Push-Pull Technology as a Climate-Smart Integrated Pest Management Strategy in Southern Ethiopia

by Gebeyehu Manie Fetene, Solomon Balew, Zewdu Abro, Menale Kassie, and Tadele Tefera

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Abstract

Push-pull technology (PPT) is developed for integrated pest and weed management in the smallholder farming systems of sub-Saharan Africa. However, there are limited farm-level rigorous studies on the effects of PPT on pest control, chemical uses to control pests, and maize production. By exploiting plot-level variation in PPT adoption among maize farmers in southern Ethiopia, we estimate the effect of PPT on fall armyworm (FAW), insecticides use, and maize yield using fixed-effects models. We find that PPT reduces maize yield loss due to FAW by 10-17%. We also find that PPT increases maize yield by 12-15%. This study implies PPT can make farmers resilient to shocks of pests.

Keywords: fall armyworm, insecticides, push-pull technology, maize yield, yield loss

1. Introduction

Maize is a strategic crop for food and feed in sub-Saharan Africa (SSA) (Matova et al., 2020; Ranum et al., 2014; Shiferaw et al., 2011). However, the production of maize faces multiple constraints. Historically, stemborers and the Striga weed are the main maize pests that could cause a complete maize production failure (De Groote, 2002). Stemborers could cause a yield loss of 20-40% (De Groote, 2002; Prasanna, 2015; Samuel et al., 2018; Shiferaw et al., 2011). Striga affects food production in Africa by infesting nearly 100 million hectares and a yield loss that varies from 20% to 100% destruction depending on the infestation level (Ejeta and Gressel, 2007; Kim et al., 2002; Menkir et al., 2020; Mudereri et al., 2021; Yacoubou et al., 2021). Since 2016, fall armyworm (FAW) become one of the economically important pests of maize, further exacerbating the existing maize production problems in the region (Banson et al., 2020; Day et al., 2017; De Groote et al., 2020; Feldmann et al., 2019; Kassie et al., 2020; Rwomushana et al., 2018; Sisay et al., 2019; Tambo et al., 2020). It affects about 37 million hectares of maize in SSA with an economic loss of US$ 2.5 to 6.2 billion per annum (Abrahams et al., 2017; Day et al., 2017; Early et al., 2018; Hruska, 2019; Rwomushana et al., 2018). Protecting maize production from FAW could protect the livelihood and food security of 300 million people in SSA who rely on maize for consumption to fulfill their daily calorie demand (FAO, 2020).

Governments and development partners in SSA rely on pesticides as an emergrency strategy to mitigate production losses caused by FAW. However, the effectiveness of this strategy to mitigate the pest is weak (Kassie et al., 2020). Also, the indiscriminate use of insecticides to control FAW affects biodiversity, environmental, and human health (Abro et al., 2021; Rwomushana et al., 2018). The push-pull technology (PPT) could be an alternative viable integrated pest management strategy to control FAW while safeguarding the environment and human health (Guera et al., 2021; Hailu et al., 2018; Harrison et al., 2019; Khan et al., 2018). PPT involves intercropping cereals with desmodium and planting brachiaria rounding the intercropped plot. While the leguminous desmodium has a unique chemical that repels (pushes) insects and suppresses Striga weed, brachiaria has a unique chemical that attracts (pulls) pests (Khan et al., 2018, 2008; Pickett et al., 2014). The desmodium improves soil fertility by improving the availability of nitrogen and phosphorus and reducing soil erosion (Ndayisaba et al., 2021). Furthermore, desmodium and brachiaria are rich in protein and carbohydrates, making them suitable for livestock feed (Khan et al., 2014; Pickett et al., 2014). Because PPT provides a natural method of controlling pests and fertilizing the soil, the technology may reduce production costs as the fertilizer and insecticides requirement may decline

(Ndayisaba et al., 2020). A decline in insecticide use may reduce environmental and human health risks. PPT's benefits may enable farmers to practice sustainable and efficient mixed farming, increasing maize and livestock productivity.

