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How does adoption of labor saving agricultural technologies affect intrahousehold resource allocations? The case of push-pull technology in Western Kenya

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ABSTRACT

Considerable research documents why women farmers have lower technology adoption rates than men farmers, but relatively little is known about what happens within a household after technology uptake. This study contributes through an investigation of the intrahousehold distribution of benefits and costs of agricultural technology adoption in western Kenya. Using gender-disaggregated data and an endogenous switching regression approach, we elucidate the causal effects of push pull technology (PPT) adoption on intrahousehold labor and expenditure allocation. Results show that adoption increases household labor allocation for harvesting of maize, the staple crop, but reduces the labor required for other tasks (e.g., ploughing and weeding). In net, the technology is labor saving, with men experiencing a slightly greater workload reduction than women. In terms of expenditure impacts, PPT uptake increases household expenditures on children's education and consumption goods commonly associated with female preferences. Study findings support wider uptake of PPT to trigger gains in social and economic wellbeing for both men and women farmers. Implications for policy and practice are discussed.

1. Introduction

The agricultural productivity gap between men and women farmers in sub-Saharan Africa (SSA), is persistent and large, with recent estimates of average productivity deficiency at 13–25 percent (O'Sullivan et al., 2014; Kilic et al., 2014). To close this gender productivity gap, rural development programs in SSA highlight technology adoption by women farmers as an essential strategy. Uptake of improved agricultural technologies also offers promise for promoting women's empowerment and advancing broader welfare outcomes, such as improved food and nutrition security and reduced poverty (Jones et al., 2019; Larochelle et al., 2014; Malapit and Quisumbing, 2015; Magrini and Vigani, 2016; Zeng et al. 2015). To inform the implementation of such a strategy, considerable research has investigated the influence of gender roles and responsibilities on the three phases of technology adoption: awareness, tryout, and continued adoption (Lambrecht et al., 2014; Lindner et al., 1979).

Studies show that prevailing gender norms hinder the ability of women to gain awareness of new technologies by limiting their mobility, access to extension services, interactions with other farmers, and educational opportunities (Fisher et al., 2000; Fletschner and Mesbah, 2011). Lower tryout and continued adoption of new agricultural technologies by women vs. men farmers is most often attributed to women having reduced access to resources that enable technology uptake, such as financial capital, land, labor, and agricultural extension (Doss and Morris, 2001; Smale, 2005; Fisher and Kandiwa, 2014). Also implicated are gender-based differences in technology preferences (Beuchelt and Badstue, 2013; Fisher and Carr, 2015) coupled with a culture among those disseminating technologies that perceive the farmer client as male (Ragasa, 2014).

While much is known about why women farmers have lower technology adoption rates than men farmers, there is relatively limited understanding of "what happens within a household after it adopts a technology" (Theis et al. 2018, p. 671), that is, how the benefits and

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costs are distributed among women, men, and child household members. This knowledge gap partly reflects that agricultural technology impact assessments have often been guided by the unitary household model (Becker, 1981). Since the unitary model assumes that households possess a single utility function and lack conflict, analysts using that model are unlikely to look within the household when assessing impact of technical change. There are several alternatives to the unitary household model, such as bargaining models (Manser and Brown, 1980; McElroy and Horney, 1981), the cooperative-conflict model (Sen, 1990), and the transaction cost approach (Pollak, 1985). Importantly, these intrahousehold decision-making models recognize that households are characterized by variation in preferences among household members, incomplete pooling of resources, and potential for conflict among household members over the distribution of resources. Researchers employing these models are guided to investigate intra-household issues, such as how technology adoption might change the welfare of individual household members or their relative position or status within the household.

This study, guided by intrahousehold decision-making models, investigates the intrahousehold distribution of benefits and costs of adoption of agricultural technology in Kenya. Two main research questions are addressed. First, how is the agricultural workload of women and men household members differentially influenced by technology adoption? Second, what is the impact of technology adoption on household spending on children's education and consumption goods associated with women's preferences? Answering these questions is not straightforward, because the same factors that affect the outcome variables (e.g., labor supply, spending on children's education) may also affect technology adoption. Thus, there are potential endogeneity issues, which we address using an endogenous switching regression approach.

We consider the case of push–pull technology (PPT) developed and promoted by the International Centre of Insect Physiology and Ecology (*icipe*) and its partners in several SSA countries to mitigate the devastating effects of stemborers and *Striga* (witch weed species) in cereal crops production. The technology involves a planting system in which cereals are intercropped with a fodder perennial legume (*desmodium*) that repels stemborers and suppresses the *Striga* weed, and surrounded by a border perennial grass (e.g. *pennisetum purpureum*/napier grass or *brachiaria* species) that attracts (pulls) stemborers away from the cereal crop (Khan et al., 2014). The technology offers smallholder farmers an opportunity to increase crop and livestock productivity, which contributes to improved incomes and nutritional quality in smallholder households (Kassie et al., 2018). The PPT approach also holds the potential to enhance human health and increase biodiversity by reducing the use of costly synthetic insecticides and herbicides (Pickett et al., 2014). The specific characteristics of the technology such as soil replenishment, weed suppression, and fodder supply for livestock may also introduce changes in input requirements in the cereal-livestock farming systems, such as labor requirements for different activities performed by men and women.

How technology adoption influences men, women, and children in a household depends on several factors, such as characteristics of the technology (e.g., labor-saving vs. labor-increasing), existing gender norms (e.g., gender division of labor), and the relative bargaining position of household members. PPT adoption is expected to reduce labor allocation for ploughing and weeding, largely because the technology reduces ploughing frequency and intercropping suppresses weed infestation. On the other hand, the technology is expected to increase labor for harvesting, because the PPT system involves harvesting three crops per season rather than the usual one crop. These technology attributes intersect with the gender division of labor to determine how PPT ultimately affects the agricultural labor demands of women relative to men. Importantly, if PPT is net labor-saving for women, adoption holds the potential to empower rural women through reduced workload. Similarly, the labor saved can redirected to diversify production and income generation.

While PPT is known to generate economic benefits at the household level (Kassie et al. 2018; Kassie, 2020), it should not be assumed that benefits reach all household members. Research in developing countries has found that resources in the control of the household head are often not divided equitably within the household (Blumberg, 1991; Whitehead, 1990). For example, empirical studies suggest that men often spend increased earnings on personal items that do not benefit other household members and that women are more likely than men to spend increased income on the family (Mullins et al., 1996; Blumberg, 1991; Fisher et al., 2000). We investigate potential inequality in the distribution of resources by examining the impacts of PPT adoption on household spending on items known to benefit children and women.

There are a few examples of intrahousehold impact assessments of agricultural technology adoption. In a seminal work, Von Braun and Webb (1989) investigated intrahousehold impacts of new rice irrigation technologies in the Gambia. A complex web of effects was observed. Rice, formerly a woman's crop grown on individual plots, increasingly was cultivated on communal land controlled by male household heads. Accompanying this change, was an increase by both women and men in their allocation of labor to rice, although the labor increase was relatively more for women. Interestingly, while women moved out of rice production, some increasingly engaged in upland cash crop production (e.g., groundnuts). In another West African study, Fisher et al. (2000) found that the adoption of livestock stabling in Senegal increased women's already long workday and resulted in their loss of an important income source (milk sales). However, women reported an overall improvement in their family welfare, since men who adopted livestock stabling provided financial compensation to their wives for their increased labor and income loss.

In recent work, Lodin et al. (2014) sought to establish at what and whose cost rice farming was made more productive and profitable with the adoption of NERICA rice varieties in Uganda. The study revealed that the costs of technology adoption fell largely on women and children. Cultivation of NERICA varieties greatly increased labor demands for activities traditionally performed by women and children: bird scaring and weeding. Women in adopting households considered themselves "slaves to the rice" and reported feeling exhausted and unable to perform other tasks. Furthermore, the frequency of school absences for children was found to increase with NERICA adoption, as their labor was increasingly needed for rice cultivation. The three studies highlighted here make it clear that impacts of agricultural technology adoption on gender dynamics and intrahousehold labor allocation are complex and difficult to predict (Addison and Schnurr, 2016), underscoring the importance of looking within the household, not only across households, when assessing agricultural technology impacts.

The present study is motivated by both methodological and empirical concerns. From a methodological perspective to our knowledge this is the first intrahousehold study of technology adoption impacts to control for endogeneity bias using econometric techniques, allowing for improved identification of causality. Causal analysis using either experimental data or econometric approaches is standard practice in the impact assessment literature, but these techniques have rarely been used in intrahousehold studies. Commendable is a recent study that used experimental data to assess the intrahousehold impacts of the adoption of row planting in Ethiopia (Vandercasteelen et al., 2016). However, randomized control trials, like all methodologies, have limitations, including their very high cost and questionable external validity (Barrett and Carter, 2010). Promoting the use of econometric causality techniques for intrahousehold impact assessment is important from the perspective of practicality as well as in the spirit of methodological pluralism.

From an empirical standpoint, a distinctive feature is the study's focus on PPT, whose potential to improve the welfare of farming households warrants further investigation. Previous research on intrahousehold impacts of agricultural technology have largely concerned rice technologies (Nguezet et al., 2011; Lodin et al., 2014; Lodin et al.,

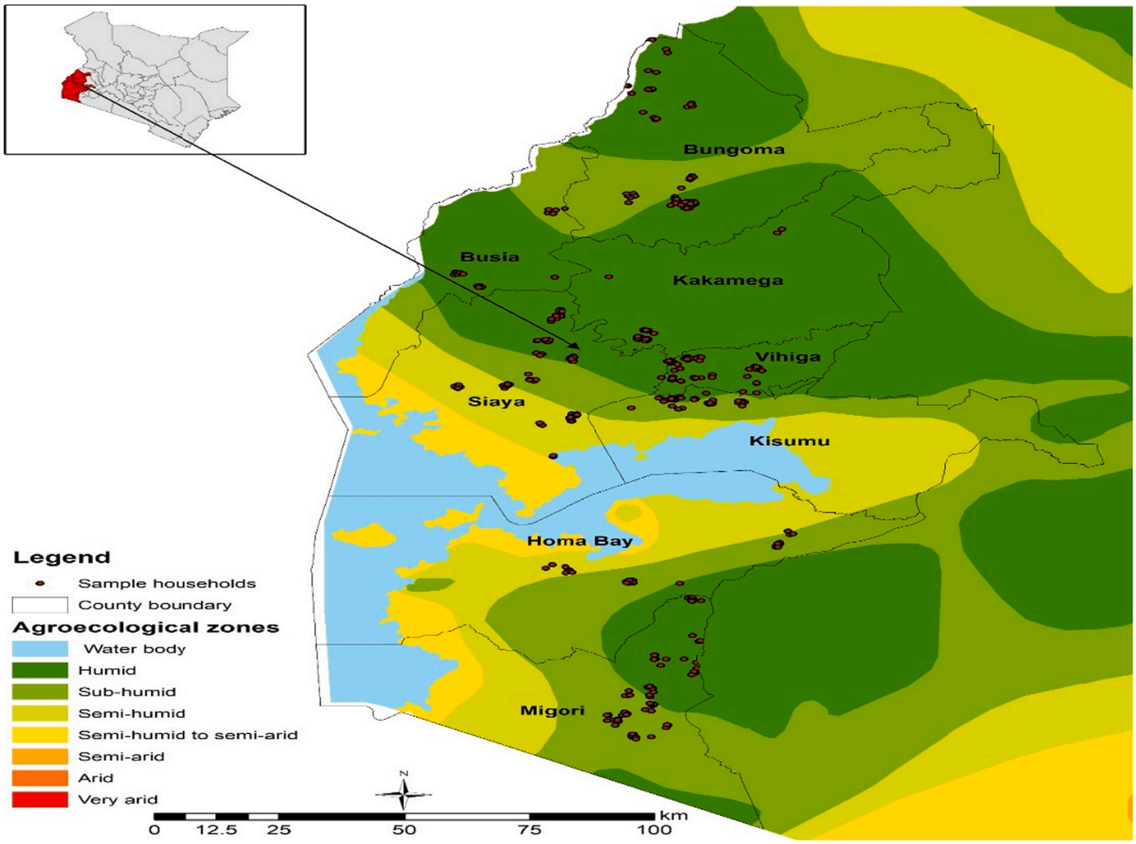

Fig. 1. Study area and distribution of sample households.

2014; Lokossou et al., 2015; von Braun and Webb, 1989), with only a few analyses of other technologies, such as livestock stabling (Fisher et al., 2000), irrigation technologies (Njuki et al., 2014; Theis et al., 2018), farm mechanization (Paris and Pingali, 1995), and conservation agriculture (Carney and Carney, 2018). We add another empirical point to the literature with evidence on a unique technology that has been shown to increase economic well-being at the household level (Kassie et al., 2018; Diiro et al., 2018). Importantly, the study makes the case for rigorous quantitative analysis of gender-related effects in assessments of agricultural technology impacts to ensure equitable outcomes of agricultural interventions.

