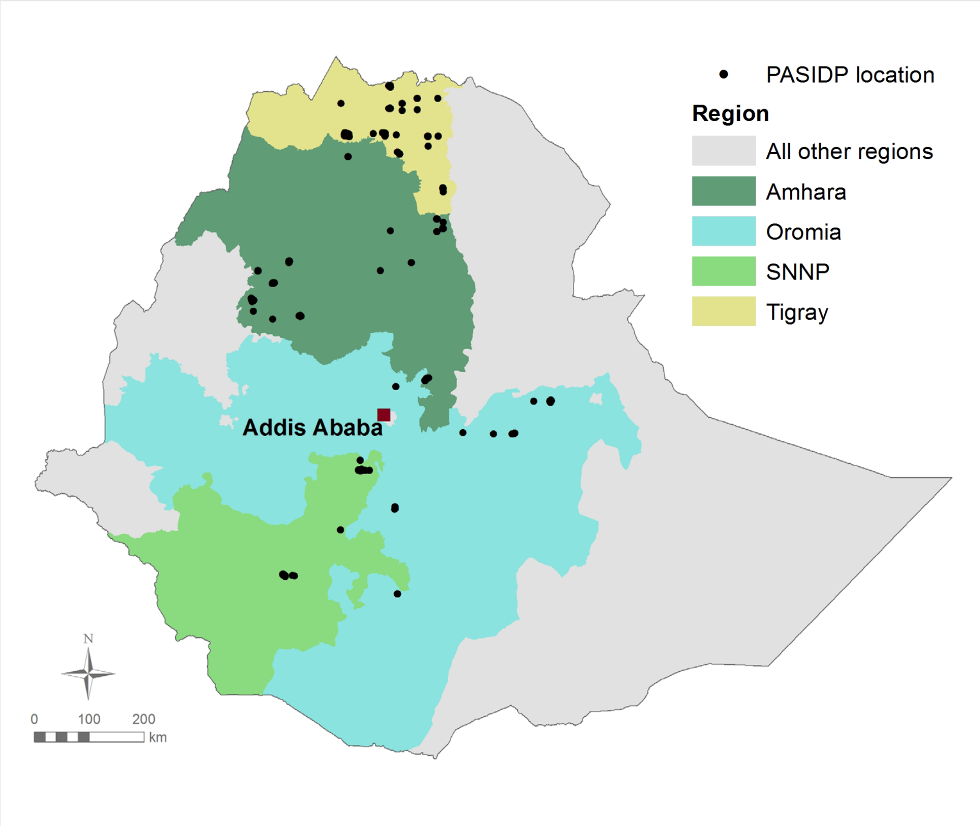
2.1 Project information

Ethiopia's geographical setting and climatic attributes contribute to a higher average amount of rainfall than the rest of SSA (Kassahun, 2007). However, its agricultural sector is constantly plagued by frequent drought and soil degradation (Matouš, Todo and Mojo, 2013). These idiosyncratic shocks to agricultural production are closely linked to the persistence of poverty in rural Ethiopia. Low coverage of irrigation infrastructure also exacerbates the presence of poverty among rural farmers, especially among the poorest of the poor (Del Carpio, Loayza and Datar, 2011; Escobal, 2005).

PASIDP was launched as part of Ethiopia's second-generation Poverty Reduction Strategy Paper (also referred to as the Plan for Accelerated and Sustainable Development to End Poverty, PASDEP). The project received its main financial support (approximately 70 per cent of the total cost) from IFAD as a grant and a highly concessional loan. The remaining cost of the programme was financed by the Government of Ethiopia, and by the beneficiary households through WUA subscription fees. Ethiopia's Ministry of Agriculture and Natural Resources was the main implementation unit of the project, responsible for coordinating project activities with the regional implementation institutions in the four regions covered. The project was specifically designed to have the local WUAs responsible for the construction, operation and maintenance activities of the modern irrigation schemes. This was mainly to create a sense of ownership among the WUA members, incentivizing them to be more committed to maintaining the installed and upgraded facilities.

The project was approved in 2008, and completed in 2015. During this time, 121 irrigation schemes were constructed and the total land area under irrigation increased by more than 12,000 hectares. The activities implemented by the project reached more than 62,000 beneficiary households in four regions (Amhara; Oromia; Southern Nations, Nationalities, and Peoples' Region [SNNPR]; and Tigray) of Ethiopia. The project targeted mainly food-deficit, drought-prone, and densely populated woredas (or districts) covered under the Productive Safety Net Programme (PSNP), but not covered by the Agricultural Growth Program (AGP). Figure 1 presents the locations of the irrigation facilities constructed and upgraded as part of PASIDP.

Figure 1 PASIDP small-scale irrigation locations (Source: IFAD)



The main focus of the project was the development of small-scale irrigation schemes: both construction of new schemes and rehabilitation or upgrading of existing schemes. These schemes vary in size of the command area (ranging from 13 to 460 hectares according to the project's administrative data). The command area refers to the land area which can be irrigated from the schemes, and is suitable for crop cultivation. The specifications (type of scheme, size of command area and other technical aspects) of the irrigation schemes constructed as part of this project were designed by a team of hydrological and environmental engineers that assessed the geographical suitability, environmental impact and potential level of benefits. The process involved in-depth field activities, plus discussions with the government staff and community leaders about the design and construction of the irrigation schemes. Of the 121 schemes built by the project, 71 (59 per cent) are modern river diversions, 18 (15 per cent) are spate (lined canals diverting water from rivers to flood arable land), 14 (11 per cent) are pump-supported, and the remaining 18 (15 per cent) are shallow wells. Extensive discussions were held with staff members of the local institutions on the details of project activities, which depended on the type of scheme built in the community.

The irrigation infrastructure schemes included an extensive network of lined irrigation canals to supply water to the agricultural plots in the command area. The water distributed through the irrigation canals is allocated by the WUA committee according to the training curriculum offered as part of the project to help ensure that the water is distributed fairly and efficiently to all beneficiaries for a given period of time.

In addition to the development of the schemes, the project also provided training and capacity-building activities to the beneficiaries. These activities focused on operational, management and maintenance issues of the irrigation systems. Specifically, project staff trained WUA on how to distribute the flow of water fairly and efficiently from the schemes to the beneficiaries. They also trained the WUA members to ensure that the irrigation canals were not blocked by dirt, sand, branches or leaves. Finally, they trained the WUA members to maintain and repair the schemes to ensure that the schemes were well functioning over the course of the project and beyond.

2.2 Conceptual framework

The offering from PASIDP included irrigation infrastructure, as well as institutional and agricultural development interventions. The interventions were expected to help improve agricultural production and household consumption outcomes of the beneficiaries in the following order. First, the project staff were mandated to help form the WUA within each community selected to receive the project activities. Second, WUA leaders and members received capacity-building and training activities from the project staff. Third, assuming that the capacity-building and training activities went well, PASIDP beneficiaries should have had improved knowledge and information about agricultural production practices.[5] Finally, the irrigation schemes were built in the project communities, and WUA leaders and members received the necessary training to operate, maintain and repair the irrigation schemes.

From the wide range of project activities delivered along with the development of small-scale irrigation, a number of hypotheses may be formulated from the project's logic to test for the possible channels through which a well-functioning irrigation infrastructure system, coupled with the project activities for the WUAs and other capacity-building and training interventions, may contribute to improving the well-being of its beneficiaries (Dillon, 2011b). Access to irrigation may help increase farmers' production by raising crop yields through greater and more stable supply of water for agriculture (Hussain and Hanjra, 2003, 2004). Irrigation also enables farmers to increase the use of other inputs that complement irrigated water such as improved seeds, fertilizer and pesticides (Evenson and Gollin, 2003), as well as expand their cropping area (Huang et al., 2006). It can also allow farmers to start growing market-oriented crops apart from traditional subsistence crops, which supports agricultural diversification (Binswanger and Von Braun, 1991; Smith, 2004). The literature has also noted other possible mechanisms, including reduced water scarcity due to improved water allocation (Prasad, Van Koppen and Strzepek, 2006), increased market access (Gidwani, 2002), increased demand for labour resulting in higher wages (Narayanamoorthy and Deshpande, 2003; Von Braun, 1995), reduced seasonal price variation (Lipton, Litchfield and Faurès, 2003) and increased risk diversification (Barrett, Reardon and Webb, 2001).

In this study, we test for the evidence of impact on the following outcomes: crop yields (as measured by total output per land area), level of input use (as measured by the level of expenditure on cash inputs, namely improved seeds, fertilizer and pesticides), cultivation area (as measured by the total harvested area) and crop diversification (as measured by the number of crops grown in a season).[6]

5. The capacity-building and training activities offered by PASIDP included activities related to vegetable and fruit agronomy, integrated pest management (IPM), post-harvest loss prevention, seed multiplication, improved stove use, and home gardening.
6. Our anecdotal evidence indicates that, due to cash constraints and limited storage space, it is unlikely that farmers would overinvest in the cash inputs for their farms each growing season.

3 Data and setting

The dataset in this study comes from a household survey collected by EIAR, commissioned by IFAD as part of an impact assessment of PASIDP. The full sample consists of 1,531 households in 20 kebeles in four regions of Ethiopia. Primary data collection took place between March and May 2015. To calculate the sample size required for the analysis, we set the parameters at 95 per cent confidence level, with a 0.03 precision level, and computed the final sample with probability proportional to the total population size of the 20 kebeles (Yamane, 1967).

Given the lack of sufficient project information, a number of qualitative interviews (mainly key-informant interviews) were conducted in rural Ethiopia in project areas to gain additional knowledge about the project's implementation. Land ownership in Ethiopia is centrally allocated to households by the government, and formal land transactions are prohibited. In our sample, most of the households in the sample had been assigned the land long before the start of the project.