As an integrated pest management strategy to control FAW, PPT has been the subject of two lines of literature. The first line of literature estimates the agronomic and economic benefits of PPT at the experimental level (Hailu et al., 2018; Khan et al., 2018; Midega et al., 2018; Ndayisaba et al., 2020). This literature shows that PPT reduces production losses caused by FAW, stemborers, and Striga and improves soil fertility. However, there is limited empirical research on PPT's effects to control FAW control and insecticide use under farmers' field management conditions. As a result, these studies may potentially bias the estimated benefits of the technology in the farmers' fields.

The second line of literature addresses the experimental studies' limitation by reaching as many farmers as possible. The projects associated with these studies provided the necessary training on PPT and start-up seeds of the companion crops to smallholder farmers. Some documented the adoption status and the various strategies of promoting PPT in western Kenya (Amudavi et al., 2009a, 2009b; D'Annolfo et al., 2021; Murage et al., 2015, 2012, 2011). Other studies focused on estimating the effects of PPT on productivity, income, and economic surplus. A pioneering study in this line is Kassie et al. (2018), who find that PPT increases maize productivity and net farm income in Striga-prone western Kenya by 62% and 39%, respectively. They also estimated that scaling up PPT at the regional-level could generate an economic surplus of US$ 72-34 million, which could lift seventy-five thousand people out of poverty. Overall, this line of literature reports benefits lower than the experimental studies. For instance, the estimated yield gain of adopting PPT by Kassie et al. (2018) is 24 percentage points lower than the experimental study by Khan et al. (2008) in western Kenya.

Despite these remarkable documented benefits, PPT adoption remains limited to a quarter of a million farmers in SSA (*icipe*, 2021). Lack of information by smallholder farmers and limited involvement of local partners constrained the adoption of the technology in SSA. The International Centre of Insect Physiology and Ecology (*icipe*) and its partners introduced PPT as an integrated pest management strategy for maize production in southern Ethiopia. However, rigorous evaluation of the technology in abating losses and increasing maize productivity of the project is yet to be made. Outside Kenya and Uganda, to our knowledge, there are two studies in Ethiopia that provide valuable information on farmers' perception about PPT but failed to control for confounding factors (Gebreyesus et al., 2020; Kumela et al., 2019). In this paper, we contribute to the existing literature by quantifying the effect of PPT on FAW infestation in southern Ethiopia. The empirical evidence informs policymakers to invest in agricultural research and extension on PPT to improve farmers' resilience to pests and climate change in Ethiopia and beyond.

We use a comprehensive household- and plot-level data to control for plot-invariant unobserved heterogeneities that may drive adoption decisions of PPT, maize yield losses, and yield gains. Using a relatively large dataset of 1,181 households and 2,135 plots, we estimate the effects of PPT on the outcome variables employing a fixed-effects model. Our results show that PPT reduces maize yield loss due to FAW by 10-17% and positively affects maize yield by 12-15%. Our findings suggest that the technology can support farmer's resilience to shocks by reducing pest pressure and increasing productivity.

The rest of this paper is organized as follows. In section two, we describe the study area and data collection strategy. In section three, we present the descriptive statistics. In section four, we present the empirical strategy. In section five, we discuss the empirical results. Finally, we conclude in section six.

2. Study area and data

We conduct this study in the Hawassa Zuria district of the newly formed Sidama Regional State of Ethiopia. The district occupies 1.5 percent of the country's maize cultivated area (CSA, 2020). It represents 28% and 35% of the maize area and production of the region, respectively (CSA, 2020). Farmers in the district allocate about 70% of the total cultivated land to maize, showing the crop's economic importance in the district (Kassie et al., 2020). Maize production is affected by several productivity-limiting factors, including pests harming farmers' food security and livelihoods. FAW is an economically important pest in the district (Kassie et al., 2020). In addition to FAW, soil erosion is a key production constraint (Gebretsadik, 2014). Farmers in the district use insecticides and several other cultural practices to control pests and soil erosion, albeit with limited success (Kassie et al., 2020). The production loss associated with pests and soil erosion is further exacerbated by the district's shortage of livestock feed (Wondatir and Damtew, 2015).