2. Study context and data

2.1. Gender inequalities in rural Kenya

Available evidence indicates women form a sizable proportion of Kenya's agricultural labor force for activities such as weeding, threshing, and harvesting. Rural women in eastern and western Kenya constitute 49–60% of the agricultural labor force, depending on the agricultural activity (Kassie et al. 2014). Despite this, rural women in Kenya have less access and control over many productive resources (land, labor, education, information, and financial resources) compared with men farmers. As little as 0.5% of women in Kenya have access to financial services (ERH 2016). And only about 6% of Kenyan women own land (FIDA 2009), largely due to cultural norms and traditions that restrict women's land inheritance (Kameri-Mbote 2005; Manda and Mwakubo, 2014). Women have limited access to labor and agricultural markets (Farnworth and Colverson 2015; Kameri-Mbote, 2005; Wekwete, 2014) and tend to have less control over revenue from agricultural production than men (Heyer 2006; Fischer and Qaim 2012).

Since women spend more time in caregiving and domestic work than men (Saito et al., 1994; Wekwete, 2014), they are less able to participate in income-generating activities (Wekwete, 2014) and have less access to productive resources such as extension and advisory services (Farnworth and Colverson 2015; Meinzen-Dick et al. 2010). Moreover, extension workers have traditionally tended to favour male adults over female adults (Blumberg, 1991; FAO 1988). These inequalities constrain women's productivity in maize and other agricultural enterprises.

2.2. Study area and data collection

Data for this study come from a 2016 household survey in western Kenya where PPT was developed, tested, and promoted for its potential to increase maize productivity. Western Kenya is a major maize growing area for the country, with maize being cultivated by both men and women. Total annual maize production in Kenya is about 3,000 MT per year produced on 2,500 ha (FAOSTAT, 2019). Maize is the most widely consumed staple crop in the country, contributing about 68 percent of daily per capita cereal consumption, 35 percent of total dietary energy consumption, and 32 percent of total protein consumption (FAOSTAT, 2019). The crop is also a source of employment to many households in both rural and urban areas. Unfortunately, maize production is constrained by several factors especially insect pests (stemborers) and fall army worm (FAW), parasitic striga weeds, and low soil fertility (Khan et al., 2014). Stemborers cause significant yield losses estimated at $1.5 billion of crops produced in Africa (Kfir et al., 2002). Similarly, striga causes grain yield losses of about $40.8 million per year (Kanampiu et al., 2002). To address these challenges, icipe and partners have developed and disseminated the push–pull technology (PPT) described in the Introduction. The technology has been actively disseminated to farmers in different sub counties in western Kenya since the year 2007, mainly through field days held regularly at the end of each cropping season. Recent studies report that about 58 percent of small-scale maize farmers have adopted either the conventional or the climate-smart push–pull technology variants in different agro-climatic conditions

Table 1a
Descriptive statistics: Labor supply (Person-days/hectare/season, $n = 2410$).

Outcome variables	Plot with PPT(n = 1,678)		Plot without PPT (n = 732)		Mean difference
	Mean	SD	Mean	SD	
Family labor supply by females					
Ploughing	8.743	0.472	17.291	0.670	−8.548
Weeding	14.468	0.858	30.640	1.015	−16.173
Ploughing and weeding	23.210	1.088	47.931	1.408	−24.721
Harvesting	23.955	1.728	16.998	0.477	6.957
Threshing	14.983	1.126	24.385	0.995	−9.402
Family labor supply by males					
Ploughing	60.192	3.001	100.646	3.078	−40.454
Weeding	8.767	0.511	19.848	0.772	−11.081
Ploughing and weeding	68.959	3.324	120.494	3.511	−51.535
Harvesting	18.332	1.290	12.243	0.417	6.089
Threshing	18.320	1.290	12.243	0.417	6.077
Hired labor					
Ploughing	5.442	0.655	13.856	0.766	−8.414
Weeding	3.976	0.605	17.126	0.958	−13.150
Ploughing and weeding	9.418	1.071	30.982	1.569	−21.565
Harvesting	3.314	0.668	5.801	0.476	−2.487
Threshing	2.082	0.534	2.715	0.403	−0.633
Investment and other variables					
Applied pesticides	0.007	0.003	0.014	0.003	−0.007
Fertilizer applied/ hectare)	65.474	2.800	60.113	4.238	5.361
Applied manure (1 = yes)	0.715	0.017	0.687	0.011	0.029
Used draft power on plot (1 = yes)	0.142	0.013	0.552	0.012	−0.410
No. of times plot was ploughed	2.163	0.024	2.145	0.016	0.018
Weeding frequency per season	1.871	0.017	1.870	0.012	0.002
Distance from residence to plot (walking minutes)	2.916	0.349	4.362	0.280	−1.446***
Crop diversity on a plot (No. of crops grown on the plot)	14.763	0.170	11.861	0.127	2.903
Plot tenure (1 = owned, 0 = rented)	0.951	0.008	0.899	0.007	−0.051
Plotmanager1(man only)	0.584	0.018	0.552	0.012	0.032
Plotmanager2 (woman only)	0.219	0.015	0.225	0.010	−0.006
Plotmanager3(joint)	0.197	0.015	0.223	0.010	−0.026

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

and farm typologies in the country (Muriithi et al., 2018).

The data collection process was carried out in several stages. First, nine out of 11 counties in western Kenya were purposively selected. The selected counties are Bungoma, Busia, Homa Bay, Kakamega, Kisumu, Migori, Siaya, Trans-Nzoia, and Vihiga (Fig. 1). Next, between 3 and 11 villages were randomly selected in each county using probability proportional to size (PPS) sampling. This was followed by a random selection of between 2 and 21 households in each village, also via PPS sampling, using lists obtained from extension officers tasked with technology promotion. In total, 60 villages and 711 farm households were surveyed. After dropping outliers and observations with missing values, the usable sample amounted to 702 households and 2410 maize plots.

Household- and plot-level data were collected using semi-structured questionnaires through face-to-face farmer interviews by trained enumerators conversant in local languages. Respondent participation in the survey was voluntary and oral informed consent was obtained for those who agreed to participate. The questionnaires elicited information on a variety of topics, including household and individual demographic characteristics; crop and livestock production and utilization; ownership of productive assets by sex; plot-level labor supply by sex; farming practices; plot characteristics and management; access to markets, credit, and agricultural extension; household expenditure on education and consumption goods; and social capital. Table 1 presents the definitions and summary statistics for all analysis variables.

3. Econometric model and estimation strategy

This study seeks to understand how smallholder farmer households adjust their labor allocation decisions in response to PPT adoption, and how the benefits from technology adoption are distributed between men, women, and children in the adopting households. An important econometric challenge of using observational data to estimate a causal effect of technology adoption is the potential endogeneity of adoption decisions when the technology is not randomly assigned to the farmers in the areas surveyed. As a result, some households might have self-selected into adoption, whereas others could have adopted it because they were targeted by the technology dissemination agents. Thus, potential differences in outcomes between adopters and non-adopters may be due to unobserved heterogeneity (e.g., motivation, farm management skills, and farmer preferences). Failure to account for selectivity and endogeneity bias may obscure the true impact of technology adoption.

We address these potential bias problems by controlling for both observable and unobservable farmer attributes. This is done with an endogenous switching regression (ESR) framework, which is a variant of the instrumental variable (IV) approach (Lokshin & Sajaia, 2011). The ESR is more flexible compared to the standard IV approaches because it allows the coefficient estimates to vary across subgroups (treatment and non-treatment variables) and thus estimates heterogeneous effects for each of the exogenous factors on the outcome (Besley and Case, 2000). That is, ESR enables the analyst to capture both intercept and slope effects of treatment variables (PPT adoption in our case) on outcomes (i.e., labor supply and expenditures). Furthermore, estimating separate outcome regressions helps to control for the differential effects of the exogenous variables of the treated and nontreated samples that can contribute to outcome differences.

The ESR framework is a two-stage estimation procedure aimed at eliminating selection bias. The first stage involves regression modeling of households' technology adoption status with two primary objectives: (i) understand the determinants of adoption status, and (ii) generate inverse Mills ratios variables to be included in the second-stage model. The second stage involves regression modeling to estimate the effects of adoption status on outcomes, using the inverse Mills ratios as additional regressors to purge potential selection bias. Recent empirical studies have used the ESR framework to study the impact of modern technologies on livelihood indicators in the SSA region (e.g. Asfaw et al., 2012; Shiferaw et al., 2014; Kassie et al., 2018).

3.1. ESR model for PPT adoption and impact on labor supply

We assess impacts of PPT adoption on labor supply using three categories of outcome variables: family labor and hired labor allocation to maize production, and household participation in off-farm activities. Labor supplied to maize farming is captured for each activity and maize plot cultivated by sampled households. For family labor, but not hired labor, we disaggregate labor supply by gender of the farmer. We capture participation in off-farm activities using dummy variables for household and female members' participation in the off-farm sector. We implement two variants of ESR based on distribution of the outcome variables: the standard ESR for continuous labor supply variables (labor supply by men and women in a household, and hired labor), and the endogenous switching probit model to estimate the treatment effects of PPT adoption on household participation in off-farm income generating activities.

3.1.1. ESER for continuous labor outcome variables

The empirical strategy presented below focuses on plot level analysis of PPT adoption and labor supply, but it can easily be generalized to

Table 1b
Descriptives: Household and community level variables (n = 702).

Characteristic	Non-adopters (n = 340)		Adopters (n = 362)		Mean difference
	Mean	SD	Mean	SD	
Outcome variables					
Annual education expenditure (KES)	30,459.700	1,674.605	41,533.370	2,831.543	−11,073.66)
Annual expenditure on female preferred goods (KES)	11,394.510	832.904	16,233.930	1,523.875	−4,839.419
Female members alone participate in off farm activities (1 = yes)	0.241	0.023	0.268	0.023	−0.027
Household participate in off farm activities (1 = yes)	0.571	0.496	0.596	0.491	−0.261
Other selected household level variables					
Other household members participate in off farm activities (1 = yes)	0.506	0.027	0.533	0.026	−0.027
Annual education expenditure per capita (KES)	24,105.770	995.411	25,079.120	924.750	−973.35)
Number of field days attended by farmer	0.353	0.057	2.430	0.123	−2.076***
Presence of a PPT group in the village (1 = Yes)	0.356	0.026	0.675	0.025	−0.319***
No. of friends and peers practicing PPT	1.477	0.104	5.006	0.174	−3.528***
No. of members of working age	4.434	0.129	4.730	0.119	−0.296
Formal education of husband (years)	7.739	0.197	8.815	0.211	−1.077***
Average education of the household	6.162	2.625	6.934	2.599	−0.772**
Sex of household head (1 = male, 0 = female)	0.678	0.025	0.691	0.024	−0.013
Age of head when first heard of PPT (years)	50.064	0.805	49.505	0.607	−0.558
No. of cows owned now	1.624	0.112	1.837	0.107	−0.214
No. of cows owned five years ago	3.448	0.177	3.278	0.154	0.170
Quantity of other livestock owned (TLUs)	0.509	0.034	0.565	0.036	−0.057
Credit-constrained household (1 = needed credit, but did not get it, 0 otherwise)	0.670	0.025	0.562	0.026	0.108***
Confidence in skill of extension officers (1 = Yes)	0.649	0.026	0.826	0.020	−0.177***
Diversity of farmer groups in village of residence (no. of group types)	5.556	2.177	5.967	2.349	−0.411**
Community level variables					
Distance from residence to extension office (walking minutes)	66.706	2.667	70.564	2.815	−3.857
Distance from residence to nearest input supply (walking minutes)	50.234	2.058	54.004	2.496	−3.769

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

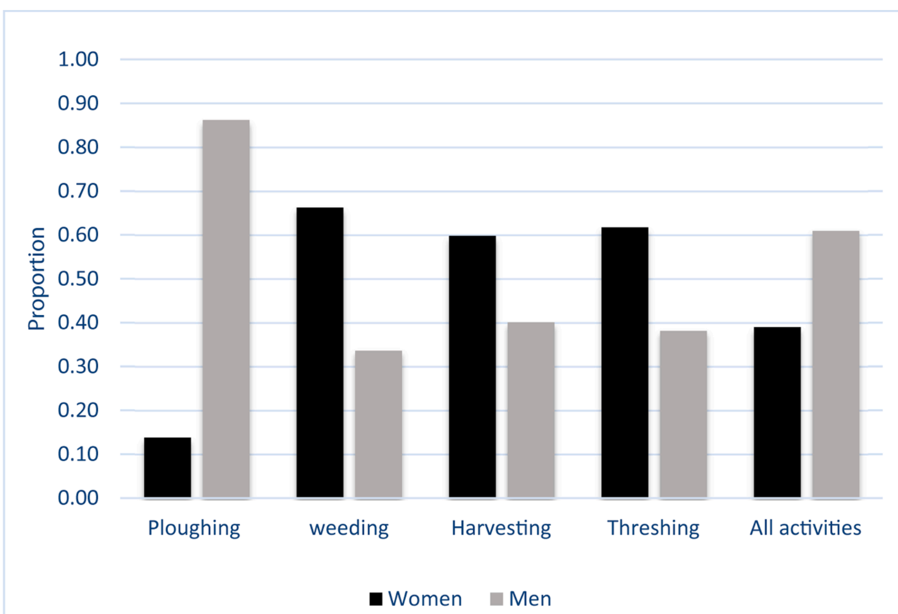

Fig.2. Female and male labor allocations, by activity.

assess impacts of PPT adoption at the household level. The first ESR stage involves estimation of a probability model for household adoption of PPT at the plot level as a linear function of observable and non-observable characteristics that affect adoption[1]:

$$T^*_{ip} = \alpha X_i + \phi P_{ip} + \delta Z_i + \varepsilon_{ip} \quad where \quad T_{ip} = \begin{cases} 1 \ if \ T^*_{ip} > 0 \\ 0 \ if \ T^*_{ip} \leq 0 \end{cases} \qquad (1)$$

where T^* is the unobservable or latent variable for technology adoption (the difference in utility with and without adoption of PPT); T is a binary variable for observed adoption (equal to one if the i^{th} farmer adopts PPT on plot p, and zero otherwise); X is a vector of socio-economic variables at the household and community level; P is a vector of plot characteristics; Z is a vector of instrumental variables that influence adoption but not the outcome variables; α, δ, and ϕ are vectors of parameters to be estimated, and ε is the error term.