Our qualitative information suggested that the agricultural setting in each kebele is relatively similar across the villages in the same kebele. The homogeneous characteristics include farm size (mostly small farms), agricultural production (main crops cultivated), agroclimatic conditions (vegetation index and precipitation), and distance to markets and paved roads. As a result, selecting the comparison or control group from another kebele may not have been appropriate in our setting since the conditions facing farmers may have been significantly different.

The household survey used a two-stage stratified sampling approach to select households for the sample as part of the data collection activities. In the first stage, kebeles with completed and functioning PASIDP irrigation schemes were selected from the full list of all PASIDP irrigation schemes at the time of the survey. In the second stage, a beneficiary mapping exercise was conducted to obtain the numbers of households in each kebele using each source of irrigation (modern irrigation, traditional irrigation and rainfed agriculture). Then, proportional sampling was conducted based on the total number of households using each irrigation source in each kebele.

In our full sample, there are 766 PASIDP modern irrigation households (50.0 per cent), 438 traditional irrigation households (28.6 per cent) and 327 rainfed agriculture households (21.3 per cent).[7] In table 1, we report the number of households sampled from each kebele based on their source of irrigation. The number of households in the sample from Oromia and SNNPR are small (representing only 8.5 per cent and 9.6 per cent, respectively, of the full sample). This is because there were fewer functioning irrigation schemes in these regions compared with Amhara and Tigray at the time of our survey. The survey collected detailed household-level characteristics, demographic information, socio-economic status, and agricultural production from the current crop year (February 2014 to January 2015) and from the previous crop year (February 2013 to January 2014). In addition, the survey asked the households to report their asset ownership back to five years preceding the time of the survey to use as baseline information.

7. The steps through which we undertook to arrive at the matched sample used in our analysis are described later in greater detail in section 4.

Table 1 Sample size by irrigation source

Region	Woreda	Kebele	Number of households			
			(1) PASIDP	(2) Traditional	(3) Rainfed	Total
Amhara	Sekela	Kevasa	31	44	11	86
	Jabi Tihnan	Jimmat Yenkonima	36	17	7	60
	Dangila	Gisa Kansen	67	16	0	83
	Guangua	Lunt Degera	17	37	30	84
	Guangua	Dangusa	31	40	0	71
	Kobo	07 (Abuarie)	96	13	7	116
	Kobo	03 (Amaya)	117	23	8	148
	Basona	Angolela	11	8	61	80
Oromia	Deder	Burka Golu	25	25	6	56
	Adola	Chenbe	11	8	6	25
	Oda Bultum	Galessa	6	3	13	22
	Munesssa	Damu Dimbiba	16	2	11	29
SNNPR	Demba Gofa	Tozha Sipe	43	4	8	55
	Meskan	Yetebo	27	31	33	91
Tigray	Enderta	Mahibere Genet	26	45	29	100
	Tselmti	Wudihet	25	15	50	90
	Ahiferom	Edaga Arbi	57	31	0	88
	Mereb Leke	May Weyni	28	24	10	62
	Adwa	Laely Lugumti	79	47	8	134
	Tanqua Abergelle	Negede Birhan	14	1	29	44
Total			**766**	**438**	**327**	**1,531**

Source: primary household survey collected by EIAR (2015).

Table 2 reports basic household-level characteristics of the households in our sample. The heads of households using traditional irrigation were more likely to be male compared with the households in the other two groups. However, they seemed to be similar in terms of age and education level across all three groups. Households using traditional irrigation had larger family size on average than those in the other two groups. While households in the three groups were similar in terms of productive- and livestock-asset ownership at baseline (using recalled information), their ownership of durable assets at baseline exhibited statistical difference. Households with PASIDP irrigation were located at lower elevation than households in the other two groups. They received lower precipitation than households under traditional irrigation, but similar precipitation to households using rainfed agriculture. They had slightly larger landholdings than households using traditional irrigation, but statistically similar to those of rainfed agriculture households. Finally, on average they spent less time travelling to the nearest market than households using rainfed agriculture, but more time than households using traditional irrigation.

Table 2 Household-level descriptive statistics

	Treatment			Overall	(1) versus (2)	(1) versus (3)	(2) versus (3)
	(1) PASIDP	(2) Traditional	(3) Rainfed				
Descriptive characteristics							
Gender of head (=1 if male)	0.868	0.934	0.887	0.891	***		**
Age of head (years)	45.132	45.342	44.037	44.958			
Education of head (years)	2.923	3.080	2.783	2.938			
Household size (head count)	5.570	5.957	5.517	5.669	***		***
Durable asset index (value)	0.491	0.441	0.528	0.484	***	***	***
Livestock asset index (value)	0.905	1.014	0.959	0.948	*		
Productive asset index (value)	1.907	2.005	1.935	1.941	*		
Elevation (km)	1.790	1.916	1.928	1.856	***	***	
Mean precipitation (m/year)	1.016	1.107	0.987	1.036	***		***
Landholding (hectares)	1.131	1.035	1.070	1.091	**		
Time to market (min.)	108.943	101.167	118.413	108.741	*	*	***
N	766	438	327	1,531			

Source: EIAR (2015).

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Durable asset index consists of housing characteristics, namely the type of floor, type of roof, type of wall, number of rooms, type of toilet, and source of water. Livestock asset index consists of the number of animals owned, namely ox, bull, cow, camel, calf, sheep, goat, donkey, horse, mule and poultry. Productive asset index consists of the number of farm implements owned, including plough, sickle, axe, shear, whip, hive, sprayer, miller and cutlass.

In terms of outcome variables, our analysis separates outcomes into intermediate outcomes (production decision and input use) and final outcomes (value of crop production and household expenditures). For the intermediate outcomes (reported in table 3 panel A), households using either PASIDP or traditional irrigation had higher average crop yields than households relying on rainfed agriculture. Households in all three groups allocated similar areas to crop cultivation. However, the crop diversity index was statistically different across all three groups. We follow an approach that uses the share of the number of crops grown by a household relative to the number of crops grown by all households within the same community to calculate the crop diversity index (Michler and Josephson, 2017).[8] PASIDP and traditional irrigation users had higher farm input expenditures on improved seeds and pesticides than households using rainfed agriculture, but there was no significant difference in terms of fertilizer investments across the households in the three groups. The main types of crop grown by the households in our sample were teff, wheat, maize, barley and sorghum. Some households grew root crops, vegetables or fruits as well as the main staple crops. We present some additional summary statistics of crop yields (broken down by crop types) in table A1 in the appendix.

8. This approach to calculate the crop diversity index is preferable to other measures of crop diversity that involve calculating the land areas allocated to each crop, as farmers tend to report cultivation areas with substantial measurement error (Carletto, Savastano and Zezza, 2013; Carletto, Gourlay and Winters, 2015).

Table 3 Household-level intermediate and final outcomes

	Treatment			Overall	(1) versus (2)	(1) versus (3)	(2) versus (3)
	(1) PASIDP	(2) Traditional	(3) Rainfed				
A. Intermediate outcomes							
Improved seed purchases (ETB)	432.503	297.196	120.932	327.246		***	***
Fertilizer purchases (ETB)	1 497.911	1 579.089	1 343.350	1 488.123			
Pesticide purchases (ETB)	126.375	106.879	34.099	101.089		***	***
Mean crop yield (kg/ha)	12 269.217	7 097.578	2 475.121	8 697.795		**	***
Mean cultivation area (ha)	0.674	0.657	0.748	0.685			
Crop diversity index	0.277	0.246	0.187	0.279	***	***	***
N	766	438	327	1,531			
B. Final outcomes[b]							
Per cap. total expenditures (week, ETB)	231.944	227.429	196.749	223.000			
Per cap. food expenditures (week, ETB)	76.951	62.228	51.757	67.376	**	***	*
Per cap. non-food expenditures (week, ETB)	153.45	158.919	142.798	152.727			
Value of crop produced (year, ETB)	11 245.393	7 416.323	5 898.302	9 007.881	*	**	
Value of crop sold (year, ETB)	9 242.478	4 793.445	2 402.215	6 508.682	**	***	***
Value of own crop consumed (year, ETB)	2 691.468	2 886.200	3 647.807	2 951.439		***	
N	766	438	327	1,531			

Source: primary household survey collected by EIAR (2015).

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 1 Ethiopian birr (ETB) = US$0.05 in 2015.

Summary statistics show considerable differences in the final outcomes for the households across the three groups (table 3 panel B). The total value of crop production (both sold and consumed by the household) for PASIDP households was higher than that of the households in the other two groups. However, there was no significant difference in terms of total value of crop production between households using traditional irrigation and those using rainfed agriculture. When specifically considering total crop revenue, PASIDP irrigation users earned significantly more than households in the other two groups. On the other hand, the value of crops consumed from own production was higher for households with rainfed agriculture. Regarding household expenditures, PASIDP irrigation users had higher expenditures on food than households in the other two groups. However, households in all three groups had similar levels in terms of total household expenditures and expenditures on non-food items.

The statistics of the three groups in our sample based on their treatment status reported in tables 1-3 exhibit considerable systematically significant differences. In particular, on average, households in each treatment status were different in terms of asset ownership and geographical attributes. Without a real baseline dataset to control for pre-existing household attributes, the extent to which the treatment effects estimates would achieve internal validity may be limited. Therefore, we acknowledge that the results obtained in the analysis need to be interpreted with caution.

4 Identification strategy

4.1 Construction of counterfactual

Central to establishing a valid counterfactual are the similar characteristics of the treatment and the control groups, and the similar conditions faced by the groups *before* the project. Given the nature of this study – an ex post impact evaluation using cross-sectional data – a direct test of such similarities between the treatment and control groups is not possible. While the household-level descriptive statistics presented in table 2 indicate that there is some evidence that the characteristics of the households across the three groups are significantly different in terms of observed household-level characteristics, several steps are necessary to ensure that the three groups of households in our sample (PASIDP irrigation, traditional irrigation and rainfed agriculture) are as similar as possible in terms of household-level characteristics and agroclimatic conditions.