To address these agricultural production challenges in the district, the *icipe* introduced PPT in 2018. We provided training to randomly selected farmers on the agronomy, management, and PPT's benefits to these farmers and extension workers. We first held the theoretical sessions at the Farmers' Training Centers of each community. Next, we demonstrated the actual implementation of PPT in practical field sessions. We also provided start-up desmodium and brachiaria seeds to farmers who wanted to try the technology. *icipe*'s project staff and the district agricultural office provided technical support and monitored the implementation of PPT.

This study's data comes from a household survey collected in September and October 2020 to assess the effect of PPT on maize production loss and maize productivity in the study area. The survey covered 1,181 households randomly selected from 17 of the 23 villages in the district (Figure 1). These households produced maize on 2,135 plots. Of the total sample, 31% of them adopted PPT. Using a structured questionnaire, experienced and well-trained enumerators collected the data. The dataset has detailed information on production losses due to FAW, actual maize production, and expected maize production had not production constraints affected maize. The dataset also has rich information on households' socioeconomic and plot characteristics (e.g., input use, investment, and plot characteristics).

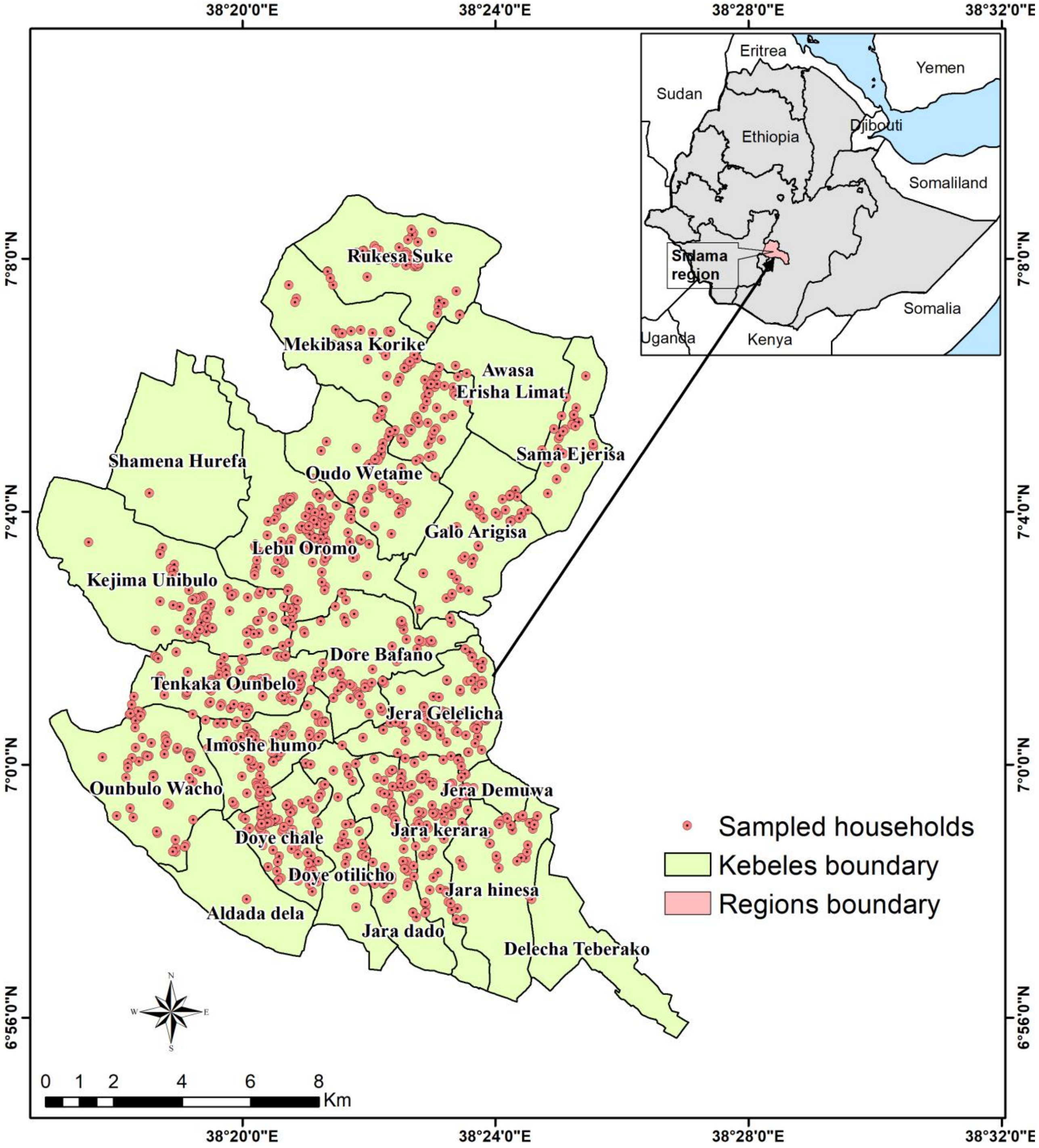

Figure 1. Map of the study areas

3. Econometric framework for estimating PPT's effect

In this section, we present the empirical strategy to estimate the effect of PPT on our three outcome variables: maize yield loss due to FAW, insecticide use (liter/ha), and maize yield (kg/ha). We estimate the following regression model:

$$Y_{ip} = \alpha + \beta PPT_{ip} + \boldsymbol{\theta} \boldsymbol{X}_{ip} + \varphi_i + \varepsilon_{ip} \qquad (1)$$