In the second stage, we estimate the effect of PPT adoption on labor allocation for plots with and without the technology separately, while accounting for the endogenous nature of the adoption decision. Plot-level labor supply is estimated as a function of both observed and un-

[1] We do not provide a detailed discussion of PPT adoption in this paper as recent research papers have documented factors that influence PPT adoption in Kenya (e.g. Muriithi et al., 2018; Kassie et al., 2018).

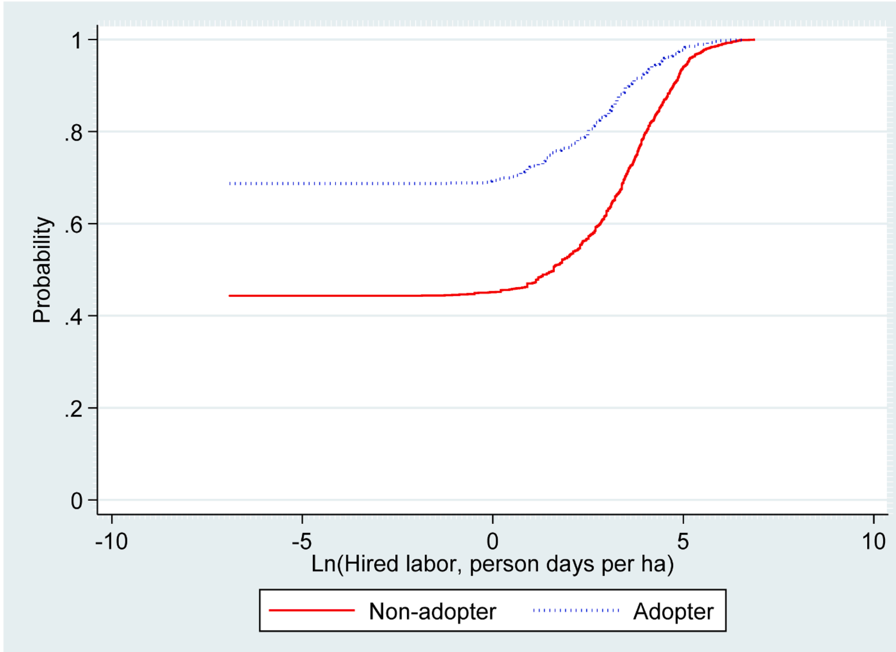

Fig. 3. Distribution of hired labor use intensity.

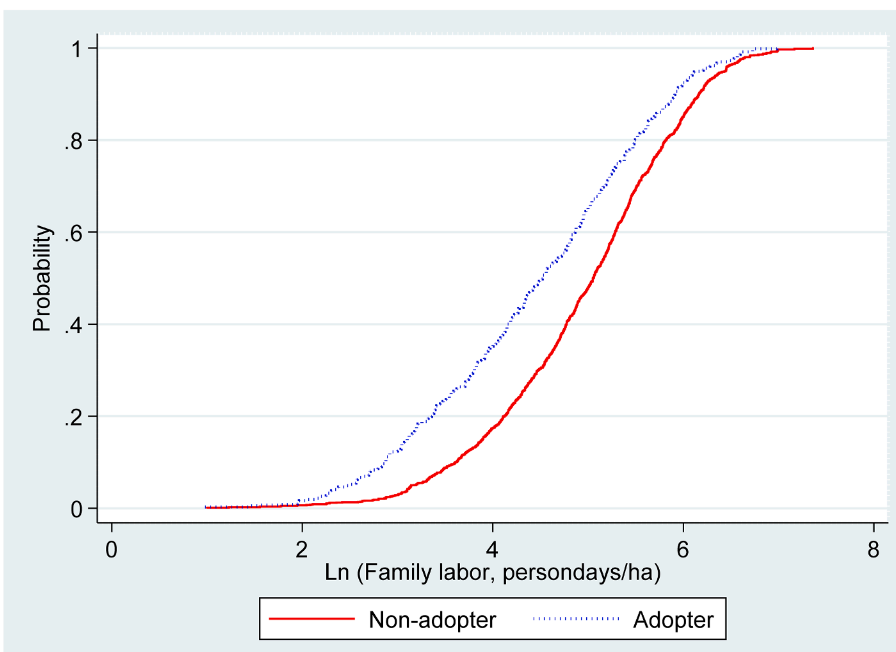

Fig. 4. Distribution of family labor supply intensity.

observed characteristics as specified in equations (2a) and (2b):

$$Y_{1ip} = \beta_1 X_{1i} + \psi_1 P_{1ip} + \sigma_{1\varepsilon}\widehat{\lambda}_{1ip} + u_{1ip} \qquad if\ T_{ip} = 1 \tag{2a}$$

$$Y_{0ip} = \beta_0 X_{0i} + \psi_0 P_{0ip} + \sigma_{0\varepsilon}\widehat{\lambda}_{0ip} + u_{0ip} \qquad if\ T_{ip} = 0 \tag{2b}$$

where Y is a vector of the outcome variables of interest (labor supply by men and women of household i on plot p) and $\widehat{\lambda}$ represent estimated selection correction terms (i.e., inverse Mills ratios) derived for each type of household from the first stage (Equation (1)) to capture unobservable regressors; σ denotes the covariance between the error terms in equations 1 and 2; u are regression error terms, and β and ψ are vectors of parameters to be estimated. The labor supply variables Y_1 and Y_0 are not observed simultaneously.

The labor functions specified in Equations (2a) and (2b) were used to generate the expected actual and counterfactual outcomes, which were then used to estimate the adoption effects. For instance the counterfactual outcome for treatment 1 is defined as the expected counterfactual outcomes of households that adopted PPT on their maize plot if the returns on their observed (X_1 and P_1) and unobserved ($\widehat{\lambda}_1$) characteristics had the same effect as the current returns ($\beta_0, \psi_0, \sigma_0$) of non-adopters' (treatment 0) observed (X_0 and P_0) and unobserved ($\widehat{\lambda}_0$) characteristics. The counterfactual for treatment 0 can be generated in a

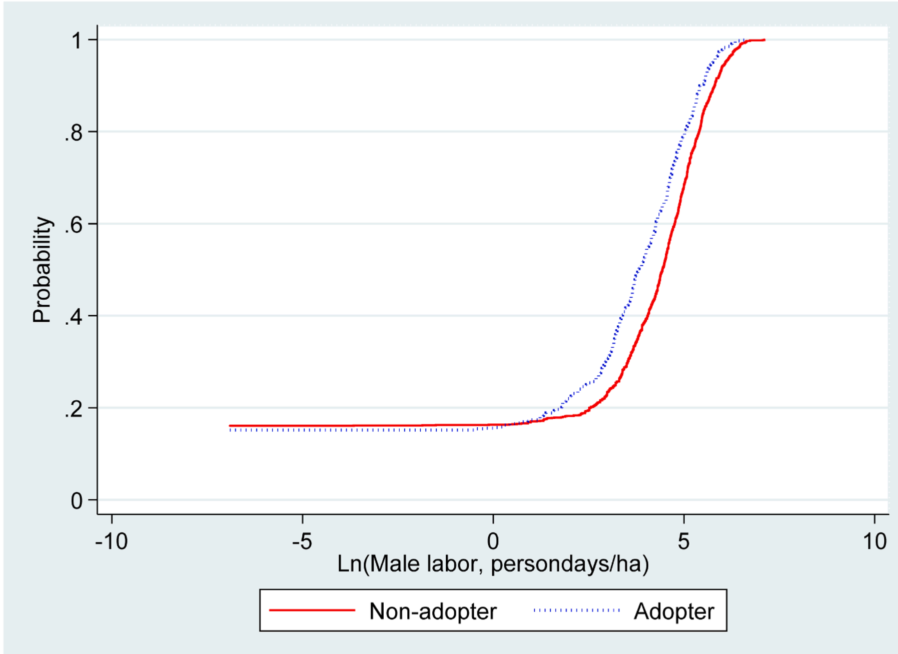

Fig. 5. Distribution of male labor supply intensity.

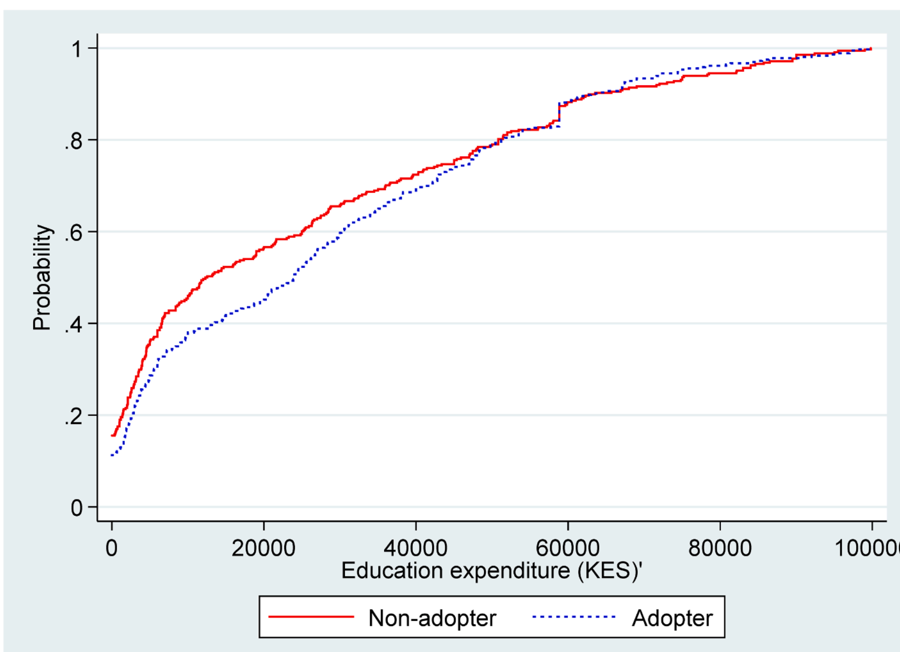

Fig. 6. Child education expenditure.

similar way. The actual expected outcome for treatment 1 and treatment 0 are observed in the data, and they reflect households observed labor supply for plot *P*. These are specified in equations (3a) and (3b)

$$E\left[Y_{1ip}\middle|X_{1ip}, P_{1ip}, \widehat{\lambda}_{1ip};\ T=1\right] = \beta_1 X_{1i} + \psi_1 P_{1ip} + \sigma_{1\varepsilon}\widehat{\lambda}_{1ip} \tag{3a}$$

$$E\left[Y_{0ip}\middle|X_{0ip},\ P_{0ip}, \widehat{\lambda}_{0ip}; T=0\right] = \beta_0 X_{0i} + \psi_0 P_{0ip} + \sigma_{0\varepsilon}\widehat{\lambda}_{0ip} \tag{3b}$$

The corresponding counterfactual labor expectations for treatment 1 and treatment 0 are defined in equations (3c) and (3d), respectively.

$$E\left[Y_{0ip}\middle|X_{1ip}, P_{1ip}, \widehat{\lambda}_{1ip};\ T=1\right] = \beta_0 X_{1i} + \psi_0 P_{1ip} + \sigma_{0\varepsilon}\widehat{\lambda}_{1ip} \tag{3c}$$

$$E\left[Y_{1ip}\middle|X_{0ip},\ P_{0ip}, \widehat{\lambda}_{0ip}; T=0\right] = \beta_1 X_{0i} + \psi_1 P_{0ip} + \sigma_{0\varepsilon}\widehat{\lambda}_{0ip} \tag{3d}$$

We bootstrapped Equations 3a-3d during estimation to account for predicted covariates, inverse Mills ratio. The average adoption effect on the labor supplied to PPT plots (average treatment effect on the treated,*ATT*) is derived as the difference between equations (3a) and (3c). This is defined in equation (4).