First, an extensive beneficiary mapping exercise in the form of a reconnaissance survey was conducted to identify a valid counterfactual by gathering information about poverty level, agricultural production system, agroecological zone and source of irrigation of the households within the 20 kebeles in the sample. Second, the sample was selected to ensure that households belonging to each group were similar in terms of poverty levels, agroclimatic conditions and agricultural production system. The sample selection was also validated through extensive interviews with project officials and focal persons from the project management unit and the development agent office at both kebele and woreda levels.

As much as we attempted to construct a valid counterfactual by controlling for the presence of selection on observable attributes and by ensuring sizable common support between the households in all treatment levels, we still needed to make a number of critical assumptions, crucial to our identification strategy. First, we account for selection on observables by controlling for a number of observed characteristics that may affect the participation into treatment; however, we cannot rule out the possibility that there may be some unobserved characteristics that might bias our results. Second, there might be potential spillover effects from PASIDP irrigation users to traditional irrigation users. As a result, our estimates of the impact of the project may underestimate its true effect. Third, we do not have information about the functionality of the irrigation schemes, which could be considered a measure of the intensity of treatment. Therefore, we cannot account for differential treatment intensity for the households that reside in each kebele. Fourth, although we cannot directly test for the presence of pre-existing conditions that may drive the heterogeneity of treatment effects, we can shed some light on this potential heterogeneity of treatment effects by providing the estimates of the conditional means and quartiles of the potential outcome distribution for both estimators.

4.2 Multivalued treatment effects

Given the set-up of our survey, which classifies households in the sample into three categories based on their source of irrigation (modern irrigation, traditional irrigation and rainfed agriculture), we follow the multivalued treatment effects approach of Cattaneo (2010) to estimate the effects of investments in small-scale irrigation schemes due to the project. This method allows researchers to estimate the treatment effects when there are more than two levels of treatment among the individuals in the sample. Further, it allows researchers to compare the treatment effects of the project on outcomes between each pair of treatment levels (PASIDP irrigation households versus traditional irrigation households, PASIDP irrigation households versus rainfall agricultural households, and traditional irrigation households versus rainfall agricultural households). In our setting, our estimation strategy allows us to estimate the additional benefit of having access to modern agriculture (PASIDP) on top of having access to just traditional irrigation.

We follow the description of the identification strategy of Haile et al. (2017), who describe the estimation of the multivalued treatment effects (Cattaneo, 2010). As the first step, we construct the conditional probability model to predict the likelihood of households i $(i = 1, ..., N)$ being in each treatment level ω according to their irrigation status (source of irrigation: 0 = rainfed agriculture, 1 = traditional irrigation, 2 = PASIDP irrigation). Thus, we can write this likelihood function as follows:

$$T(\omega) = \begin{cases} 1 \; if \; \boldsymbol{\Gamma_\omega}'\boldsymbol{Z} + \boldsymbol{\epsilon} > 0 \\ 0 \; if \; otherwise \end{cases}, \tag{1}$$

where $\omega = 0,1,2$; $\boldsymbol{Z}$ is an $n \times m$ matrix of household attributes where there are m $(m = 1, ..., M)$ attributes, and $\boldsymbol{\epsilon}$ is the error term. If we assume that the error term $\boldsymbol{\epsilon}$ is i.i.d. and follows the logistic distribution, we can use the multinomial logit model to estimate the probability that household i is in treatment level ω according to the following model:

$$P(W = \omega | \, \boldsymbol{Z}) = P(\omega) = \frac{\exp(\boldsymbol{\Gamma_\omega}'\boldsymbol{Z})}{1 + \sum_{j=1}^{2} \boldsymbol{\Gamma}_j'\boldsymbol{Z}}, \tag{2}$$

where $\omega = 1,2$, W represents the indicator of treatment status, and $\boldsymbol{Z}$ is the matrix containing household-level covariates. Note that, according to this specification, we assume that selection is largely based on observable characteristics of the households, and that there is sizable common support between the conditional probability densities of the households in all treatment levels.

Similar to the traditional impact evaluation setting, we define our evaluation problem as a potential-outcome model with three levels of treatment. Suppose each household i receives water for their agricultural production from source ω, the potential-outcome model can be written as follows:

$$y_i = \sum_{\tau=0}^{2} T_i(\omega) y_i(\omega), \tag{3}$$

where ω indicates the treatment level that each household belongs to, $T_i(\omega)$ is a dummy variable that is 1 when household i receives irrigation from source ω, and is equal to 0 otherwise, and $y_i(\omega)$ is the outcome of interest if the source of irrigation for household i is ω.

Using a linear specification, we can derive the potential outcome equation in the matrix notation from the potential outcome model as follows:

$$\boldsymbol{Y} = \mathbf{B}_{\boldsymbol{\omega}}{}'\boldsymbol{Z} + \boldsymbol{\epsilon}, \tag{4}$$

where $\boldsymbol{Y}$ is an $n \times 1$ column vector of outcomes of interest, and $\boldsymbol{X}$ is an $n \times k$ matrix of observed household-level characteristics which may contain some of the elements in $\boldsymbol{Z}$ where there are k characteristics $(k = 1, ..., K)$. Given the potential outcome framework, we can write the vector $G_i = (\omega, y(\omega), X)'$ for each household i which assumes to be i.i.d. drawn from the matrix $\boldsymbol{G}$. Thus, we assume that the potential outcome of household i for each treatment level ω, denoted as $\{y_i\,(0), y_i\,(1), y_i\,(2), \}'$ is i.i.d. drawn from $\{y(0), y(1), y(2)\}'$.

Adopting the two-step generalized method of moments approach, Cattaneo (2010) presents two estimators of multivalued treatment effects: inverse probability weighting (IPW) and efficient-influence function (EIF). In the first step, both of these estimators estimate the generalized propensity scores. Then in the second stage, inverse probability weights are calculated to recover the parameter estimates for the potential outcome model in equation (4). A notable difference between the IPW and EIF estimators is that while the IPW estimator models treatment assignment following equation (1), the EIF estimator includes an augmentation term in the potential outcome model to account for the fact that the model may be incorrectly specified. As a result, the EIF estimator contains the doubly robust qualification that will yield consistent treatment effects estimates if the model is specified correctly (Cattaneo, 2010; Tan, 2010). In this study, we present two sets of results from both estimators for comparison purposes.

4.3 Instrumental variable estimate

As mentioned in the introduction to this paper, a key challenge in evaluating the impact of an irrigation project is placement bias. That is, the presence of the project might be correlated with the certain unobservable characteristics unknown to the researcher, which might lead to the potentially endogenous placement of the irrigation scheme. For example, the project implementers may choose to place the project in areas where the project has the potential to become successful because the implementation capacity of the local institution is strong. As a result, we instrument for the treatment status of the project by using the membership size of the local WUA in the kebele. Larger WUA membership may mean that the WUA in the community can take advantage of a larger amount of fees and labour supply from the WUA members to contribute to the operation and maintenance activities of the irrigation scheme.

To qualify as a valid instrument, the size of the WUA membership must satisfy the exclusion restriction. We argue that using the size of the WUA membership to instrument the treatment status is reasonable because it is determined by the number of farmers who have plots inside the command area, and the size of the command area is usually determined by the flow of water according to the analyses carried out by water engineers. Before the construction of the small-scale irrigation schemes by PASIDP, farmers whose plots are located within the command area were invited to register in WUAs and were trained on water management issues related to the irrigation schemes. Therefore, it is unlikely that the size of the WUA membership would be correlated with the outcome variables (i.e. crop yields, crop revenues and/or household consumption). As a result, we argue that the only channel through which the size of the WUA membership can affect the outcome is through treatment.

5 Results

5.1 Multivalued treatment effects results

As the first step to estimate the impact of the project, we construct the conditional probability model to estimate the likelihood that each household would be in each treatment level (PASIDP irrigation, traditional irrigation or rainfed agriculture). In our specification, the full list of covariates to predict treatment status is gender, age and education level of the household head, household size, asset indices as proxies for wealth (durable items, livestock, farm equipment), elevation, average precipitation, size of land ownership, and travel time to the nearest market town.

Figures 2-4 report the conditional probabilities of households being in each treatment level. The estimation results in all three figures illustrate that there is considerable common support for the households in all three groups across all treatment levels, even though the level of common support is slightly lower for the likelihood of households using traditional irrigation. Busso, DiNardo and McCrary (2014) emphasize that if the estimated density contains considerable mass near the values 0 or 1, then under finite sample the IPW and EIF estimators may not perform well. This set of results helps us confirm that there is not much high-density mass at either end of the distribution in all three treatment levels. Thus, the results show that the three groups in our sample are indeed comparable based on a number of observable characteristics.