where Y_{ip} denotes the three outcome variables of household i in plot p. PPT takes one if PPT is adopted by household i on plot p, and zero otherwise. $\boldsymbol{X}_{ip}$ denotes a vector of explanatory variables that affect the outcome variables, chosen based on economic theory and previous studies (Diiro et al., 2021; Kassie et al., 2020, 2018). φ_i denotes plot-invariant household fixed effects of household i. α, β, and $\boldsymbol{\theta}$ denote parameters to be estimated, and ε_{ip} are error terms.

We estimate PPT's effect on maize yield loss due to FAW using the fixed-effect fractional probit model since the values of this outcome variable are between 0 and 1 (Papke and Wooldridge, 2008). Conditional on $\boldsymbol{X}_{ip}$ and φ_i, the marginal effect of β represents the effect of using PPT on the fraction of loss due to FAW. We estimate PPT's effect on insecticides use and maize yield using a linear fixed-effects model. Our plot-level data are cross-sectional, but about 60% of the households in our sample produce maize on more than one maize plot. We address the unobserved heterogeneities between households by exploiting the variation in PPT adoption and the outcome variables within households. For this reason, we estimate a household-level fixed-effects model that differences out unobserved heterogeneities within households to reduce potential selection bias.

Adopters and non-adopters of PPT may differ due to unobserved heterogeneities such as farm management skills. Furthermore, there might be a selection problem associated with the choice of plots where PPT should be implemented. We believe that selection is based on the characteristics of the plots, including soil fertility, plot slope, input use, and distance from home. We control these variables in our regressions. However, household-level factors may still affect plot choice. For example, risk-averse farmers may adopt PPT on poor-quality plots as the technology is new, while risk-takers may adopt it on fertile plots. Since the risk behavior of farmers does not vary among plots, the fixed-effects model addresses such heterogeneities.