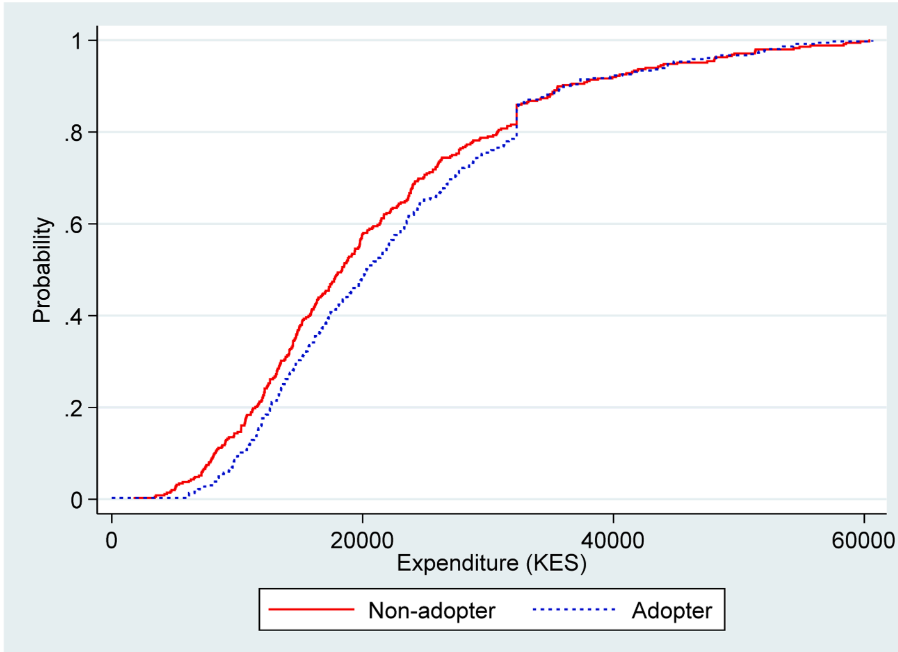

Fig. 7. Expenditure on goods associated with female preferences.

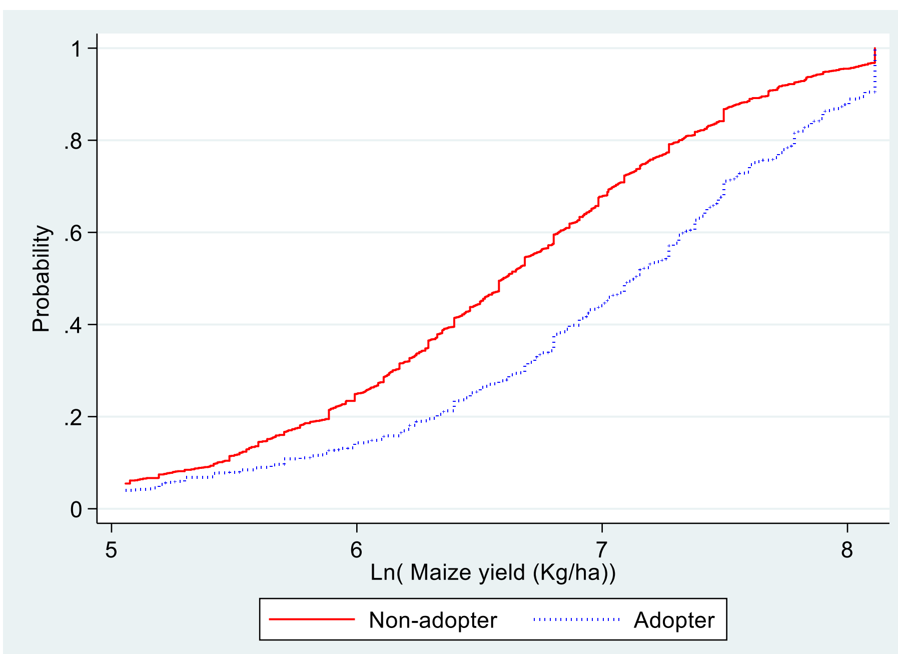

Fig. 8. Distribution of yields.

$$ATT = X_{1i}(\beta_{1-}\beta_0) + P_{1ip}(\psi_1 - \psi_0) + \widehat{\lambda}_{1i}(\rho_{1\varepsilon} - \rho_{0\varepsilon}) \tag{4}$$

The average treatment effect on the untreated (*ATU*), which represents the average adoption effect on the labor supplied to non-PPT plots, can be commutated following a similar procedure (as the difference between equation (3d) and (3b)).

3.1.2. ESER for binary outcomes variables

In this paper, we are also interested in estimating the impact of PPT adoption on household participation in off-farm activities, which is binary outcome measure of household supply of labor to the off-farm sector. We address sample selection bias in adoption decision and endogenous switching for binary outcomes using the endogenous switching probit framework, which is analogous to the endogenous switching regression for the continuous outcomes (Lokshin and Sajaia, 2011). The binary outcomes equations for household participation in off-farm income generating activities conditional on household adoption of PPT are specified as an endogenous switching regime model:

$$S_{1i}^{*} = \beta_1 X_{1i} + \mu_{1i} S_{1i} = \mathrm{I}(S_{1i}^{*} > 0) \tag{5a}$$

$$S_{0i}^{*} = \beta_0 X_{0i} + \mu_{0i} S_{0i} = \mathrm{I}(S_{0i}^{*} > 0) \tag{5b}$$

where S_{1i}^{*} and S_{0i}^{*} are the latent variables that determine the observed

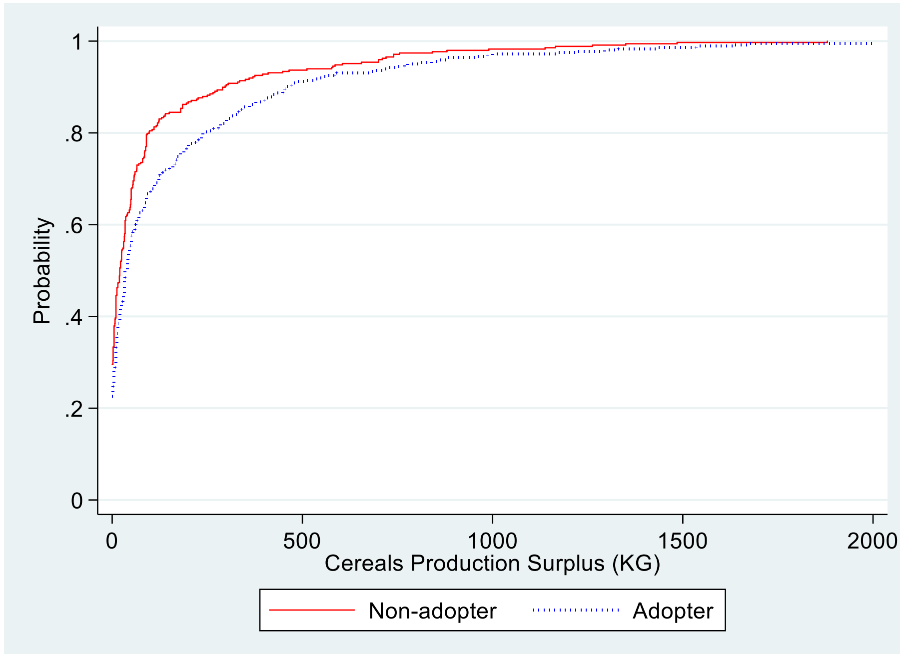

Fig. 9. Distribution of marketable surplus.

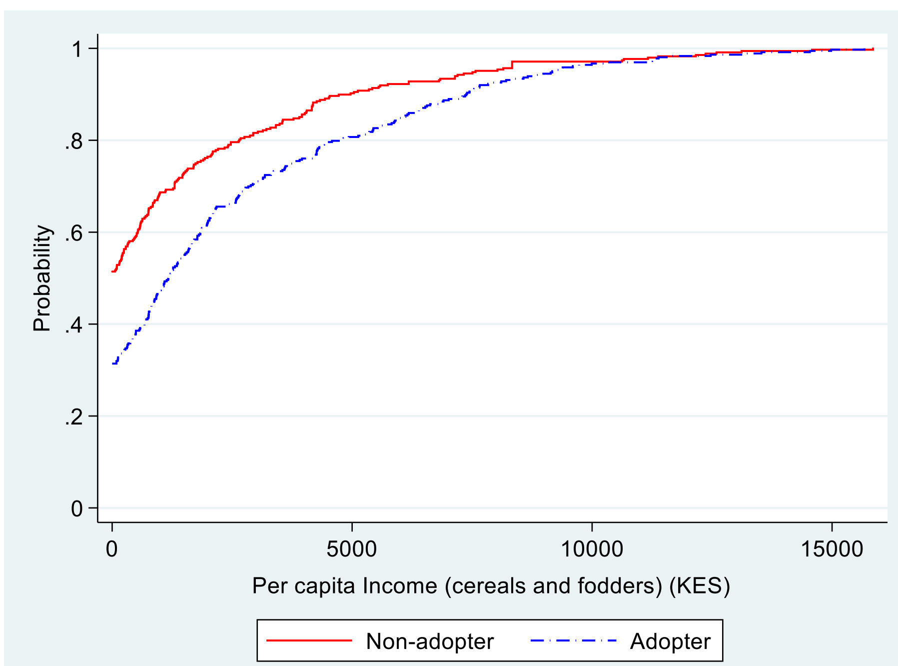

Fig. 10. Distribution of cash income from maize and fodder.

binary outcomes S_{1i} and S_{0i} for participants in off farm activities and non-participants, respectively; I is a criterion function; X_1 and X_0 are vectors of weakly exogenous variables as defined earlier; β_1 and β_0 are parameters to be estimated; μ_1 and μ_0 are the error terms in the binary outcome equations. The observed variable S_i is a dichotomous realisation of the latent variables for off-farm income participation and it is defined as:

$$S_i = \begin{cases} S_{1i,} & if\ T_i = 1 \\ S_{0i,} & if\ T_i = 0 \end{cases} \tag{6}$$

Where, T is the actual adoption dummy for household level adoption of PPT (one if household adopted PPT and zero otherwise) as defined earlier in equation (1). The probability model for household-level adoption of PPT is thus similar to equation (1), and is a function of exogenous variables (X) that affect both the off-farm sector participation and PPT adoption, and instrumental variables (Z) which determine a switch between the regimes, that is, adoption and non-adoption of PPT. We estimated selection equation (adoption decisions) and the two off-farm participation equations specified above by using full information maximum likelihood (FIML) endogenous switching probit model (Lokshin and Sajaia, 2011). The switching probit model also allows for the estimation of the treatment effect on the treated (TT) and the treatment

Table 2
Impact of PPT adoption on labor use (person-days/hectare/season), plot level analysis by type of labor used.

Farm labor activity	Farmer category	Family labor supply			Hired labor		
		Actual/ observed	Counterfactual	ATT /ATU	Actual/ observed	Counterfactual	ATT /ATU
All activities	*Adopters*	151.653 (2.946)	260.645 (2.763)	-108.992*** (4.039)	14.793 (1.197)	36.598 (1.572)	*-21.805*** (1.976)*
	Non-adopters	222.706 (2.245)	138.290 (2.010)	84.416*** (3.014)	38.369 (1.111)	18.576 (0.975)	*19.793*** (1.478)*
Land preparation, planting & weeding	*Adopters*	92.095 (1.741)	201.587 (2.274)	-109.493*** (2.863)	9.404 (0.638)	30.608 (1.250)	-21.202*** (1.404)
	Non-adopters	168.261 (1.817)	86.148 (1.249)	822.113*** (2.205)	30.997 (0.868)	12.998 (0.528)	17.999*** (1.017)
Land preparation and planting	*Adopters*	68.875 (1.445)	146.672 (1.766)	-77.794*** (2.282)	5.434 (0.334)	15.1142 (0.614)	-9.707*** (0.699)
	Non-adopters	117.796 (1.404)	59.299 (1.012)	58.472*** (1.730)	13.862 (0.422)	7.332 (0.279)	6.529*** (0.506)
weeding	*Adopters*	23.216 (0.539)	54.914 (0.755)	-31.699*** (0.929)	3.970 (0.374)	15.465 (0.661)	-11.495*** (0.759)
	Non-adopters	50.465 (0.556)	26.848 (0.409)	23.616*** (0.690)	17.135 (0.469)	5.665 (0.307)	11.469*** (0.560)
Harvesting	*Adopters*	42.372 (1.336)	33.434 (0.393)	8.938*** (1.392)	3.309 (0.336)	3.821 (0.267)	-0.511 (0.429)
	Non-adopters	29.217 (0.297)	43.411 (0.894)	-14.194*** (0.942)	5.805 (0.196)	3.578 (0.281)	2.222*** (0.344)
Threshing	*Adopters*	33.352 (0. 862)	39.896 (0.662)	-6.544*** (1.087)	2.079 (0.338)	2.903 (0.186)	-0.824 (0.385)
	Non-adopters	36.609 (0.482)	37.248 (0.603)	-0.638 (0.772)	2.716 (0.131)	3.232 (0.269)	-0.516*** (0.300)

Note: ATT denote Average Treatment Effect on the treated (adopters), and ATU denote Average Treatment Effect on the untreated (nonadopters); Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3
Impact of PPT adoption on female and male labor supply (person-days/hectare/season), plot level analysis by gender.