Figure 2 Conditional probabilities for being in PASIDP irrigation

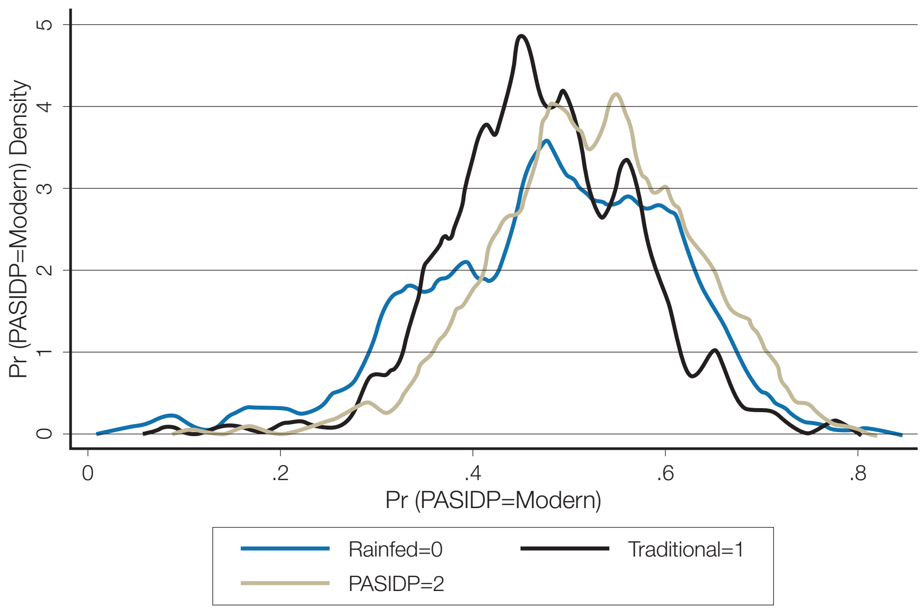


Figure 3 Conditional probabilities for being in traditional irrigation

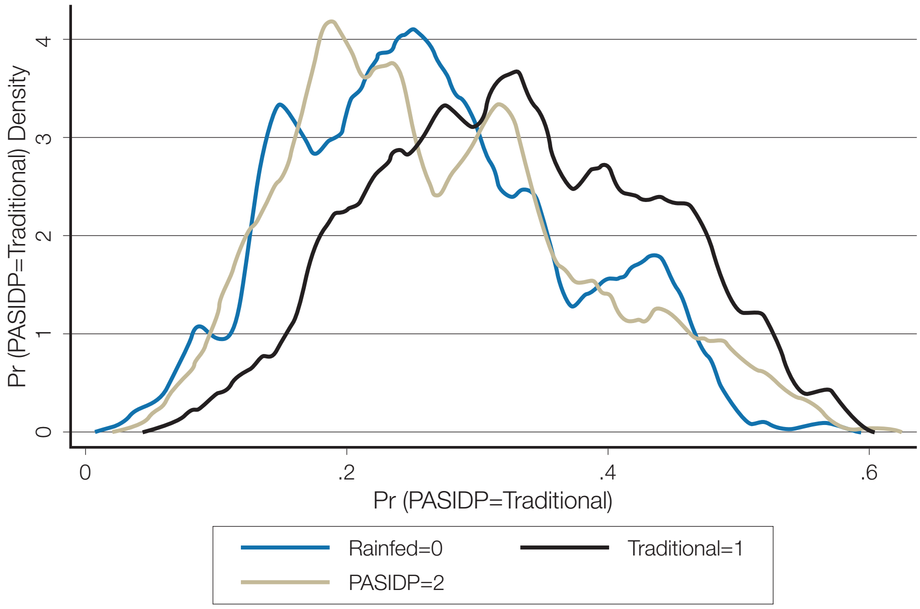
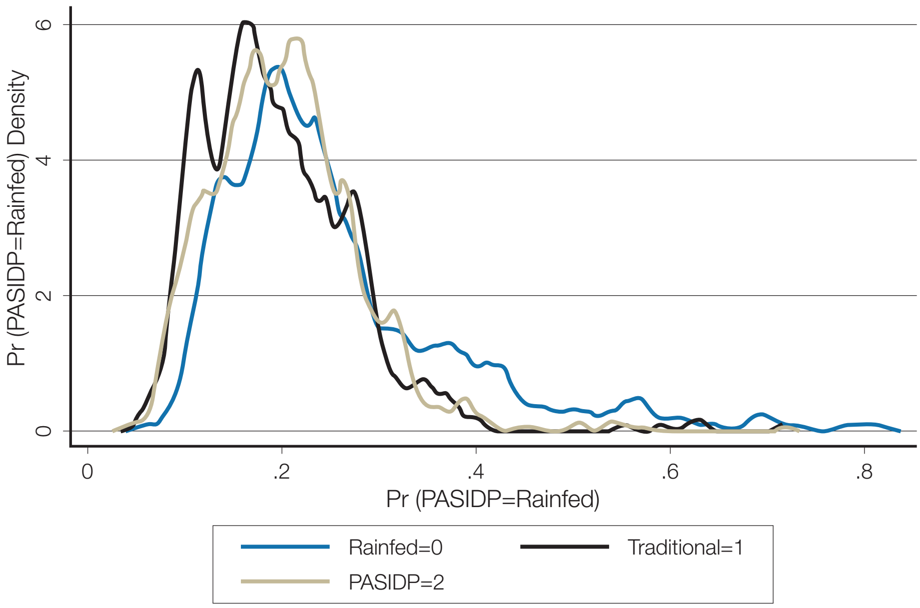


Figure 4 Conditional probabilities for being in rainfed agriculture



In the second step, we estimate the conditional means and quartiles of the outcomes of interest (both intermediate and final outcomes) using both EIF and IPW estimators.[9] Further, we calculate pairwise comparisons of the estimated parameters of the conditional means and quartiles, which represent the average and quartile treatment effects estimates of the project relative to households using traditional irrigation and rainfed agriculture.

We report both the EIF and IPW estimates of the average and quartile treatment effects in tables 5-8. We also present the 95 per cent confidence intervals from bootstrapped standard errors with 500 repetitions (Cattaneo, Drukker and Holland, 2013). The treatment effects estimates are considered to be statistically significant at the 0.05 level if the associated 95 per cent confidence interval does not contain the value 0. To investigate the size of the average and quartile treatment effects, we calculate the exponential values of the pairwise differences of the potential outcomes between two treatment levels. The exponential values of the pairwise differences denote the changes (in levels) in the outcomes of interest with respect to the change in treatment status (going from one treatment level to another). Overall, the results from EIF and IPW estimators are qualitatively similar, which confirms that they are robust and the models are correctly specified. Thus, all our references to the changes in levels will only refer to the pairwise differences from the EIF estimators.

In tables 4 and 5, we illustrate the results due to PASIDP for the intermediate outcomes. The average and quartile treatment effects for farm input investments (namely improved seeds, fertilizer and pesticides) are consistently non-significant across different quartiles for both estimators (table 4). One possible explanation for the non-significant result of the investments in farm inputs is the general scarcity of farm inputs available in the rural markets under analysis.

Next, in table 5, we examine the impact of the project on three other intermediate outcomes: average yield, total cultivation area and the number of crops grown. We observe positive and significant impact of the project on crop yields (average of all crops across the growing season) at the 95 per cent confidence level. The average crop yields of PASIDP irrigation and traditional irrigation households are statistically higher by factors of 1.97 and 1.19 at the 0.05 level when comparing with rainfed agriculture households (column 1). This finding is reasonable because the presence of the project not only provides farmers with greater access to water, but also guarantees access at the right time according to their cultivation schedule. We do not observe significant impacts on the total cultivation area (column 2), which is not surprising for our context since the arable land area is limited for farmers in our sample. We do find that the crop diversity indices of farmers with access to PASIDP irrigation and traditional irrigation are higher than those of rainfed agriculture by factors of 1.09 and 1.02 (column 3). However, the comparison between traditional irrigation households and rainfed agriculture households are only statistically significant when using the IPW estimator, not when using the EIF estimator. Finding the evidence that farmers with access to PASIDP irrigation tend to grow a greater diversity of crop types is reasonable for two reasons. First, improved water supply from irrigation allows farmers to grow crops that are more water-intensive and require water at specific times. Second, farmers can cultivate more cycles of crops in an agricultural season, which may allow them to rotate their cropping patterns in each round of cultivation.

9. These results are not reported in the paper, but are available on request.

Table 6 reports the average and quantile treatment effects of the project on household expenditures outcomes. We do not find significant impact of the project on total household spending. However, when considering only expenditures on food items (based on a seven-day recalled period), PASIDP beneficiaries on average had higher food expenditures relative to rainfed households by a factor of 1.25, which is statistically significant at the 0.05 level. Specifically at the 0.75th quantile, households using PASIDP irrigation spend more on food relative to rainfed households by a factor of 1.51. In other words, among the farmers in the top quantile, households with access to PASIDP irrigation spend as much as 51 per cent more on food purchases compared with those relying on rainfed agriculture. However, households using traditional irrigation on average did not have higher expenditures than households using rainfed agriculture. The point estimates of the project on non-food expenditures are not consistently significant when using EIF and IPW estimators, and are not significant across different quantiles. Thus, we cannot conclude that the project resulted in a significant increase in household expenditures on non-food items among its beneficiaries.

The treatment effects estimates on the value of crop production are shown in table 7. Relative to households using rainfed agriculture, the value of total crop production (sold and self-consumed combined) among PASIDP beneficiaries was significantly higher by a factor of 1.54, while among the traditional irrigation users the effect was higher by a factor of 1.13, both of which are statistically significant at the 0.05 level (table 7, column 1). These figures indicate that the value of crop production among PASIDP beneficiaries is 54 per cent higher than that of those using traditional irrigation, who achieve 13 per cent more crop production than those relying on only rainfall agriculture. When considering only the crop revenue from sales, households using PASIDP irrigation earned more crop revenue than rainfed agriculture households by a factor of 2.10, while households using traditional irrigation earned more crop revenue by a factor of 1.30 (table 7, column 2). We also find that the value of crop consumption from own production among the households significantly decreases by factors of 1.33 and 1.57 among the PASIDP beneficiaries relative to the households using traditional irrigation and households under rainfed agriculture.