4. Results and discussion

4.1. Descriptive statistics

Table 1 summarizes the socioeconomic characteristics of the farmers. On average, the farmers have 1.81 maize plots. Farmers practiced PPT in 375 of the plots. According to farmers, FAW is the most important pest that affects maize production in the study areas. The number of households that adopted PPT was 370. Farmers reported that FAW occurred in 69% of their plots. We have three outcome variables: loss due to FAW, insecticide use, and maize yield. The loss due to FAW is measured in percentage terms. When we estimate the maize loss due to FAW, we accounted for other causes of loss, including abiotic factors (e.g., drought) and biotic factors (e.g., stemborers). We first asked farmers to tell us the actual maize production of each plot in the presence of all production constraints, including FAW. Next, we asked farmers to estimate the attainable maize production in each plot without these production constraints. Finally, we asked farmers to quantify the contribution of FAW from the production gap, which is the difference between the attainable and actual maize production. We measure insecticide use and maize yield in liters/ha and kg/ha, respectively.

Table 1. Definition of variables and summary statistics

	PPT plots		Non-PPT plots		
Variables	Mean	Standard deviations	Mean	Standard deviations	Difference
Outcome variables					
Maize yield loss due to FAW (%)	0.24	0.27	0.26	0.29	-0.02
Insecticides use (kg/ha)	0.78	2.27	0.25	1.28	0.53***
Maize yield (kg/ha)	4,429.47	2,243.96	3,301.22	1,758.47	1,128.25***
Plot investment					
DAP use (kg/ha)	166.77	97.97	131.85	73.58	34.92***
UREA use (kg/ha)	170.42	101.25	135.22	75.91	35.20***
Hired labor (1/0)	0.38	0.49	0.42	0.49	0.18***
Other pest control strategies used (1/0)	0.70	0.46	0.62	0.49	0.08***
Plot characteristics					
Good plot fertility (ref)	0.77	0.42	0.72	0.45	0.05*
Medium plot fertility (1/0)	0.22	0.42	0.26	0.44	-0.03
Poor plot fertility (1/0)	0.03	0.16	0.04	0.19	-0.01
Shallow depth plot (1/0)	0.05	0.21	0.07	0.25	-0.02
Medium depth plot (1/0)	0.21	0.40	0.18	0.38	0.03
Deep depth plot (ref)	0.76	0.43	0.77	0.42	-0.01
Flat plot (ref)	0.86	0.35	0.80	0.40	0.07***
Medium slope plot (1/0)	0.14	0.34	0.18	0.38	-0.04***
Steep slope plot (1/0)	0.02	0.14	0.04	0.19	-0.02*
Soil color is black (ref)	0.37	0.48	0.34	0.47	0.03
Soil color is brown (1/0)	0.25	0.43	0.19	0.39	0.05**
Soil color is gray (1/0)	0.37	0.48	0.44	0.49	-0.07**
Soil color is red (1/0)	0.01	0.11	0.03	0.16	-0.02
Manure or compost used in the plot (1/0)	0.64	0.48	0.45	0.50	0.19***
Legume-maize intercropping (1/0)	0.61	0.49	0.35	0.48	0.25***
Irrigation used (1/0)	0.01	0.11	0.02	0.13	0.00
Plot distance to residence (walking minutes)	7.36	29.06	39.91	64.46	-32.55***
Owned plot by the household (1/0)	0.99	0.09	0.93	0.25	0.06***
Household characteristics					
Age of household head (years)	45.05	12.06	45.13	11.69	-0.08
Family size (number)	5.73	1.61	5.89	1.73	-0.17*
Education of household head (years)	5.43	4.39	5.10	4.71	0.33
Distance to extension services (walking minutes)	26.71	20.86	30.66	25.05	-3.95***
Household confident in extension officers (1/0)	0.97	0.17	0.94	0.23	0.03**
Cellphone ownership (1/0)	0.78	0.41	0.76	0.43	0.03
Value of livestock ownership (ETB)	51,169.03	46,903.78	51,893.77	54,283.98	-724.75

Altitude (meters above sea level)	1,698.24	158.07	1,726.05	48.61	-27.81***
Number of plots (households)	1760 (811)		375 (370)		

Note: * p<0.10, ** p<0.05, *** p<0.001

We expect that PPT reduces loss due to FAW, insecticide use, and increased maize yield. However, the unconditional mean differences show mixed results. The unconditional mean of the losses due to FAW in PPT plots is 2% lower than non-PPT plots, but the differences are not statistically significant. Insecticides use is higher on PPT plots (0.53 liters/ha) than non-PPT plots. The observed unconditional mean maize yield shows that PPT plots have 1,128 kg more yield than non-PPT plots.