Farm labor activity	Farmer category	Female labor supply			Male labor supply		
		Actual/ observed	Counterfactual	ATT /ATU	Actual/ observed	Counterfactual	ATT /ATU
All activities	*Adopters*	59.125 (1.332)	97.211 (0.999)	-38.085*** (1.665)	88.957 (1.888)	156.057 (1.912)	-67.099*** (2.687)
	Non-adopters	85.857 (0.770)	64.064 (0.905)	21.792 *** (1.188)	130.981 (1.509)	75.424 (1.326)	55.557*** (1.926)
Land preparation, planting and weeding	*Adopters*	23.189 (0.465)	55.759 (0.647)	-32.569*** (0.796)	68.905 (1.415)	145.916 (1.821)	-77.011*** (2.307
	Non-adopters	47.906 (0.505)	22.617 (0.353)	25.289*** (0.616)	120.355 (1.422)	62.878 (1.004)	57.476*** (1.741)
Land preparation, planting	*Adopters*	8.735 (0.209)	22.676 (0.318)	-13.940*** (0.380)	60.143 (1.248)	124.009 (1.498)	-63.865*** (1.950)
	Non-adopters	17.278 (0.248)	8.047 (0.150)	9.230*** (0.290)	100.518 (1.188)	50.814 (0.884)	49.704*** (1.481)
Weeding	*Adopters*	14.455 (0.398)	33.084 (0.475)	-18.628*** (0.620)	8.761 (0. 250)	21.907 (0.429)	-13.145*** (0.496)
	Non-adopters	30.629 (0.347)	14.569 (0.297)	16.059*** (0.456)	19.836 (0.297)	12.063 (0.197)	7.772*** (0.365)
Harvesting	*Adopters*	23.977 (1.069)	19.284 (0.242)	4.692*** (1.097)	18.395 (0.541)	14.165 (0.224)	4.229*** (0.585)
	Non-adopters	16.998 (0.177)	22.900 (0.712)	-5.912*** (0.733)	12.229 (0.161)	20.343 (0.374)	-8.115*** (0.407)
Threshing	*Adopters*	14.969 (0.534)	25.830 (0.523)	-10.861*** (0.747)	18.383 (0.540)	14.166 (0.224)	4.218*** (0.585)
	Non-adopters	24.380 (0.380)	16.920 (0.378)	7.459*** (0.536)	12.229 (0.161)	20. 282 (0. 374)	-8.05*** (0.407)

Note: ATT denote Average Treatment Effect on the treated (adopters), and ATU denote Average Treatment Effect on the untreated (nonadopters); Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

effect on the untreated (TU).We estimate the expected effect of PPT adoption on households who participated in an off-farm activities (TT). We also estimate the expected effect of the PPT adoption on households who did not participate in an off-farm activities (TU). The ATT and ATU are then the respective average of TT and TU for the corresponding subgroups of the agricultural households.

3.2. ESER model for PPT adoption and impact of adoption on education expenditure and female expenditure

The second objective of the study is to estimate the impact of PPT adoption on household spending on children's education and consumption goods associated with women's preferences. Our measure of children's education expenditure is comprehensive and includes expenditure on the school uniform, tuition and fees, boarding fees, transportation, and school lunch/meals. Household expenditure on goods associated with women's preferences includes a variety of items, such as clothing, kitchen utensils, beddings, home energy (e.g., kerosene and fuel wood), grain milling, church contributions, health care, and household hygiene. We specify empirical strategy similar the ESR strategy presented in sub-section 3.1.1 above to analyse how PPT adoption affects the education and consumption expenditure at the household level. The first ESR stage in this case involves estimation of a probability model for adoption of PPT at the household level as a linear function of observable and non-observable characteristics that affect adoption. We take average values of the plot level attributes of each household and use them as covariates in the household level model. The second stage involves estimation of the effect of PPT adoption on education and consumption expenditure for PPT adopting households and non-adopters separately, while accounting for the endogenous nature of

Table 4
Household level impacts of PPT adoption on family labor supply ((person-days/hectare/season), by gender.

Farm labor activity	Farmer category	Total Family labor supply			Female labor supply			Male labor supply		
		Actual/ observed	Counterfactual	ATT /ATU	Actual/ observed	Counterfactual	ATT /ATU	Actual/ observed	Counterfactual	ATT /ATU
All activities	*Adopters*	424.477 (9.672)	586.673 (8.940)	-162.225*** (13.171)	161.463 (3.420)	220.893 (3.574)	-59.429*** (4.946)	253.706 (6.571)	347.716 (5.490)	-94.011*** (8.438)
	Non-adopters	313.106 (8.945)	238.896 (9.762)	74.207 *** (13.240)	123.960 (3.475)	84.638 (3.716)	39.321 *** (5.088)	179.242 (6.279)	158.466 (6.279)	20.776*** (8.363)
Land preparation, planting and weeding	*Adopters*	300.653 (7.184)	436.395 (6.767)	-135.742*** (9.855)	125.902 (1.736)	80.902 (2.002)	-45.819*** (2.651)	220.570 (5.692)	310.532 (4.879)	-89.923*** (7.497
	Non-adopters	232.303 (6.599)	181.121 (7.182)	51.1822*** (9.754)	68.762 (1.907)	39.246 (1.353)	-29.517*** (2.662)	163.874 (4.853)	141.875 (5.709)	21.666*** (7.494)
Land preparation, planting	*Adopters*	216.817 (5.789)	308.580 (4.835)	-91.764*** (7.543)	29.802 (0.827)	45.968 (0.844)	-16.160*** (1.182)	187.009 (4.999)	262.623 (4.103)	-75.602*** (6.467)
	Non-adopters	160.356 (4.797)	145.983 (5.753)	14.746** (7.491)	24.195 (0.828)	19.533 (0.833)	4.651*** (1.175)	136.533 (4.097)	126.438 (4.976)	10.095 (6.446)
Weeding	*Adopters*	83.836 (1.785)	127.814 (2.117)	-43.978*** (2.769)	50.275 (1.149)	79.934 (1.362)	-29.659*** (1.782)	33.561 (0.878)	47.880 (0.883)	-14.320*** (1.246)
	Non-adopters	71.574 (2.062)	35.138 (2.109)	36.436*** (2.949)	44.567 (1.314)	19.702 (1.402)	24.134*** (1.923)	27.007 (0.875)	15.436 (1.014)	11.571*** (1.339)
Harvesting	*Adopters*	80.516 (2.187)	70.827 (1.018)	9.689*** (2.412)	45.496 (1.597)	42.058 (0.690)	3.438** (1.739)	35.010 (0.892)	28.769 (0.418)	6.250*** (0.985)
	Non-adopters	39.878 (1.081)	49.386 (2.285)	-9.508*** (2.528)	23.981 (0.700)	21.179 (1.770)	2.711 (1.904)	15.986 (0.462)	28.206 (0.852)	-12.219*** (0.969)
Threshing	*Adopters*	76.883 (1.460)	92.2777 (1.569)	-15.394*** (2.348)	41. 875 (1.132)	63.507 (1.281)	-21.633*** (1.709)	35.008 (0.892)	28.769 (0.419)	6.238*** (0.985)
	Non-adopters	53.513 (1.687)	47.405 (1.687)	6.108** (1.502)	37.526 (1.341)	19.204 (1.354)	18.322*** (1.906)	15.986 (0.462)	28.201 (0.853)	-12.970*** (0.407)

Note: ATT denote Average Treatment Effect on the treated (adopters), and ATU denote Average Treatment Effect on the untreated (nonadopters); Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 5
Impact of PPT adoption on household participation in off-farm income activities (estimates based on endogenous switching Probit).

Type of treatment effect	Participation by woman	Household participation
Average treatment effect on the treated (ATT)	0.063*** (0.012)	0.083*** (0.135)
Average treatment effect on the untreated (ATU)	0.001*** (0.010)	0.096*** (0.013)
Average treatment effect (ATE)	0.021*** (0.004)	0.091*** (0.01)
Marginal treatment effect (MTE)	0.025*** (0.004)	0.084 *** (0.001)

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 6
Impact of PPT adoption on household expenditure on child education and women consumption.

	Farmer category	Actual/ observed	Counterfactual	ATT/ATU
Expenditure on education (KES/year)	*Adopters*	39,667.080 (1,931.386)	34,654.370 (1,288.911)	5,012.712** (2,321.97)
	Non-adopters	29,756.190 (1241.845)	36,121.290 (2,011.87)	−6,365.100*** (2,364.276)
Expenditure (KES) on goods with women preferences (KES/year)	*Adopters*	25,369.320 (346.345)	23,588.420 (330.482)	1,780.903*** (478.721)
	Non-adopters	23,591.070 (327.317)	27,314.038 (438.241)	−3,722.966*** (546.980)

Note: ATT denote Average Treatment Effect on the treated (adopters), and ATU denote Average Treatment Effect on the untreated (nonadopters); Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

the adoption decision. We include households and the community level variables, in the empirical models, that affect expenditure and adoption as presented later in section 3.4. We estimate the adoption equation and expenditure equations at the household level. We then follow the procedure discussed earlier in subsection 3.1.1 to estimate the expenditure equations and generate the expected actual and counterfactual outcomes, which we use to estimate the adoption effects on expenditure. The average adoption effect on the children education expenditure and expenditure on goods associated with women preferences (average treatment effect on the treated,*ATT*) are analogous to equation (4).

3.3. Exclusion restrictions for identification

As discussed above, adoption decisions are likely endogenous to outcomes. We address the potential endogeneity bias of adoption in the outcome equations using instrumental variables (exclusion restrictions) in addition to the inverse Mills ratio. Economic theory and empirical studies guide our selection of three instrumental variables related to the role of social learning in technology adoption (Conley and Udry, 2010; Duflo et al. 2008): number of PPT field days attended by the farmer, presence of a PPT group in the village of residence, and number of friends and neighbors who have adopted the technology. We expect these instruments are strongly associated with PPT adoption but have no direct association with labor supply and expenditures (Kassie et al., 2018; Kassie, et al., 2020). Existence of a PPT group in the village of residence and knowing other farmers that have adopted PPT can greatly reduce transaction costs associated with learning about new technology, thereby facilitating adoption (Conley and Udry, 2010). Likewise, attending field days and being a member of a farmer group can facilitate farmer acquisition of credible information about the technology, build an understanding of the technology's performance and benefits, and increase opportunities for farmers to learn from each other (BenYishay and Mobarak, 2014). As noted earlier in section 2.2 several farmer field days have been conducted at the subcounty level over the years,

Table A1
Estimates of endogenous switching regression model for PPT adoption and impact of adoption on labor supply (plot level analysis).