Table 4 EIF and IPW estimates of average and quartile treatment effects, intermediate outcomes

	Improved seed purchase (ETB)						Fertilizer purchase (ETB)						Pesticide purchase (ETB)					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment effects																		
Traditional versus Rainfed	0.256	-0.203	0.716	0.163	-0.296	0.623	-0.007	-0.174	0.161	0.035	-0.132	0.203	0.444	-0.348	1.236	0.319	-0.473	1.111
PASIDP versus Rainfed	0.278	-0.133	0.689	0.223	-0.189	0.634	0.065	-0.091	0.222	0.091	-0.065	0.247	0.437	-0.348	1.221	0.360	-0.424	1.145
PASIDP versus Traditional	0.022	-0.183	0.226	0.059	-0.145	0.263	0.072	-0.079	0.223	0.056	-0.095	0.207	-0.007	-0.264	0.251	0.041	-0.217	0.298
0.25 quartile treatment effects																		
Traditional versus Rainfed	0.461	-0.501	1.422	0.444	-0.518	1.406	-0.116	-0.355	0.124	-0.078	-0.318	0.161	-0.138	-0.778	0.503	-0.259	-0.899	0.382
PASIDP versus Rainfed	0.367	-0.598	1.332	0.367	-0.598	1.332	-0.117	-0.307	0.072	-0.103	-0.293	0.086	-0.014	-0.639	0.610	-0.107	-0.731	0.517
PASIDP versus Traditional	-0.094	-0.387	0.200	-0.077	-0.371	0.216	-0.002	-0.234	0.231	-0.025	-0.258	0.207	0.123	-0.188	0.435	0.152	-0.160	0.463
0.50 quartile treatment effects																		
Traditional versus Rainfed	0.154	-0.507	0.814	0.131	-0.530	0.792	0.090	-0.116	0.297	0.110	-0.097	0.317	0.506	-0.125	1.137	0.388	-0.243	1.019
PASIDP versus Rainfed	0.154	-0.442	0.749	0.154	-0.442	0.749	0.211	0.042	0.381	0.225	0.055	0.394	0.318	-0.323	0.960	0.265	-0.377	0.907
PASIDP versus Traditional	0.000	-0.263	0.263	0.023	-0.241	0.286	0.121	-0.062	0.304	0.115	-0.068	0.298	-0.188	-0.603	0.227	-0.124	-0.539	0.291
0.75 quartile treatment effects																		
Traditional versus Rainfed	0.179	-0.233	0.590	0.158	-0.254	0.569	0.051	-0.144	0.246	0.090	-0.104	0.285	0.548	-0.149	1.244	0.436	-0.260	1.133
PASIDP versus Rainfed	0.259	-0.116	0.634	0.259	-0.116	0.634	0.108	-0.091	0.307	0.141	-0.059	0.340	0.604	-0.083	1.290	0.537	-0.150	1.224
PASIDP versus Traditional	0.080	-0.147	0.307	0.101	-0.126	0.328	0.057	-0.086	0.201	0.050	-0.094	0.194	0.056	-0.328	0.440	0.101	-0.283	0.485
N	823			823			1,336			1,336			529			529		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table 5 EIF and IPW estimates of average and quartile treatment effects, intermediate outcomes (cont.)

	Mean crop yield (kg/ha)						Mean cultivation area (ha)						Crop diversity index					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment effects																		
Traditional versus Rainfed	0.762	0.590	0.934	0.779	0.607	0.951	-0.035	-0.238	0.167	-0.044	-0.247	0.158	0.067	0.051	0.084	0.065	0.049	0.082
PASIDP versus Rainfed	0.992	0.847	1.136	1.009	0.865	1.153	-0.096	-0.195	0.004	-0.098	-0.198	0.001	0.083	0.071	0.095	0.082	0.070	0.093
PASIDP versus Traditional	0.230	0.083	0.376	0.230	0.084	0.377	-0.061	-0.265	0.144	-0.054	-0.258	0.150	0.016	-0.001	0.032	0.016	0.000	0.033
0.25 quartile treatment effects																		
Traditional versus Rainfed	0.553	0.390	0.716	0.553	0.390	0.716	-0.063	-0.129	0.003	-0.063	-0.129	0.003	0.042	0.022	0.062	0.049	0.029	0.069
PASIDP versus Rainfed	0.735	0.610	0.861	0.735	0.610	0.861	-0.001	-0.084	0.082	-0.001	-0.084	0.082	0.049	0.034	0.064	0.049	0.034	0.064
PASIDP versus Traditional	0.182	0.048	0.317	0.182	0.048	0.317	0.062	-0.005	0.129	0.062	-0.005	0.129	0.007	-0.007	0.022	0.000	-0.015	0.015
0.50 quartile treatment effects																		
Traditional versus Rainfed	0.734	0.578	0.889	0.742	0.586	0.897	-0.004	-0.174	0.166	-0.004	-0.174	0.166	0.073	0.056	0.091	0.073	0.056	0.091
PASIDP versus Rainfed	1.090	0.945	1.236	1.090	0.945	1.236	0.000	-0.133	0.133	0.000	-0.133	0.133	0.073	0.065	0.081	0.073	0.065	0.081
PASIDP versus Traditional	0.357	0.188	0.526	0.349	0.180	0.518	0.004	-0.096	0.104	0.004	-0.096	0.104	0.000	-0.019	0.019	0.000	-0.019	0.019
0.75 quartile treatment effects																		
Traditional versus Rainfed	0.877	0.663	1.091	0.955	0.741	1.169	-0.004	-0.174	0.166	-0.188	-0.300	-0.075	0.090	0.068	0.112	0.085	0.063	0.107
PASIDP versus Rainfed	1.124	0.971	1.276	1.202	1.050	1.355	0.000	-0.133	0.133	-0.188	-0.320	-0.055	0.098	0.083	0.112	0.093	0.078	0.107
PASIDP versus Traditional	0.247	0.050	0.444	0.247	0.050	0.444	0.004	-0.096	0.104	0.000	-0.085	0.085	0.008	-0.008	0.023	0.008	-0.008	0.023
N	1,531			1,531			1,531			1,531			1,531			1,531		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table 6 EIF and IPW estimates of average and quartile treatment effects, final outcomes

	Per cap. total expenditures (ETB)						Per cap. food expenditures (ETB)						Per cap. non-food expenditures (ETB)					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment effects																		
Traditional versus Rainfed	0.153	-0.009	0.316	0.215	0.052	0.377	0.076	-0.062	0.215	0.090	-0.049	0.229	0.122	-0.059	0.304	0.199	0.017	0.381
PASIDP versus Rainfed	0.179	0.044	0.314	0.228	0.093	0.363	0.264	0.141	0.388	0.273	0.150	0.397	0.115	-0.056	0.286	0.174	0.004	0.345
PASIDP versus Traditional	0.025	-0.115	0.165	0.013	-0.127	0.153	0.188	0.068	0.307	0.184	0.064	0.303	-0.007	-0.156	0.141	-0.025	-0.173	0.124
0.25 quartile treatment effects																		
Traditional versus Rainfed	0.213	-0.128	0.553	0.259	-0.081	0.600	0.000	-0.202	0.202	0.059	-0.143	0.261	0.094	-0.095	0.282	0.157	-0.031	0.345
PASIDP versus Rainfed	0.180	-0.059	0.418	0.213	-0.025	0.452	0.208	-0.024	0.439	0.267	0.036	0.499	0.120	-0.034	0.274	0.148	-0.006	0.303
PASIDP versus Traditional	-0.033	-0.340	0.274	-0.046	-0.353	0.261	0.208	0.009	0.407	0.208	0.009	0.407	0.026	-0.133	0.186	-0.009	-0.168	0.151
0.50 quartile treatment effects																		
Traditional versus Rainfed	0.144	-0.070	0.359	0.220	0.006	0.435	0.096	-0.119	0.310	0.111	-0.104	0.325	0.234	-0.124	0.593	0.306	-0.052	0.665
PASIDP versus Rainfed	0.158	-0.044	0.360	0.232	0.030	0.434	0.175	-0.013	0.363	0.187	-0.001	0.375	0.216	-0.110	0.542	0.299	-0.027	0.625
PASIDP versus Traditional	0.014	-0.169	0.197	0.012	-0.171	0.195	0.079	-0.109	0.267	0.076	-0.112	0.265	-0.019	-0.263	0.225	-0.007	-0.252	0.237
0.75 quartile treatment effects																		
Traditional versus Rainfed	0.181	-0.076	0.438	0.303	0.047	0.560	0.295	0.122	0.468	0.302	0.129	0.475	0.066	-0.216	0.348	0.167	-0.115	0.449
PASIDP versus Rainfed	0.253	0.053	0.453	0.324	0.124	0.524	0.450	0.249	0.651	0.458	0.257	0.659	0.063	-0.120	0.246	0.129	-0.055	0.312
PASIDP versus Traditional	0.072	-0.098	0.242	0.021	-0.149	0.190	0.155	0.005	0.305	0.156	0.006	0.306	-0.003	-0.271	0.265	-0.038	-0.307	0.230
N	1,443			1,443			1,450			1,450			1,519			1,519		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table 7 EIF and IPW estimates of average and quartile treatment effects, final outcomes (cont.)