Figure 2, show the the distrubtion of outcome variables by PPT adoption status. We observe no statistically significant differences in loss due to FAW between the two distributions (Figure 2, Panel A) using Kaplan's test statistics (Kaplan, 2019). However, we observe statistically significant differences in the distributions of insecticide use and maize yield between PPT and non-PPT plots (Figure 2, Panels B and C). Consistent with the mean differences, insecticides use is higher in PPT than non-PPT plots throughout the entire distribution of insecticide use. As expected, maize yield is higher in PPT than non-PPT plots throughout the two distributions.

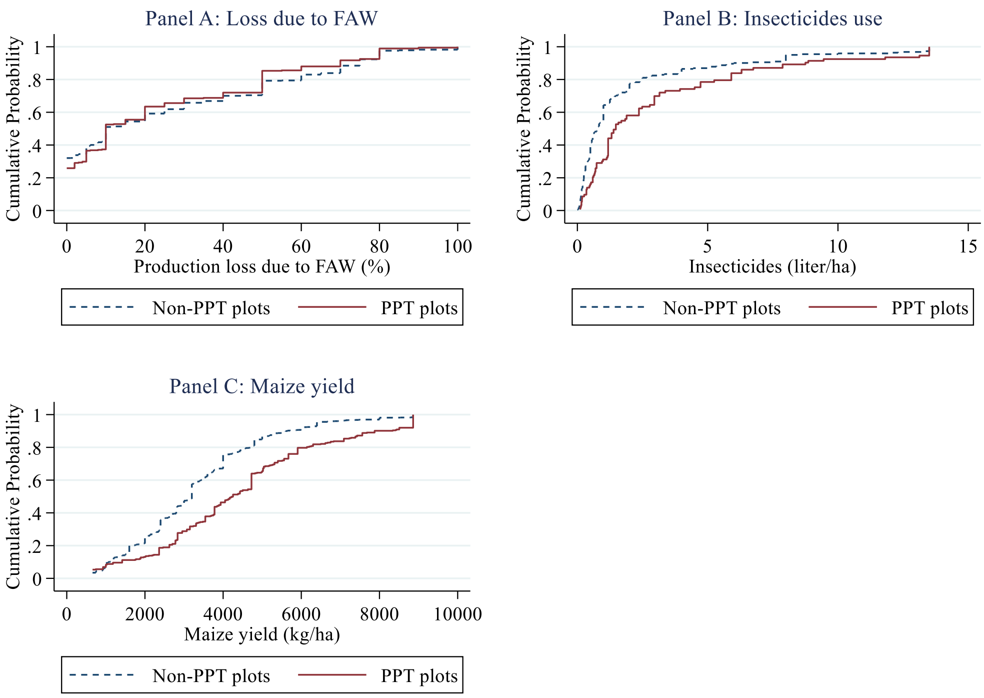

Figure 2. Distributions of the outcome variables by PPT adoption status

The descriptive statistics suggest that PPT increases yield and reduces loss due to FAW while insecticide use remains high in PPT plots. However, these comparisons are misleading because the outcome variables are not only affected by PPT but also other factors. This is confirmed by the statistically significant differences between PPT and non-PPT plots on several variables. Table 1 reveals that input use in PPT plots is consistently higher than non-PPT plots. Most of the plot characteristics differ between PPT and non-plots. The characteristics of most of the PPT adopting farmers differ from other households. Therefore, in the next section, we estimate the effects of PPT on loss due to FAW, insecticides use, and maize yield conditional on these covariates.

4.2. Empirical results

In this section, we discuss the effect of PPT adoption on the outcome variables. Here, we present the coefficients of PPT, and the full regression results are in Appendix A. Table 2 reports the effects of PPT on loss due to FAW. In column A, we report the results from the full sample by comparing the outcome variables of the PPT plots against all plots regardless of the households' adoption status. In column B, we report the results by comparing PPT and non-PPT plots of households who adopted the technology.