VARIABLES	First stage	Family labor supply		Female labor supply		Male labor supply	
		Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters
Number of field days attended	0.061***						
	(0.017)						
Presence of a PPT group in the village (1 = Yes)	0.262***						
	(0.077)						
No. of friends and peers practicing PPT	0.048***						
	(0.012)						
No. of working age male members	0.009	17.620***	20.977***	3.004	3.445**	11.713***	15.120***
	(0.026)	(4.760)	(4.114)	(2.217)	(1.661)	(2.793)	(2.646)
No. of working age female members	−0.001	18.170***	−0.993	9.522***	3.912**	3.634	−5.457**
	(0.024)	(4.670)	(3.926)	(2.135)	(1.580)	(2.985)	(2.771)
Sex of household head (1 = male, 0 = female)	−0.176**	14.702	41.661***	−19.041***	−7.611*	43.511***	51.982***
	(0.088)	(16.961)	(14.972)	(6.229)	(4.534)	(10.337)	(9.984)
Ln (Age of head when first heard of PPT (years))	0.066	6.714	−25.248	16.246	14.845**	−26.557	−44.923***
	(0.125)	(25.628)	(15.558)	(11.216)	(6.544)	(18.456)	(10.505)
Ln(No. of cows owned 5 years ago)	0.021*	1.224	−3.770**	−0.305	−1.552***	0.431	−2.282
	(0.011)	(1.606)	(1.853)	(0.875)	(0.584)	(1.150)	(1.418)
Ln(No. of cows owned now)	−0.005	1.956	1.842	−0.698	−1.643***	2.316**	2.188**
	(0.009)	(1.446)	(1.726)	(0.654)	(0.557)	(0.969)	(1.026)
Ln (Other livestock owned 5 years ago, TLUs)	−0.058**	−6.538	−5.219	−1.671	−1.988	−4.357	−3.298
	(0.024)	(4.646)	(4.058)	(1.925)	(1.538)	(2.925)	(2.881)
Crop diversity on a plot	0.047***	5.197***	−0.714	0.219	1.328*	2.295*	−0.944
	(0.008)	(1.933)	(1.917)	(0.809)	(0.686)	(1.374)	(1.171)
Diversity of farmer groups in village	−0.028*	10.989***	−3.528	2.967**	0.828	7.915***	−2.808
	(0.016)	(2.661)	(2.679)	(1.253)	(1.081)	(1.766)	(1.897)
Size of household 5 years ago	−0.018	−8.013***	−0.553	−3.449***	−1.132	−1.787	1.188
	(0.014)	(2.749)	(2.339)	(1.278)	(0.797)	(1.733)	(1.504)
Land size (acres) owned 5 years	0.020*	−3.414	−13.847***	−0.253	−4.807***	−1.467	−8.398***
	(0.012)	(2.119)	(2.015)	(1.032)	(0.727)	(1.266)	(1.263)
Ln(Average formal education of household, years)	0.140	−16.048	−32.015**	−15.805*	−6.738	−4.660	−12.832
	(0.092)	(16.555)	(15.406)	(8.089)	(4.543)	(10.712)	(11.371)
Household is credit-constrained (1 = Yes)	0.153**	63.058***	−22.136*	19.896***	−6.837*	28.386***	−10.680
	(0.072)	(13.391)	(11.308)	(4.387)	(4.053)	(7.733)	(8.288)
Confidence in skill of extension officers (1 = Yes)	0.202**	33.202**	21.768	11.014*	4.457	13.002	16.071*
	(0.081)	(16.057)	(13.745)	(5.726)	(4.696)	(10.986)	(8.947)
Ln(Distance to extension office, walk minutes)	−0.005	−38.512***	−28.120***	−15.296***	−3.015	−10.799**	−13.412**
	(0.044)	(8.286)	(7.995)	(5.339)	(2.033)	(4.829)	(5.440)
Ln(Distance to nearest input supply, walk minute)	0.148***	8.949	2.833	4.711	−1.932	6.558	−2.661
	(0.041)	(9.912)	(7.062)	(4.220)	(2.726)	(5.889)	(5.283)
Ln(distance to plot, walk minutes)	−0.122***	4.166	2.269	6.061**	−1.201	4.470	4.793
	(0.037)	(6.191)	(6.532)	(2.927)	(2.019)	(4.527)	(4.446)
Applied pesticides on plot	−0.209	−11.961	−46.674*	20.440	−9.373	−28.724	−46.738**
	(0.379)	(53.598)	(27.674)	(40.676)	(11.478)	(38.090)	(19.690)
Used manure on plot	−0.090	−27.324*	16.942	8.131	14.325***	−34.728***	5.591
	(0.072)	(14.095)	(11.692)	(5.290)	(4.069)	(10.708)	(8.966)
Used draft power on plot	−1.391***	−55.354	−12.700	6.207	−21.954**	−16.657	8.629
	(0.081)	(37.539)	(24.562)	(16.835)	(9.473)	(22.572)	(17.607)
No. of times plot was ploughed	0.180***	9.441	−17.809**	−9.480**	−8.366***	13.953	−8.575
	(0.051)	(11.051)	(8.031)	(3.826)	(2.793)	(8.799)	(6.640)
No. of times plot was weeded	−0.026	26.975**	20.958*	7.560	11.139***	21.057**	13.598*
	(0.068)	(11.543)	(11.504)	(4.956)	(3.827)	(8.492)	(7.646)
Ln(Fertilizer applied, kg/acre)	0.017*	4.964***	1.510	2.433***	0.672	1.811	−0.367
	(0.009)	(1.603)	(1.620)	(0.715)	(0.543)	(1.112)	(1.153)
Plot is owned (1 = yes)	0.076	7.695	−5.949	8.110	2.449	−3.206	−4.344
	(0.136)	(29.090)	(18.866)	(12.876)	(7.580)	(19.116)	(13.787)
Plotmanager1(man only)	0.030	−31.651	−12.012	−16.739**	−14.098**	−10.248	−5.020
	(0.102)	(20.047)	(14.882)	(8.161)	(6.611)	(11.754)	(11.216)
Plotmanager2 (woman only)	−0.115	−80.350***	−68.655***	−22.736***	−23.827***	−56.287***	−47.202***
	(0.098)	(16.732)	(13.732)	(7.560)	(6.042)	(10.575)	(9.954)
Female members alone participate in off farm activities (1 = yes)	−0.042	−18.654	14.779	−4.392	10.018*	−12.783	5.879
	(0.077)	(16.547)	(13.629)	(5.815)	(5.354)	(12.348)	(8.861)
Others members participate in off farm activities (1 = yes)	−0.067	3.838	−6.152	9.952**	−0.817	9.784	0.935
	(0.070)	(11.685)	(10.229)	(4.941)	(4.148)	(6.995)	(6.278)
Season (1 = maim season)	0.008	8.214	12.228	5.810	5.425	0.562	6.770
	(0.064)	(11.030)	(10.104)	(5.352)	(3.547)	(6.869)	(6.898)
Gentle slope	−0.169	0.703	4.475	29.881*	11.889	−45.474	−20.470
	(0.282)	(35.050)	(38.128)	(16.331)	(12.406)	(29.786)	(29.854)
Medium slope	−0.324	11.160	12.331	47.081***	10.393	−39.209	−13.202
	(0.281)	(34.957)	(39.356)	(17.064)	(12.206)	(30.985)	(29.734)
Good soil fertility	0.699***	81.587**	−24.107	−1.629	3.187	55.215**	−24.973*
	(0.164)	(34.257)	(19.934)	(12.583)	(6.860)	(26.039)	(14.009)
Medium soil fertility	0.272*	48.953	10.294	−4.668	5.934	41.444*	−3.299
	(0.161)	(30.993)	(15.995)	(12.281)	(6.200)	(24.489)	(12.281)

(*continued on next page*)

Table A1 (*continued*)

VARIABLES	First stage	Family labor supply		Female labor supply		Male labor supply	
		Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters
Shallow soil depth	−0.063	13.602	−9.317	10.877	5.085	3.958	−25.869**
	(0.141)	(28.212)	(17.753)	(12.281)	(6.882)	(18.791)	(12.611)
Medium soil depth	−0.101	−54.809***	30.375**	−14.348**	7.746*	-32.661***	12.486
	(0.073)	(14.390)	(12.327)	(6.922)	(4.526)	(9.836)	(8.189)
Mills ratio		55.676	−45.448**	0.838	5.616	14.958	−44.129***
		(34.766)	(22.368)	(13.855)	(8.350)	(23.131)	(15.626)
County fixed effects	yes	yes	yes	yes	yes	yes	yes
Constant	−2.080***	−76.140	537.940***	−11.919	32.458	−0.232	461.145***
	(0.650)	(159.869)	(129.079)	(65.435)	(44.756)	(116.804)	(78.078)
Observations	2,410	732	1,678	732	1,678	732	1,678
R-squared		0.228	0.162	0.255	0.146	0.213	0.157

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

presenting an open opportunity to farmers residing in the respective subcounties to learn about the technology and its benefits. One may argue that validity of the field days as an instrument could be compromised by variations in farmer access to field days that may arise due to differences in factors such as residing in villages with closer proximity to the field day sites in the subcounty, and other wealth related variable that may influence access to such opportunities. We thus include the community level variables such as distance to extension offices and distance to input markets in the empirical models to control for the location effects that may drive adoption. We also control for wealth of households using several indicators such as land ownership, and livestock ownership, participation in off farm activities, being credit constrained, and distance to markets.

3.4. Explanatory variables

The selection of explanatory variables draws on two bodies of literature: the literature on gender and agricultural technology adoption (e.g., Doss and Morris, 2001; Fisher and Carr, 2015; Smale, 2005; Muriithi et al 2018; Kassie et al., 2018) and empirical research on the determinants of education and consumption expenditure in developing countries (Lampietti and Stalker, 2000; Sahn and Younger, 2000; Cameron and Worswick, 2001). Explanatory variables reflect attributes of the maize plot, individual farmers, and households, as well as community-level variables. Individual and household characteristics include sex, age, and education of household head; household size; livestock ownership at the time of the survey and before PPT was introduced; binary variables to indicate farmer perceived credit constraints and farmer confidence in the quality of agricultural extension and advisory services; and dummies for participation in off-farm activities. Plot-level variables pertain to agricultural practices on the maize plot (intercropping, crop diversity, application of synthetic chemicals and manure, draft power use, and frequency of ploughing and weeding); plot tenure and management (joint or individual); and proximity of the maize plot to the household's residence. Community-level variables include the distance from the household to the nearest input supply shop, and extension offices, and county dummy variables (not included in Table 1 for brevity) to control for location-specific effects such as unobserved cultural and agroecological attributes. Most of the covariates listed above are universal in the analysis of the three categories of outcomes, although we include factors that uniquely explain the respective outcome variables. For instance we include number of school going children (in primary and secondary school), women empowerment, and formal education of spouse (husband) in the expenditure equations but not in the labor equations. Table 1 includes descriptive statistics for the identifying instruments discussed in section 3.3.

4. Results and discussion

4.1. Descriptive analysis of PPT and the selected outcomes

4.1.1. PPT and intrahousehold labor allocation

Among the sampled households, 51 percent had adopted PPT, with about 30 percent of maize plots were planted with PPT. On average, women farmers at the study sites provided 39 percent of the total labor inputs to maize production and 65 percent of maize weeding labor (Fig. 2). These figures agree well with other estimates for western and eastern Kenya (e.g., Kassie et al. 2014).

The study data reveal that PPT has the potential to reduce farm labor allocation to maize production. Results of a stochastic dominance analysis show that, in net, plots with PPT dominate plots without PPT with respect to the distribution of hired labor (Fig. 3) and family labor supplied by men and women (Figs. 4 and 5). Harvesting labor requirements increase with PPT, due to the technology-related increase in the number of crops harvested per season. For example, sampled households used 29 person-days/hectare for harvesting maize on plots without PPT, whereas the corresponding figure for PPT plots was 42 (Table 1). On the other hand, labor is saved, mainly during land preparation and weeding, but also at threshing. For instance, an average farm household devoted 69 person-days/hectare (ploughing) and 23 person-days/hectare (weeding) on maize plots with PPT. Corresponding figures for plots without PPT are 117 and 50 person-days/hectare. Labor requirements at ploughing may reduce after PPT adoption on a plot because a farmer would plough only a portion of the plot that they need to plant with maize seed. The technology also suppresses weed infestations reducing the labor needed for weeding. Since the PPT-associated labor savings for planting, weeding, and threshing outweigh the labor increase at harvest, the technology appears to be labor-saving. Importantly, labor freed up because of PPT adoption could be re-directed to increase productivity and income from other (i.e., non-maize) crop enterprises, tending livestock, and off-farm activities, although we leave most of such analysis, except off farm activities, for future work.

The data in Table 1 allows for comparison between women and men farmers in labor supplied to maize production on plots planted with and without PPT. For a given maize season, women farmers working in maize plots with PPT devoted 27 person-days/hectare less than their women counterparts in non-PPT plots. The corresponding figure for men farmers is 39. In summary, the descriptive results indicate that PPT may be labor-saving in net, with differences in labor effects by activity. Furthermore, men farmers appear to see greater labor savings with PPT adoption vs. women farmers. We subject these results to a more rigorous analysis with the econometric model (section 4.2).

Table A2
Estimates of endogenous switching regression model for PPT adoption and impact of adoption on labor supply (Household level analysis).