	Value of crop produced (ETB)						Value of crop sold (ETB)						Value of own crop consumed (ETB)					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment effects																		
Traditional versus Rainfed	0.482	0.245	0.718	0.517	0.281	0.754	0.628	0.295	0.961	0.676	0.343	1.009	-0.133	-0.445	0.179	-0.072	-0.384	0.240
PASIDP versus Rainfed	0.598	0.368	0.828	0.639	0.409	0.869	0.882	0.563	1.201	0.938	0.619	1.257	-0.476	-0.762	-0.190	-0.439	-0.724	-0.153
PASIDP versus Traditional	0.117	-0.067	0.300	0.122	-0.061	0.305	0.254	0.003	0.505	0.262	0.011	0.513	-0.342	-0.538	-0.147	-0.366	-0.562	-0.171
0.25 quartile treatment effects																		
Traditional versus Rainfed	0.443	0.133	0.753	0.436	0.127	0.746	0.411	0.028	0.793	0.430	0.048	0.812	0.017	-0.223	0.258	0.035	-0.205	0.276
PASIDP versus Rainfed	0.505	0.242	0.768	0.515	0.252	0.777	0.585	0.234	0.936	0.673	0.322	1.024	-0.068	-0.336	0.200	-0.068	-0.336	0.200
PASIDP versus Traditional	0.062	-0.166	0.290	0.078	-0.149	0.306	0.174	-0.227	0.575	0.243	-0.158	0.644	-0.085	-0.382	0.211	-0.104	-0.400	0.193
0.50 quartile treatment effects																		
Traditional versus Rainfed	0.257	0.072	0.442	0.273	0.089	0.458	0.642	0.366	0.917	0.642	0.366	0.917	-0.034	-0.169	0.100	0.000	-0.135	0.135
PASIDP versus Rainfed	0.375	0.220	0.530	0.394	0.239	0.549	0.818	0.564	1.072	0.830	0.575	1.084	-0.053	-0.201	0.095	-0.020	-0.168	0.127
PASIDP versus Traditional	0.118	-0.042	0.278	0.121	-0.039	0.281	0.176	-0.070	0.423	0.188	-0.059	0.435	-0.019	-0.104	0.067	-0.020	-0.105	0.065
0.75 quartile treatment effects																		
Traditional versus Rainfed	0.429	0.221	0.638	0.511	0.303	0.719	0.993	0.779	1.208	0.993	0.779	1.208	-0.154	-0.372	0.064	-0.090	-0.307	0.128
PASIDP versus Rainfed	0.576	0.365	0.788	0.658	0.447	0.870	1.188	0.966	1.411	1.188	0.965	1.411	-0.144	-0.345	0.057	-0.086	-0.287	0.115
PASIDP versus Traditional	0.147	-0.083	0.377	0.147	-0.083	0.377	0.195	-0.028	0.418	0.195	-0.028	0.418	0.010	-0.128	0.148	0.003	-0.135	0.141
N	1,474			1,474			1,474			1,474			1,474			1,474		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

5.2 Instrumental variable results

To supplement our results from the multivalued treatment effects approach, we run the IV estimator to control directly for the potential endogeneity of project placement. By using the size of the command area and the planned abstraction rate of the irrigation systems in each kebele to predict the treatment status of the households in our sample, we assume that households that have access to modern irrigation under PASIDP in areas where the command area is larger, and the rate of water abstraction is higher, are more likely to experience a larger project impact. The first-stage regressions for the specifications presented in table 8 can be found in table A2 of the appendix, which helps confirm that our IV meets the exclusion restriction.

We present the results from the IV estimates in table 8, which are coherent with our main results. Specifically, relative to households using rainfed agriculture, households using PASIDP and traditional irrigation had significantly higher crop yields, crop diversity index, crop revenues and per capita food expenditures by 1.789, 0.272, 4.492 and 0.534 times. The Kleibergen-Paap F-statistics of the estimates reported in table 8 indicate that the size of maximal relative bias is lower than 10 per cent when compared with the Stock-Yogo weak identification critical values, which helps to ensure that our results do not suffer from bias due to weak instruments. The statistical significance of the instruments (the size of the command area and the water abstraction rate of the irrigation systems) helps guarantee that the first-stage regressions can accurately predict treatment status. As alternative specifications, we present the pairwise IV results (PASIDP versus traditional, PASIDP versus rainfed and traditional versus rainfed), along with their first-stage regressions in tables A3 and A4 of the appendix.

Table 8 Instrumental variable estimates of average treatment effects

	Crop yields (kg/ha)	Crop diversity (index)	Crop revenue (ETB)	Food expenditures (ETB)
	(1) IV	(2) IV	(3) IV	(4) IV
IV results	1.789***	0.272***	4.492***	0.534***
Treatment status	(0.158)	(0.026)	(0.463)	(0.145)
Kleibergen-Paap F-statistic	69.163	69.163	69.163	67.501
N	1 277	1 277	1 277	1 199

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parenthesis. All outcome variables are in the logarithmic scale. ETB, Ethiopian birr; IV, instrumental variable. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

6 Robustness checks

In this section, we further corroborate our positive findings by providing two additional robustness checks for the presence of potential confounding factors. First, individual unobserved characteristics among the farmers with high (e.g. outside options) and low (e.g. ability) agricultural performance may drive the results due to the possible targeting strategy of the project implementation. We explore this possibility by removing households with the highest 5 per cent and the lowest 5 per cent in terms of productivity levels within each kebele in our sample and re-estimate the multivalued treatment effects model. Second, we test for the possibility that our results might be contingent on the method we use. Thus, we compare our results from the multivalued treatment effects approach to the results obtained from standard matching estimation approaches. Note that the results presented in this section are only for the final outcomes (household expenditures and value of crop production).

6.1 Individual unobserved heterogeneity

One source of concern for the results showing positive and significant impact of PASIDP may be driven largely by specific targeting rules of the project. On the one hand, the project might have specifically targeted high-performing farmers to achieve the highest possible impact. On the other hand, it might have targeted low-performing farmers who may benefit from the project the most. Either possibility may limit the generalizability of the project outcomes, and any attempt to scale up the project should be considered with caution (Bandiera and Rasul, 2006; Liverpool-Tasie and Winter-Nelson, 2012).

Since there is insufficient information about the implementation procedure of the project, we use the average crop yield (as measured in kilograms of output per hectare) as a measure of agricultural performance. To test for potential targeting of the project based on agricultural performance which may drive the results and limit the external validity of the project, we exclude farmers who belong to the highest 5 per cent and the lowest 5 per cent in terms of average yields within each kebele from our matched sample.[10] We report the results from these estimates in tables A5 and A6 of the appendix. Results from this smaller sample still show positive and significant impact of the project on food expenditures and crop revenues among the households using PASIDP irrigation and traditional irrigation (appendix: table A5, column 3 and table A6, column 3). Thus, we may rule out the concern that the project may have targeted households specifically in terms of agricultural performance, which may drive the results obtained.

10. These households account for 13 per cent of the sample in our analysis.

6.2 Alternative estimation methods

Another concern which might arise from our empirical approach is whether the positive and significant results of the project might be method-driven. To rule out such concern, we compare our main results against two other estimators: inverse probability weighting (IPW) and inverse probability weighting with regression adjustment (IPWRA) estimators after conducting propensity score matching as the first step. IPWRA estimators are considered to be "doubly robust" for the method allows greater flexibility of the model being incorrectly specified (Wooldridge, 2007, 2010).[11]

The results from the traditional matching approach using IPW and IPWRA estimators are presented in tables 9 and 10. Our results indicate that households using PASIDP and those using traditional irrigation had higher expenditures on food relative to those of households using rainfed agriculture (table 9, column 4). Similarly to our main results, compared with households under rainfed agriculture, PASIDP irrigation households and traditional irrigation households earned higher crop revenues (table 10, column 4). These two sets of results help us verify that our results are robust across different estimation approaches and communicate consistent findings.

Table 9 Robustness check: IPW and IPWRA estimates of average treatment effects

	Total expenditures (ETB)		Food expenditure (ETB)		Non-food expenditure (ETB)	
	(1) IPW	(2) IPWRA	(3) IPW	(4) IPWRA	(5) IPW	(6) IPWRA
Traditional versus	0.195**	0.204**	0.140	0.177*	0.151	0.175*
Rainfed	(0.090)	(0.087)	(0.098)	(0.092)	(0.106)	(0.100)
PASIDP versus	0.236***	0.224***	0.281***	0.253***	0.190**	0.207**
Rainfed	(0.074)	(0.070)	(0.080)	(0.078)	(0.088)	(0.083)
PASIDP versus	0.001	-0.003	0.138*	0.109	-0.023	-0.007
Traditional	(0.069)	(0.069)	(0.078)	(0.077)	(0.081)	(0.079)
N	688	688	689	689	725	725

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parenthesis. All outcome variables are in the logarithmic scale, and are normalized by the household size (per capita). ETB, Ethiopian birr; IPW, inverse probability weighting; IPWRA, inverse probability weighting with regression adjustment. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

11. The results presented use the kernel option in the matching routine. We also use the five nearest neighbour matching as the first step, and we obtain qualitatively similar results. The results are not presented here, but are available on request.

Table 10 Robustness check: IPW and IPWRA estimates of average treatment effects

	Value of crop production (ETB)		Value of sales (ETB)		Value of own consumption (ETB) (1)	
	IPW (2)	IPWRA (3)	IPW (4)	IPWRA (5)	IPW (6)	IPWRA
Traditional versus	0.493***	0.507***	0.665***	0.546***	-0.236	0.199
Rainfed	(0.161)	(0.154)	(0.222)	(0.201)	(0.182)	(0.175)
PASIDP versus	0.663***	0.718***	0.918***	0.936***	-0.496***	-0.424**
Rainfed	(0.141)	(0.140)	(0.174)	(0.163)	(0.167)	(0.167)
PASIDP versus	0.004	0.004	0.109	0.116	-0.397***	-0.362***
Traditional	(0.091)	(0.093)	(0.125)	(0.120)	(0.139)	(0.137)
N	739	739	524	524	739	739

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parenthesis. All outcome variables are in the logarithmic scale, and are monetary values in Ethiopian birr. ETB, Ethiopian birr; IPW, inverse probability weighting; IPWRA, inverse probability weighting with regression adjustment. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Although the results from the matching method indicate significant and positive impacts of PASIDP on average crop yields, crop diversity, crop revenues and food expenditure among the project beneficiaries, there may still be estimation biases due to any unobservable characteristics at the household or community level. For example, some households may have access to agricultural plots with favourable soil quality while other households may not. Thus, households whose plots have better soil quality tend to have greater productivity levels.[12] Similarly, some communities may receive greater exposure to agricultural extension services, which would allow them to take advantage of the knowledge provided by the extension agents to increase their agricultural productivity, resulting in higher crop revenues.