We find that PPT adoption has a negative and statistically significant effect on the fraction of loss due to FAW.Our results suggest that, on average, PPT reduces the fraction of loss due to FAW by 0.047, equivalent to a 17% reduction in the fraction of loss. When we use the sub-sample of PPT adopters, PPT reduces the fraction of loss due to FAW by 0.027 (10% reduction in the fraction of loss). When we use the sub-sample of households who adopted PPT, the marginal effect tends to be lower perhaps because the variation in the outcome and independent variables may be lower. Unlike the unconditional mean differences shown in section 3, controlling for the confounding factors reveal that PPT adoption may help framers reduce the fraction of loss due to FAW.

Table 2. PPT's effect on loss due to FAW-marginal effects from the fractional probit model (FL)

Variables	FL-fixed effects	
	Full-sample	Sub-sample
	A	B
PPT plot (1/0)	-0.047***	-0.027*
	(0.012)	(0.015)
Constant	-2.214***	-2.001***
	(0.610)	(0.819)
Plot investment	Yes	Yes

Plot characteristics	Yes	Yes
Household characteristics	Yes	Yes
Village fixed effects	Yes	Yes
Mundlak fixed effects	Yes	Yes
Number of plots	2,135	726

Notes: Bootstrapped standard errors clustered at the household-level are reported in parentheses. ∗p<0.10, ∗∗p<0.05, ∗∗∗p<0.01.

In Table 3, we report results on PPT's effect on insecticide use and maize yield. In our estimation, we transformed these into an inverse hyperbolic sine (IHS) transformation because some of the right-hand-side and left-hand-side variables have zero values. The PPT adoption variable's elasticity to the IHS transformed outcome variables can be calculated as exp(β)–1 (Bellemare and Wichman, 2020). After controlling and unobserved heterogeneities and confounding factors, the results of both the full- and sub-sample suggest that PPT has no effect on insecticides use. It appears that farmers indiscriminately sprayed insecticides regardless of PPT adoption.

Table 3. PPT's effect on insecticides use (liter/ha) and maize yield (kg/ha)-fixed effects model

Variables	Insecticide use (liter/ha)-IHS		Maize yield (kg/ha)-IHS	
	Full-sample	Sub-sample	Full-sample	Sub-sample
	A	B	C	D
PPT plot (1/0)	0.035	0.026	0.151***	0.117***
	(0.036)	(0.045)	(0.040)	(0.042)
Plot investment	Yes	Yes	Yes	Yes
Plot characteristics	Yes	Yes	Yes	Yes
Constant	0.058	0.086	6.191***	6.552***
	(0.199)	(0.415)	(0.240)	(0.403)
R^2	0.107	0.138	0.304	0.380
Number of plots	2,135	726	2,135	726

Notes: robust standard errors clustered at the household-level are reported in parentheses. ∗p<0.10, ∗∗p<0.05, ∗∗∗p<0.01.

In columns C and D of Table 3, we present PPT's adoption effect on maize yield (kg/ha). We find that PPT adoption has a positive and statistically significant effect on maize yield. After controlling for household-level unobserved heterogeneities and confounding factors that influence yield, PPT increases maize yield by 15% in the full sample, and by 12% for the sub-sample of households who adopted PPT.

Our findings agree with both experimental and observational studies that reported a significant increase in maize yield due to PPT (Kassie et al., 2018; Ndayisaba et al., 2021). However, the size of our estimated yield effects is significantly smaller than previous studies in western Kenya. Ndayisaba et al. (2020) reported a 70% increase in yield due to PPT adoption. Kassie et al. (2018) demonstrated that PPT increases yield by 62% for the adopted farmers. This might be attributable to several factors. First, western Kenya is highly infested with Striga while it is not a problem in the study area in southern Ethiopia. PPT's adoption effect in western Kenya thus helps farmers obtain more yield gains than the farmers Ethiopia. Second, there is significant differences in experience in implementing PPT between our sample and the farmers in western Kenya. The farmers in this study were introduced to PPT in 2018, and we measure PPT's effect a year after the introduction. On the other hand, farmers in western Kenya have several years of experience implementing PPT, which was introduced in 1997 (Murage et al., 2012). Finally, heterogeneities associated with farming techniques, agroecology, and farmers' characteristics may bring variation in PPT use and yield.