	(1)	Family labor supply		Female labor supply		Male labor supply	
VARIABLES	First stage	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-adopters
Number of field days attended	0.320***						
	(0.084)						
Presence of a PPT group in the village (1 = Yes)	0.465***						
	(0.117)						
No. of friends and peers practicing PPT	0.241***						
	(0.026)						
No. of working age male members	−0.053	36.780***	28.821***	5.468	8.333**	25.384***	18.403***
	(0.040)	(11.633)	(9.982)	(3.795)	(4.069)	(7.974)	(6.591)
No. of working age female members	−0.083**	9.060	16.078	11.387***	11.132**	−7.761	0.207
	(0.037)	(11.375)	(11.578)	(3.909)	(4.336)	(7.409)	(7.232)
Sex of household head (1 = male, 0 = female)	−0.349***	81.116*	4.608	−23.779*	−14.278	124.025***	19.753
	(0.113)	(41.573)	(29.444)	(12.985)	(10.158)	(31.005)	(20.618)
Ln (Age of head when first heard of PPT, years))	0.445**	−84.792	−51.610	14.971	32.216**	−114.932***	−83.146***
	(0.173)	(54.420)	(36.566)	(20.618)	(16.349)	(35.812)	(24.640)
Ln(No. of cows owned 5 years ago)	0.029	−2.025	−6.333	−2.275	−2.020	−0.859	−2.888
	(0.018)	(4.497)	(4.736)	(1.605)	(1.851)	(3.294)	(3.138)
Ln(No. of cows owned now)	0.014	2.323	5.022	−3.191*	−2.803**	4.285	4.342*
	(0.016)	(4.361)	(3.662)	(1.659)	(1.291)	(3.283)	(2.279)
Ln (Other livestock owned 5 years ago, TLUs)	−0.069*	−3.824	−14.382	−3.977	−2.862	−0.887	−10.842
	(0.037)	(9.156)	(12.296)	(3.588)	(4.856)	(6.675)	(7.700)
Mean crop diversity on a maize plot	0.901***	236.550***	191.184***	80.381***	77.590***	152.295***	122.828***
	(0.081)	(24.450)	(41.177)	(9.665)	(14.924)	(17.382)	(29.149)
Diversity of farmer groups in village	−0.017	5.218	3.502	1.808	4.197	2.543	2.189
	(0.025)	(5.883)	(6.582)	(2.084)	(2.817)	(4.479)	(4.345)
Size of household 5 years ago	−0.009	−16.558***	−3.709	−7.567***	−2.292	−5.883	0.575
	(0.020)	(6.225)	(5.936)	(2.420)	(2.134)	(4.340)	(4.140)
Land size (acres) owned 5 years	−0.011	−14.542***	−19.854***	−3.933**	−8.388***	−8.028**	−11.282***
	(0.018)	(4.944)	(4.295)	(1.587)	(1.639)	(3.307)	(2.679)
Ln(Average formal education of household (years)	0.065	−5.777	−17.923	−4.676	1.523	−0.819	−8.092
	(0.042)	(10.885)	(18.881)	(4.370)	(6.837)	(6.234)	(11.316)
Household is credit-constrained (1 = Yes)	−0.061	46.661*	−45.557	25.817***	−25.430*	11.609	−10.572
	(0.117)	(27.368)	(36.014)	(9.902)	(13.708)	(19.085)	(22.751)
Confidence in skill of extension officers (1 = Yes)	0.266***	94.316***	35.432	20.542**	4.356	65.660***	21.913
	(0.102)	(29.981)	(25.708)	(10.359)	(9.808)	(22.888)	(17.880)
Ln(Distance to extension office, walk minutes)	−0.149**	−78.564***	−25.736	−24.673***	4.362	−26.856**	−12.449
	(0.059)	(24.603)	(23.176)	(8.281)	(5.957)	(13.394)	(14.761)
Ln(Distance to nearest input supply, walk minute)	0.331***	8.746	12.111	4.365	−5.710	2.598	3.974
	(0.063)	(21.130)	(19.360)	(6.297)	(6.555)	(14.357)	(12.405)
Ln(distance to plot, walk minutes)	−0.412***	2.146	31.294	6.985	7.579	4.291	16.172
	(0.071)	(16.146)	(19.182)	(5.574)	(6.893)	(12.036)	(12.527)
Ln(Fertilizer applied, kg/acre)	0.054***	5.703	−10.284**	1.802	−3.538**	2.359	−7.550**
	(0.012)	(3.493)	(4.260)	(1.289)	(1.642)	(2.566)	(3.060)
Applied pesticides on any maize plot	−0.300	−25.059	−247.114***	−3.253	−95.739***	−27.191	−146.391**
	(0.365)	(67.121)	(89.725)	(36.948)	(31.301)	(48.488)	(65.798)
Used manure on any maize plot	0.144	20.437	−4.490	32.530***	20.065**	−24.297	−3.949
	(0.112)	(32.218)	(26.048)	(10.000)	(10.156)	(24.656)	(16.996)
Used draft power on any maize plot	−0.118	−172.241***	−14.140	−50.630***	−12.327	−97.243***	−8.974
	(0.120)	(32.055)	(32.751)	(12.542)	(11.556)	(23.629)	(23.249)
No. of times plot was ploughed	0.052	−37.164	−18.661	−22.969**	−21.724**	−16.883	4.814
	(0.083)	(29.503)	(23.575)	(9.344)	(9.342)	(23.313)	(14.460)
No. of times plot was weeded	−0.045	53.541*	44.322	15.207	38.115***	36.105	23.897
	(0.112)	(29.593)	(32.239)	(11.073)	(11.256)	(23.937)	(20.467)
Female members alone participate in off farm activities (1 = yes)	−0.130	−29.091	49.806*	0.050	26.794**	−35.255	26.917
	(0.125)	(33.371)	(28.594)	(11.728)	(12.160)	(24.461)	(19.878)
Other participate in off farm activities (1 = yes)	−0.035	4.256	−37.659	6.088	5.961	14.463	−21.582
	(0.109)	(28.385)	(31.357)	(9.456)	(11.966)	(19.918)	(20.693)
Season (1 = maim season)	−0.114	34.078	12.862	15.724	6.871	15.032	5.517
	(0.101)	(26.957)	(24.905)	(10.883)	(10.456)	(19.376)	(15.496)
County fixed effects	yes	yes	yes	yes	yes	yes	yes
Mills ratio		8.410	−81.849***	−16.998	−18.248*	23.521	−52.134***
		(38.393)	(28.269)	(15.278)	(10.367)	(25.906)	(17.346)
Constant	−4.516***	450.454*	378.828*	25.642	−136.943	389.141**	376.727***
	(0.843)	(251.384)	(220.964)	(100.175)	(95.713)	(170.994)	(140.130)
Observations	1,302	692	610	692	610	692	610
R-squared		0.335	0.365	0.336	0.369	0.308	0.336

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table A3
Estimates of ESR model for PPT adoption and impact of adoption on education expenditure (Household level analysis).

VARIABLES	(1) First stage	(2) Adopters	(4) Non-adopters
Number of field days attended	0.294**		
	(0.125)		
Presence of a PPT group in the village (1 = Yes)	0.435***		
	(0.161)		
No. of friends and peers practicing PPT	0.245***		
	(0.035)		
Ln(No. of cows owned 5 years ago)	0.032	608.006	−109.415
	(0.026)	(711.911)	(527.761)
Ln(No. of cows owned now)	0.021	−577.236	−389.606
	(0.022)	(711.142)	(431.208)
Ln (Other livestock owned 5 years ago, TLUs)	−0.092*	1,973.243	579.829
	(0.054)	(1,560.943)	(1,554.343)
Diversity of farmer groups in village	−0.022	2,382.924*	−1,755.920**
	(0.032)	(1,390.242)	(702.881)
Size of household 5 years ago	0.046	2,155.672*	541.724
	(0.030)	(1,303.711)	(708.551)
No. of working age members of household	−0.034	2,266.173	1,817.794*
	(0.040)	(1,486.433)	(1,035.171)
Land size (acres) owned 5 years	−0.028	−2,808.641**	−220.448
	(0.024)	(1,359.664)	(720.690)
Ln(Average formal education of household, years)	0.096	1,177.549	21,618.601***
	(0.104)	(5,955.419)	(5,098.573)
No. of children in Secondary	−0.013	11,284.276***	4,646.654***
	(0.064)	(2,750.145)	(1,539.847)
Number of children in primary	−0.152***	−6,348.231***	−2,207.316*
	(0.050)	(2,205.789)	(1,217.555)
Sex of household head (1 = male, 0 = female)	−0.340**	3,271.957	−11,256.303***
	(0.145)	(6,191.754)	(3,265.397)
Age of head	0.055***	−584.542	265.323
	(0.020)	(844.859)	(476.218)
Ln (Age of head when first heard of PPT (years))	−0.050***	−24.771	−306.029
	(0.018)	(756.699)	(447.451)
Ln(Distance to extension office, walk minutes)	−0.097	−10,942.383***	1,378.677
	(0.084)	(3,787.568)	(2,050.551)
Ln(Distance to nearest input supply, walk minute)	0.275***	11,344.933***	726.513
	(0.080)	(4,035.729)	(2,266.847)
Ln(distance to plot, walk minutes)	−0.146	6,567.577	457.422
	(0.090)	(4,279.279)	(1,728.660)
Household is credit-constrained (1 = Yes)	−0.178	2,315.126	2,101.853
	(0.161)	(5,612.488)	(3,664.320)
Confidence in skill of extension officers (1 = Yes)	0.233	−3,000.802	11,343.587***
	(0.148)	(6,781.069)	(3,344.114)
Main occupation of head	0.005	−3,649.065	−254.105
	(0.163)	(6,465.242)	(3,857.341)
Ln(value of assets)	−0.037	4,832.683*	5,116.117***
	(0.055)	(2,888.296)	(1,639.889)
Ln (Percapita nonfarm income)	−0.009	278.148	1,203.193***
	(0.013)	(553.424)	(331.531)
County fixed effects	−0.609***	−20,702.607**	476.416
Mills ratio		448.902	1,423.848
		(8,272.897)	(3,210.713)
Constant	−1.029	−18,317.734	−95,681.449***
	(0.871)	(44,746.243)	(25,640.557)
sigma		40,488.343***	21,175.436***
		(3,234.271)	(988.335)
Observations	597	314	283

Robust standard errors in parentheses
*** p < 0.01, ** p < 0.05, * p < 0.1

4.1.2. *PPT adoption and intrahousehold expenditure allocations*

The summary statistics also show that PPT adoption may improve intrahousehold expenditure allocations, particularly towards child investment and women-related purchases. For instance, PPT adopters appear to spend more on child education although when probability is lower than 0.8 (Fig. 6) and on goods preferred by women in a household (Fig. 7) compared to their non-adopting counterparts.[2] The pathways for higher child investment and expenditure associated with PPT adopters could be due to improved yields from PPT adoption, leading to a higher marketable surplus and increased income. For example, adopters appear to stochastically dominate non-adopters with respect to yields (Fig. 8), marketable surplus (Fig. 9), and income from fodder and cereals (Fig. 10). Other potential pathways for increased child investment and women-related expenditures may be due to increased empowerment of women from PPT adopting households. The probability of empowerment measured using the index of Women's Empowerment in Agriculture (WEAI) (Alkire et al., 2013), is higher among women from PPT adopting households (33 percent) compared with nonadopters (31 percent). Similarly, the overall WEAI score for PPT adopters is 0.64 relative to 0.62 for the nonadopters. Recent empirical work shows that women's empowerment in agriculture increases maize productivity in the region (Diiro et al. 2018).

4.2. *Estimation results of the treatment effects of PPT adoption*

This section presents and discusses the results from the analysis of the impact of PPT adoption on intrahousehold labor and consumption allocations. Since the main objective of this study is to assess the impacts of adoption, we do not discuss the regression results from the treatment and outcome equations. We however, provide the results of the regressions in the Appendix (Tables A1–A5).

4.2.1. *Impact of PPT adoption on agricultural labor supply*

Table 2 reports results for the impact of PPT adoption on the amount of family and hired labor a household in western Kenya allocates to maize farming activities. Overall, the average treatment effect (ATT) results show that adoption has a negative and significant effect on the amount of labor allocated to maize production per season. Findings indicate that if maize plots with PPT had not adopted with PPT, household family labor allocation would have been considerably higher: 260 person-days/hectare (without PPT) vs. 151 person-days/hectare. Farmers would reduce labor supply to maize plots without PPT from 223 to 138 person-days/hectare if they were to adopt PPT on those plots. Table 2 also reveals the heterogeneous effects of PPT adoption with respect to farming activities. As shown, PPT adoption significantly reduces labor requirements during ploughing, weeding, and threshing but significantly increases labor for harvesting. Labor savings due to the adoption of PPT are greatest during land preparation and planting, followed by weeding. The causal effects of adoption on hired labor allocations reveal a similar pattern. The changes in labor requirements noted above corroborate with qualitative findings from our survey on

[2] The vertical distance between the two cumulative density functions is significant at better than the 5 percent level.

Table A4
Estimates of ESR model for PPT adoption and impact of adoption on female participation in the off farm sector.