We test for the extent to which our estimates may be biased due to the underlying observable characteristics using the Rosenbaum bounds method (Rosenbaum, 2002). By increasing the magnitude of hidden bias, γ, the Rosenbaum bounds report the robustness of the estimates from matching due to unobservable characteristics at various levels of increases in the effect of unobservable characteristics. Table A7 in the appendix reports the upper bound significance of the Rosenbaum bounds estimates for the results in tables 9 and 10 by increasing the magnitude of γ up to double, which is considered a high threshold of robustness of results (Aakvik, 2001; DiPrete and Gangl, 2004; Caliendo and Kopeinig, 2008; Dillon, 2011b). The results comparing households using PASIDP irrigation and rainfed agriculture are robust for average yields and crop revenues, but are robust only up to a 40 per cent increase in γ for per capita food expenditures, a finding similar to one found by Dillon (2011a).

12. While we acknowledge that soil quality is an important determinant of agricultural productivity, this information is unavailable in our dataset. We acknowledge that this is a limitation of the study.

With regards to the matching results comparing households under PASIDP irrigation and traditional irrigation, the Rosenbaum bounds indicate that our results are robust to a certain extent: at least 20 per cent for average yields, and at least 10 per cent for crop revenues and per capita food expenditures.[13]

One possible explanation of the Rosenbaum bound results for the comparison between PASIDP and traditional irrigation is treatment heterogeneity in our sample. Two possible sources of treatment heterogeneity may arise in the context of PASIDP. First, it is likely that the performance of the irrigation schemes may vary across locations due to differential local capacity to operate and maintain the irrigation schemes. And second, the length of time since the irrigation schemes became operational may indicate the extent to which the WUA members have learned to operate and maintain the irrigation schemes more efficiently over time. However, we do not have reliable data on the functionality or the completion date of the irrigation schemes to control directly for these two possible sources of heterogeneity. Dillon (2011a) also notes a similar explanation for the limited robustness of his findings for some of the outcome variables in his study of an irrigation project in Mali.

13. The full set of Rosenbaum bound results are available on request.

7 Conclusion

Small-scale farmers in the developing world face multiple challenges that limit their opportunities to achieve higher agricultural productivity and improve their living conditions. One promising channel to help farmers attain more desirable agricultural outcomes is to increase their access to water, an important input for agricultural activities. Several studies have noted the positive and significant benefits of irrigation infrastructure on agriculture. However, the mechanisms through which the access to irrigation may correlate with the observed changes in outcomes are not well documented. A study by Lipton, Litchfield and Faurès (2003) provides detailed explanations of several channels through which irrigation may generate benefits to those who have access to it.

Our study also contributes to the growing need for rigorously conducted impact evaluations of agriculture-related projects made by international financial institutions, including the Inter-American Development Bank (IDB) and the World Bank (IDB, 2010; World Bank, 2010; Winters, Maffioli and Salazar, 2011). Specifically, our study adds to the small but growing number of counterfactual-based impact evaluations of irrigation projects (Del Carpio, Loayza and Datar, 2011; Dillon, 2011a,b).

Our results document significant positive impact of PASIDP, an irrigation development project in Ethiopia carried out between 2008 and 2015. Relative to households resorting to rainfed agriculture for their crop production, we find that households using PASIDP and traditional irrigation had higher crop yields on average and tended to grow a more diverse range of crops, but the effects are not significant on intermediate outcomes such as investments in farm inputs (improved seeds, fertilizer and pesticides), size of cultivation area and number of crops grown. However, in terms of final outcomes, the effects are positive and significant mainly for crop revenue and household food expenditures, and PASIDP beneficiaries consume lower values of crops from their own production. Although we used the multivalued treatment effects approach as the main methodology of reference to estimate the impact of the project, we also conducted robustness checks using different estimators. To this end, the IV estimates also provide qualitatively similar results, illustrating significant impacts of the project and accounting for the possible presence of endogeneity and selection on unobservable characteristics. These results support the hypotheses at the basis of the theory of change, notably that an irrigation project may help farmers improve their well-being by raising their agricultural productivity. However, given the cross-sectional nature of this study and its inherent data limitations, we were not able to control directly for any time-varying unobservable characteristics that may drive the results, such as changing market conditions or agroclimatic factors.

We acknowledge a number of limitations in our study. First, while we have ruled out the possibility that the project targeted specifically more productive farmers, we cannot rule out the possibility that the project may have been designed to target selected local communities based on a number of observed attributes. The implications of this targeting process might hinder the generalizability of the results obtained from this study and the potential to advise future efforts to scale up the project in regions where pre-existing conditions are very different. Second, the sampling strategy of the household survey used in this study did not allow us to estimate spillover effects due to the programme. Given the nature of this irrigation project, the presence of spillovers within kebeles is highly likely. Estimating spillover effects, when they exist, may help identify the additional indirect benefits of a project beyond its direct beneficiaries. This finding motivates future research into the mechanisms through which an irrigation project may generate additional impacts beyond its direct beneficiaries, as well as additional ex ante research that could take into account both the presence of spillovers and the possible implications of systematic targeting.

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Appendix: additional tables and results

Table A1 Yield estimates by crop type

	Treatment						
	(1) PASIDP	(2) Traditional	(3) Rainfed	Overall	(1) versus (2)	(1) versus (3)	(2) versus (3)
Average yields by crop type (kg/hectare)							
All crops	7 200.161	4 518.342	2 293.990	5 385.037	**	***	***
All grains	2 710.826	1 945.278	2 084.476	2 358.033	***	***	
All cereals	2 669.262	1 910.949	1 987.272	2 306.655	***	***	
Teff	589.867	485.076	302.614	498.534	**	***	***
Wheat	365.652	392.764	591.627	421.674		***	***
Maize	1 653.389	1 281.216	1 017.034	1 410.998	***	***	*
Barley	190.042	210.481	547.145	272.162		***	***
Sorghum	1 149.695	517.598	525.335	835.505	***	***	
Vegetables	1 370.538	813.593	50.478	929.257	**	***	***
Roots	3 623.991	2 704.928	342.635	2 660.207	**	***	***
Fruits	333.485	255.474	0.979	240.148			***
Other permanent crops	1 598.948	602.947	310.755	1 038.864			
N	766	438	327	1,531			

Source: EIAR (2015).

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

Table A2 IV results: first stage IV estimates

	Treatment	Treatment	Treatment	Treatment
	(1) OLS	(2) OLS	(3) OLS	(4) OLS
Size of command area	-0.001***	-0.001***	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Abstraction rate	0.328***	0.328***	0.328***	0.332***
	(0.035)	(0.035)	(0.035)	(0.035)
Gender of head (=1 if male)	-0.097	-0.097	-0.097	-0.104
	(0.071)	(0.071)	(0.071)	(0.073)
Age of head (years)	0.004**	0.004**	0.004**	0.004**
	(0.002)	(0.002)	(0.002)	(0.002)
Education of head (years)	0.009	0.009	0.009	0.009
	(0.006)	(0.006)	(0.006)	(0.007)
Household size (head count)	0.004	0.004	0.004	0.006
	(0.011)	(0.011)	(0.011)	(0.012)
Durable asset index (value)	0.212**	0.212**	0.212**	0.222**
	(0.111)	(0.111)	(0.111)	(0.112)
Livestock asset index (value)	-0.070***	-0.070***	-0.070***	-0.080***
	(0.026)	(0.026)	(0.026)	(0.028)
Productive asset index (value)	-0.008	-0.008	-0.008	-0.008
	(0.027)	(0.027)	(0.027)	(0.027)
Elevation (km)	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
Mean precipitation (m/year)	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Landholding (hectares)	0.122***	0.122***	0.122***	0.118***
	(0.028)	(0.028)	(0.028)	(0.031)
Time to market (min.)	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
N	1 277	1 277	1 277	1 199

Note: Statistical significance at * p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors in parenthesis. The number of WUA membership variable is in the logarithmic scale. OLS, ordinary least squares. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table A3 Alternative specification: IV estimates of average treatment effects

	Crop yields (kg/ hectare)	Crop diversity (index)	Crop revenue (ETB)	Food expenditure (ETB)
	(1) IV	(2) IV	(3) IV	(4) IV
Traditional versus	3.277***	0.203***	8.438***	0.369
Rainfed	(0.422)	(0.054)	(1.279)	(0.402)
Kleibergen-Paap F-stat.	20.957	20.957	20.957	20.331
N	591	591	591	546
PASIDP versus	3.399***	0.466***	8.889***	1.027***
Rainfed	(0.286)	(0.048)	(0.872)	(0.274)
Kleibergen-Paap F-stat.	71.092	71.092	71.092	68.967
N	899	899	899	855
PASIDP versus	4.128***	1.329***	11.334***	3.238***
Traditional	(0.798)	(0.286)	(2.738)	(0.886)
Kleibergen-Paap F-stat.	11.329	11.329	11.329	11.550
N	1,064	1,064	1,064	997

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parenthesis. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table A4 Alternative specification: first stage IV estimates

	Traditional versus Rainfed	PASIDP versus Rainfed	PASIDP versus Traditional
	(1) OLS	(2) OLS	(3) OLS
Size of command area	-0.001***	-0.001***	-0.000
	(0.000)	(0.000)	(0.000)
Abstraction rate	0.243***	0.190***	0.045*
	(0.040)	(0.021)	(0.026)
Gender of head (=1 if male)	0.145**	-0.147	-0.148***
	(0.066)	(0.042)	(0.049)
Age of head (years)	0.003	0.003**	-0.000
	(0.002)	(0.001)	(0.004)
Education of head (years)	0.009	0.008*	0.002
	(0.006)	(0.004)	(0.004)
Household size (head count)	0.015	0.005	-0.008
	(0.010)	(0.008)	(0.008)
Durable asset index (value)	0.331***	0.196***	-0.102
	(0.094)	(0.068)	(0.074)
Livestock asset index (value)	-0.014	-0.047***	-0.030
	(0.023)	(0.018)	(0.019)
Productive asset index (value)	0.003	0.004	0.013
	(0.024)	(0.017)	(0.019)
Elevation (km)	0.000***	0.000***	-0.000***
	(0.000)	(0.000)	(0.000)
Mean precipitation (m/year)	0.000**	0.000	-0.000**
	(0.000)	(0.000)	(0.000)
Landholding (hectares)	0.040	0.063***	0.057***
	(0.027)	(0.018)	(0.021)
Time to market (minutes)	-0.001***	-0.000	0.000***
	(0.000)	(0.000)	(0.000)
N	591	899	1,064

Note: Statistical significance at * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parenthesis. The number of WUA membership variable is in the logarithmic scale. Covariates include household size, sex, age, and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock, and productive farm assets), land ownership, elevation, average precipitation during the past ve years, and time to the nearest market.