VARIABLE		Female participation		Household participation	
	(1) First stage	(2) Off farm sector participants	(3) Non-participants	(4) Off farm sector participants	(5) Non-participants
Number of field days attended by respondent	0.302***				
	(0.047)				
Presence of a PPT group in the village (1=Yes)	0.469***				
	(0.148)				
No. of friends and peers practicing PPT	0.240***				
	(0.031)				
Proportion of households engaged in some form of off farm activity	0.148	0.547	0.965	2.718***	3.337***
	(0.476)	(0.622)	(0.626)	(0.615)	(0.642)
No. of working age male members	0.010	−0.116*	0.111*	−0.040	0.113*
	(0.051)	(0.064)	(0.067)	(0.059)	(0.068)
No. of working age female members	−0.054	0.041	−0.012	−0.004	0.034
	(0.050)	(0.068)	(0.060)	(0.062)	(0.064)
Size of household 5 years ago	−0.001	0.028	0.024	0.041	0.066*
	(0.028)	(0.037)	(0.039)	(0.034)	(0.037)
Land size (acres) owned 5years	−0.019	0.018	0.031	0.037	0.004
	(0.023)	(0.031)	(0.026)	(0.029)	(0.026)
Ln(No. of cows owned 5 years ago)	0.024	−0.010	−0.031	−0.019	−0.090***
	(0.022)	(0.027)	(0.028)	(0.026)	(0.030)
Ln(No. of cows owned 5 now)	0.022	−0.032	−0.080***	0.008	−0.050**
	(0.017)	(0.021)	(0.023)	(0.020)	(0.023)
Ln (Other livestock owned 5 years ago, TLUs)	−0.083*	0.046	0.152**	0.004	0.267***
	(0.048)	(0.060)	(0.068)	(0.055)	(0.065)
Ln(Average formal education of household (years)	0.031	0.218	0.114	0.321	0.116
	(0.076)	(0.205)	(0.192)	(0.197)	(0.167)
Sex of household head (1 = male, 0 = female)	−0.464***	1.182***	0.910***	0.510***	0.828***
	(0.156)	(0.215)	(0.216)	(0.171)	(0.184)
Age of husband (years)	0.064***	−0.008	−0.052**	−0.016	−0.073***
	(0.018)	(0.024)	(0.024)	(0.023)	(0.025)
Ln (Age of head when first heard of PPT (years))	−0.053***	0.004	0.039*	0.009	0.073***
	(0.017)	(0.023)	(0.022)	(0.022)	(0.023)
Ln(Distance to extension office, walk minutes)	−0.156*	0.010	0.072	0.015	−0.053
	(0.088)	(0.114)	(0.114)	(0.103)	(0.109)
Ln(Distance to nearest input supply, walk minute)	0.296***	0.169	−0.265**	0.066	−0.097
	(0.089)	(0.111)	(0.113)	(0.099)	(0.111)
Ln(Distance to water source, walk minute	−0.019	0.024	−0.037	0.024	−0.019
	(0.020)	(0.026)	(0.026)	(0.023)	(0.027)
Ln(distance to plot, walk minutes)	−0.111	−0.050	0.035	−0.028	0.048
	(0.082)	(0.107)	(0.101)	(0.104)	(0.100)
Diversity of farmer groups in village	−0.025	−0.022	−0.023	0.007	0.005
	(0.031)	(0.036)	(0.042)	(0.034)	(0.039)
Household is credit-constrained (1 = Yes)	−0.231	−0.056	0.032	−0.398**	−0.188
	(0.142)	(0.166)	(0.197)	(0.157)	(0.193)
Confidence in skill of extension officers (1 = Yes)	0.295*	0.212	0.121	−0.159	−0.094
	(0.153)	(0.218)	(0.187)	(0.202)	(0.188)
Constant	−2.622***	−2.423**	−1.101	−2.138**	−2.461***
	(0.720)	(0.977)	(0.956)	(0.951)	(0.937)
Observations	702	702	702	702	702

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

farmer perceptions of labor supply changes resulting from PPT adoption. Among adopters, 61 percent felt that labor requirements for weeding and ploughing had decreased when they intercropped *desmodium* with their maize crop, while 77 percent perceived an increased labor demand for harvesting.

Table 3 reveals gender-based differences in the labor supply impacts of PPT adoption on maize plots. Relative to men, women save fewer labor hours during land preparation and planting but more labor hours during weeding and threshing (in fact, threshing labor for men is higher with PPT than without PPT). While PPT adoption increases harvesting labor requirements for both men and women, the incremental change is lower for women than men. For all maize activities combined, the technology appears to offer greater savings to men than women farmers for our sampled households, with reductions of 38 person-days/hectare for women vs. 67 person-days/hectare for men. Interestingly, qualitative data from the survey suggest that women are perceived to benefit more from the labor savings of PPT than men. In a follow-up question, farmers were asked to list the members of their household who would benefit most from PPT-induced labor reduction. Among respondents, 46 percent perceived that only females benefit in terms of labor savings, another 46 percent reported both females and males benefit, whereas only 8 percent reported that only males benefit.

We further provide results of household level analysis of PPT adoption on labor supply (Table 4), and note the pattern of impact of PPT adoption on labor supply by men and women to all maize plots in a household. Overall, if PPT adopting household had not adopted, their family labor allocation per season would have been considerably higher: 586 person-days/hectare vs. 424 person-days/hectare. Non-adopters could reduce their seasonal maize labor supply per from 313 to 238 person-days/hectare if they were to adopt PPT. Similarly men appear to gain more savings from PPT adoption than women. The reductions in female labor supply 59 person-days/hectare/season compared to 94

Table A5
Estimates of ESR model for PPT adoption and impact of adoption on female expenditure (Household level analysis).

VARIABLES	First stage	Adopters	Non-adopters
Number of field days attended by respondent	0.312**		
	(0.123)		
Presence of a PPT group in the village (1 = Yes)	0.408***		
	(0.145)		
No. of friends and peers practicing PPT	0.258***		
	(0.034)		
Ln(No. of cows owned 5 years ago)	0.028	563.449**	380.281
	(0.023)	(268.134)	(293.350)
Ln(No. of cows owned now)	0.030	−185.738	−231.238
	(0.019)	(262.729)	(232.611)
Ln (Other livestock owned 5 years ago, TLUs)	−0.070	−138.473	−294.451
	(0.045)	(754.706)	(666.390)
Diversity of farmer groups in village	−0.023	370.881	−663.634
	(0.031)	(437.529)	(472.416)
Size of household 5 years ago	0.008	−50.014	482.614
	(0.025)	(344.642)	(486.895)
No. of working age members of household	−0.028	148.714	−258.872
	(0.033)	(480.722)	(455.870)
Land size (acres) owned 5 years	−0.016	1,223.114***	−200.346
	(0.020)	(408.539)	(282.973)
Ln(Average formal education of household (years)	−0.005	984.276	1,937.490
	(0.059)	(1,324.628)	(1,858.950)
Women empowerment index (WEAI)	−0.130	4,450.622	8,923.617
	(0.422)	(7,236.551)	(5,850.320)
Sex of household head (1 = male, 0 = female)	−0.471**	552.415	−1,226.647
	(0.203)	(3,110.471)	(3,809.091)
Age of husband (years)	0.024***	−85.475	−106.686
	(0.009)	(124.007)	(207.734)
Education of husband (years of formal schooling)	0.024	360.517	608.127*
	(0.019)	(269.450)	(319.041)
Ln (Age of head when first heard of PPT (years))	−0.011	54.632	183.465
	(0.008)	(108.840)	(165.416)
Ln(Distance to extension office, walk minutes)	−0.148*	193.226	647.294
	(0.076)	(1,031.130)	(1,291.765)
Ln(Distance to nearest input supply, walk minute)	0.291***	−419.602	119.020
	(0.074)	(1,077.997)	(1,339.844)
Ln(distance to plot, walk minutes)	−0.139*	3,451.834***	3,595.717***
	(0.077)	(1,216.907)	(1,097.564)
Household is credit-constrained (1 = Yes)	−0.233	1,939.501	6,636.634***
	(0.153)	(1,847.895)	(1,962.666)
Confidence in skill of extension officers (1 = Yes)	0.292**	2,929.317	6,534.576***
	(0.125)	(2,364.080)	(2,173.178)
County fixed effects	−0.319	−8,462.181***	−3,686.028
Mills ratio		1,888.322	408.768
		(3,109.255)	(2,410.433)
Constant	−1.865***	9,960.503	−3,816.311
	(0.603)	(11,544.364)	(10,785.824)
Observations	702	362	340
R-squared		0.157	0.146

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

person-days/hectare for men.

These results notably imply that PPT may be a labor-saving technology and can provide households with an opportunity to diversify production and income generation since the labor saved can be shifted to other productive enterprises such as the off-farm activities or livestock production. Furthermore, the accrued labor-savings for women, although less than that for men, may be an important pathway for empowering rural women through reducing their workload, especially during weeding, ploughing, and planting activities.

4.2.2. PPT adoption and off farm participation

Estimates for the effect of PPT adoption on participation in off-farm income generating activities by female members and other members of the household are presented in in Tables 5. We also present but do not discuss the results of endogenous switching probit model that we used to estimate the adoption effects in appendix. The results show that females in PPT adopting households had 63% probability of participating in off-farm activities compared with the counterfactual scenario of non-adopting households. A similar pattern is observed for other household members from adopting household, exhibiting about 83% likelihood to engage off farm income generation relative to their counterparts from non-adopting households. These results demonstrate that PPT adoption can provide households with an opportunity to diversify income generation by redirecting the labor saved to generate income from the off farm sector. Thus, the technology provides both direct and indirect pathways to improve livelihoods of rural farmers.

4.2.3. Impacts of technology adoption on intrahousehold expenditure allocations

Table 6 documents that the adoption of PPT in a household led to an increase in household expenditures on children's education and had positive gender equality spillover effects. An adopting household spent KES 39,667 per year on children's education compared to KES 29,756 spent by a non-adopting household. The average treatment effects for adoption is KES 5,013, implying that adopters would have spent 14.6 percentage points less on child education if they had not adopted. Similarly, the ATT with respect to expenditure on goods associated with female preferences is significant and positive, suggesting that the adoption of PPT can increase the allocation of income to women's consumption expenditure in households. Adoption increased women's consumption expenditure by 7.5 percentage points. These results suggest that adoption of PPT technology can stimulate household investment in human capital, and improvements in women's welfare and that of their household members, through productivity and income pathways. Similar results have also been reported in an earlier study by Kassie et al. (2020), which demonstrated PPT adoption increased women's dietary quality.

5. Summary and conclusions

This study demonstrates how adoption of labor saving agricultural technology can affect the intrahousehold distribution of work and consumption, focusing on the case of push–pull technology (PPT) adoption in western Kenya. Previous research has documented the high potential of this unique technology to improve the welfare of farming households (Kassie et al., 2018; Kassie et al., 2020), but further investigation was needed to establish if the PPT-induced increase in maize productivity and profitability comes at a significant cost to some household members. Analysis of intrahousehold effects was possible due to the availability of gender-disaggregated data from a 2016 survey of 702 households and 2410 maize plots. An endogenous switching regression framework was used to control for selection bias stemming from observed and unobserved heterogeneity.

The labor supply results reveal that, on average, the adoption of PPT reduces total family labor allocation to maize production, with different effects depending on the maize farm activity. Farm households allocated less labor to PPT maize plots than plots without PPT during land preparation, weeding, and threshing. However, the amount of labor for harvesting increased on plots with PPT relative to plots without PPT. The reduced agricultural workload due to PPT adoption is significant for both men and women. Importantly, this indicates that the adoption of PPT technology can increase women's empowerment, through workload reductions. As far as consumption impacts, findings suggest that PPT uptake increases household expenditures on children's education and consumption goods commonly associated with female preferences. The findings further show that adoption of PPT increases the probability of women and household participation in nonfarm income. Taken together, the results presented in this paper demonstrate the importance of looking within the farm household to determine the impacts of technology adoption.

Findings herein alongside earlier results that PPT increases the dietary quality of households and women (Kassie et al., 2020) may suggest that scaling up the adoption of PPT will generate livelihood opportunities, increase productivity, food security and enhance human capital development in rural economies, especially those that rely on cereal crop enterprises. Towards that end, development partners promoting the PPT technologies need to address the main barriers to increased adoption of the technology. Qualitative data collected during the survey revealed that limited availability and high cost of seeds for PPT companion crops (*desmodium* and *brachiaria*), coupled with liquidity constraints limit the widespread adoption of the technology. National Governments and development partners need to facilitate the establishment of a commercially sustainable system for production and certification of PPT companion plant seed to increase access to and availability of quality seeds to farmers.

Although our study provides valuable insight into the intrahousehold impacts of technology adoption in a typical rural household, our findings are based on cross-sectional data, which reveal short-run impacts only. Further research utilizing panel datasets is thus necessary to better understand impacts and account for the dynamics of gender roles. Furthermore, although we capture the effect of PPT adoption on child investment, we do not explore its effect on child labor and school attainment. Children in SSA provide substantial labor to farming, which may compromise their school attendance, performance and education attainment (Admassie, 2002; Lodin et al., 2014). Thus, additional survey data with questions aimed at understanding child labor, school attendance, and performance would also be important.

CRediT authorship contribution statement

Gracious M. Diiro: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. **Monica Fisher:** Conceptualization, Methodology, Writing - review & editing. **Menale Kassie:** Methodology, Supervision, Project administration. **Beatrice W. Muriithi:** Methodology, Data curation, Writing - review & editing. **Geoffrey Muricho:** Investigation.

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Appendix

See Tables A1–A5

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