Table A5 Robustness check: EIF and IPW estimates of average and quartile treatment effects

	Per cap. total exp. (ETB)						Per cap. food exp. (ETB)						Per cap. non-food exp. (ETB)					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment effects:																		
Traditional versus Rainfed	0.082	-0.106	0.270	0.163	-0.025	0.352	0.040	-0.138	0.219	0.056	-0.122	0.235	0.062	-0.125	0.249	0.165	-0.022	0.352
PASIDP versus Rainfed	0.091	-0.040	0.223	0.160	0.029	0.292	0.225	0.052	0.398	0.238	0.065	0.411	0.011	-0.162	0.183	0.097	-0.076	0.269
PASIDP versus Traditional	0.009	-0.143	0.160	-0.003	-0.155	0.148	0.185	0.029	0.340	0.182	0.026	0.337	-0.052	-0.179	0.076	-0.069	-0.196	0.059
0.25 quartile treatment effects:																		
Traditional versus Rainfed	0.082	-0.302	0.467	0.230	-0.154	0.614	0.007	-0.217	0.230	0.051	-0.173	0.274	0.096	-0.135	0.328	0.115	-0.117	0.346
PASIDP versus Rainfed	0.027	-0.217	0.271	0.158	-0.086	0.401	0.203	-0.019	0.426	0.246	0.023	0.468	0.027	-0.142	0.196	0.046	-0.123	0.214
PASIDP versus Traditional	-0.055	-0.344	0.234	-0.072	-0.362	0.217	0.197	-0.005	0.399	0.195	-0.007	0.397	-0.069	-0.262	0.124	-0.069	-0.262	0.124
0.50 quartile treatment effects:																		
Traditional versus Rainfed	0.095	-0.122	0.312	0.176	-0.040	0.393	0.030	-0.276	0.336	0.067	-0.239	0.373	0.138	-0.195	0.470	0.321	-0.012	0.653
PASIDP versus Rainfed	0.093	-0.112	0.298	0.169	-0.036	0.374	0.137	-0.078	0.352	0.171	-0.044	0.387	0.073	-0.233	0.379	0.203	-0.103	0.509
PASIDP versus Traditional	-0.002	-0.168	0.164	-0.007	-0.173	0.159	0.107	-0.142	0.356	0.104	-0.145	0.354	-0.065	-0.322	0.193	-0.118	-0.376	0.140
0.75 quartile treatment effects:																		
Traditional versus Rainfed	0.036	-0.298	0.370	0.204	-0.131	0.538	0.264	0.005	0.524	0.289	0.030	0.548	0.021	-0.219	0.262	0.123	-0.117	0.364
PASIDP versus Rainfed	0.081	-0.200	0.363	0.248	-0.033	0.530	0.415	0.141	0.689	0.436	0.162	0.710	-0.023	-0.250	0.204	0.066	-0.161	0.293
PASIDP versus Traditional	0.046	-0.176	0.267	0.045	-0.177	0.266	0.151	-0.051	0.353	0.147	-0.055	0.349	-0.045	-0.275	0.185	-0.058	-0.287	0.172
N	1,307			1,307			1,314			1,314			1,319			1,319		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table A6 Robustness check: EIF and IPW estimates of average and quartile treatment effects (cont.)

	Value of crop produced (ETB)						Value of sales (ETB)						Value of own cons. (ETB)					
	(1) EIF			(2) IPW			(3) EIF			(4) IPW			(5) EIF			(6) IPW		
	Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.		Contrast	95% C.I.	
Average treatment *effects*																		
Traditional versus Rainfed	0.309	0.039	0.580	0.369	0.099	0.639	0.476	0.169	0.782	0.557	0.251	0.864	-0.168	-0.581	0.244	-0.082	-0.494	0.331
PASIDP versus Rainfed	0.429	0.189	0.670	0.487	0.247	0.728	0.741	0.515	0.966	0.822	0.597	1.048	-0.454	-0.866	-0.043	-0.395	-0.807	0.016
PASIDP versus Traditional	0.120	-0.108	0.347	0.118	-0.109	0.346	0.265	0.030	0.500	0.265	0.029	0.500	-0.286	-0.546	-0.026	-0.314	-0.574	-0.053
0.25 quartile treatment *effects*																		
Traditional versus Rainfed	0.275	-0.025	0.575	0.296	-0.004	0.596	0.287	-0.177	0.751	0.356	-0.108	0.820	-0.004	-0.260	0.253	0.008	-0.248	0.265
PASIDP versus Rainfed	0.322	0.101	0.542	0.344	0.123	0.564	0.470	0.079	0.860	0.538	0.148	0.929	-0.008	-0.301	0.285	0.000	-0.293	0.293
PASIDP versus Traditional	0.046	-0.203	0.295	0.048	-0.201	0.297	0.182	-0.259	0.623	0.182	-0.259	0.623	-0.005	-0.256	0.247	-0.008	-0.260	0.243
0.50 quartile treatment *effects*																		
Traditional versus Rainfed	0.164	0.004	0.324	0.175	0.014	0.335	0.545	0.284	0.806	0.624	0.363	0.885	-0.111	-0.314	0.092	-0.034	-0.237	0.169
PASIDP versus Rainfed	0.281	0.125	0.437	0.300	0.144	0.456	0.693	0.491	0.894	0.757	0.556	0.959	-0.116	-0.297	0.065	-0.040	-0.221	0.140
PASIDP versus Traditional	0.117	-0.042	0.276	0.126	-0.033	0.284	0.148	-0.083	0.378	0.133	-0.097	0.364	-0.005	-0.146	0.135	-0.006	-0.147	0.134
0.75 quartile treatment *effects*																		
Traditional versus Rainfed	0.287	0.009	0.564	0.379	0.102	0.656	0.826	0.599	1.054	0.886	0.658	1.113	-0.220	-0.475	0.035	-0.104	-0.360	0.151
PASIDP versus Rainfed	0.437	0.209	0.666	0.530	0.301	0.758	1.028	0.801	1.256	1.077	0.849	1.305	-0.182	-0.393	0.028	-0.073	-0.284	0.137
PASIDP versus Traditional	0.151	-0.066	0.367	0.151	-0.066	0.367	0.202	-0.082	0.486	0.192	-0.092	0.475	0.038	-0.125	0.201	0.031	-0.132	0.194
N	1,390			1,390			1,123			1,123			1,390			1,390		

Note: All standard errors are bootstrapped with 500 repetitions. All outcome variables are in the logarithmic scale. Covariates include household size, sex, age and education level of the household head, asset-based wealth index at baseline from recalled information (durable, livestock and productive farm assets), land ownership, elevation, average precipitation during the past five years, and travel time to the nearest market.

Table A7 Rosenbaum bounds of impact estimates from matching

Gamma	Average crop yields (kg/hectare)			Crop revenue (ETB)			Per capita food expenditure (ETB)		
	Upper bound C.I. significance level			Upper bound C.I. significance level			Upper bound C.I. significance level		
Traditional versus Rainfed									
1	0.000	0.636	0.839	0.000	0.447	0.846	0.017	0.044	0.345
1.2	0.000	0.549	0.947	0.000	0.267	1.017	0.270	-0.096	0.490
1.4	0.000	0.466	1.038	0.007	0.112	1.156	0.747	-0.214	0.608
1.6	0.000	0.399	1.109	0.071	-0.030	1.281	0.962	-0.319	0.714
1.8	0.000	0.346	1.182	0.275	-0.152	1.397	0.997	-0.413	0.807
2.0	0.000	0.290	1.242	0.570	-0.262	1.502	0.999	-0.493	0.890
PASIDP versus Rainfed									
1	0.000	0.861	1.019	0.000	0.742	1.060	0.000	0.254	0.475
1.2	0.000	0.760	1.125	0.000	0.548	1.253	0.000	0.114	0.614
1.4	0.000	0.677	1.210	0.000	0.386	1.416	0.055	-0.003	0.727
1.6	0.000	0.602	1.288	0.000	0.247	1.559	0.449	-0.108	0.826
1.8	0.000	0.539	1.354	0.002	0.126	1.691	0.878	-0.198	0.912
2.0	0.000	0.481	1.416	0.037	0.014	1.809	0.990	-0.278	0.992
PASIDP versus Traditional									
1	0.000	0.091	0.255	0.052	-0.002	0.306	0.002	0.085	0.318
1.2	0.081	-0.011	0.356	0.624	-0.183	0.491	0.212	-0.061	0.465
1.4	0.639	-0.103	0.448	0.975	-0.335	0.650	0.823	-0.181	0.588
1.6	0.970	-0.178	0.523	0.999	-0.470	0.790	0.992	-0.285	0.693
1.8	0.999	-0.248	0.591	0.999	-0.589	0.914	0.999	-0.376	0.787
2.0	0.999	-0.310	0.654	1.000	-0.696	1.025	1.000	-0.456	0.870

Note: Rosenbaum bounds are calculated at the 10% significance level.

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International Fund for Agricultural Development
Via Paolo di Dono, 44 - 00142 Rome, Italy
Tel: +39 06 54591 - Fax: +39 06 5043463
Email: ifad@ifad.org
www.ifad.org

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