5. Conclusions

Maize is an important food security crop in sub-Saharan Africa, with significant contribution to daily calorie intake and livelihood to most smallholder farmers. However, the region could not exploit the crop's full potential due pests such as fall armyworm (FAW). To address these maize production constraints, push-pull technology (PPT) could be a viable integrated pest management strategy. Existing experimental studies reveal that PPT can reduce FAW and increase maize yield, thereby promoting the technology for further scaling up.

Despite the benefits, PPT adoption remains low in SSA. This is partly because PPT is unknown to many smallholder farmers. To increase adoption, the International Centre of Insect Physiology and its partners introduced PPT as a participatory integrated pest management strategy for maize production in Ethiopia. In this paper, we evaluate the effects of the introduction of PPT to farmers. Particularly, we estimated the effects of push-pull technology (PPT) on loss due to FAW, insecticides use, and maize yield in southern Ethiopia. This is the first comprehensive study undertaken in Ethiopia and one of the existing few studies outside Kenya and Uganda where PPT was experimented and promoted by research organizations and donors. Quantifying the effects of PPT helps to promote agricultural research and extension work on the technology to improve farmers' resilience to pests.

We do the analysis using econometric methods applied to comprehensive cross-sectional household and plot-level data collected from 1,181 maize farmers. The results from fixed-effects regressions reveal that PPT reduces yield losses due to FAW by 10-17% depending on the model used. Similarly, PPT increased maize yield by 12-15% for the adopted farmers. However, we did not find an economically and statistically significant reduction in insecticides use in PPT plots. Perhaps, this is because farmers and the local government were in panicking mood due to the arrival of FAW and indiscriminately applied insecticides regardless of PPT adoption, which is supposed to reduce insecticidee use.

Despite these benefits of PPT, farmers could not exploit the technology fully because adoption is low in the study areas. This calls for more research on PPT knowledge diffusion and identifying causes for limited adoption and potential dis-adoption of PPT. We also use a cross-sectional dataset that do not capture the dynamics of PPT adoption and its effect over time. Our data were collected immediately after the implementation PPT, but the impact of the technology will likely increase overtime as the companion crops are well-established in the plots. Addional studies might be required two to three years after the full establishment of the brachiaria and desmodium crops that may further increase soil fertlitiy, and suppress weeds and FAW occurrence. Finally, future studies may need to collect detailed information of production of feed from brachiaria and desmodium and livestock productivity indicators to document PPT’s effect on livestock productivity, which we did not address it due to data limitations.

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Appendix A: Tables with full regression results for all outcome indicators

Table 1A. PPT's effect on loss due to FAW (%)-fractional probit-fixed effects model, marginal effects

	FL-fixed effects	
Variables	Full-sample	Sub-sample
PPT plot (1/0)	-0.047***	-0.027*
	(0.012)	(0.015)
DAP use (kg/ha)-IHS	0.015	0.022
	(0.020)	(0.042)
Urea use (kg/ha)-IHS	0.002	0.019
	(0.023)	(0.045)
Seed use (kg/ha)-IHS	0.023	-0.013
	(0.020)	(0.038)
Weeding frequency	0.033*	0.019
	(0.020)	(0.023)
Ploughing frequency	-0.029	-0.044
	(0.018)	(0.031)
Hired labour (1/0)	0.014	-0.008
	(0.021)	(0.031)
Medium plot fertility (1/0)	-0.014	-0.028
	(0.016)	(0.021)
Poor plot fertility (1/0)	-0.010	-0.041
	(0.030)	(0.048)
Shallow depth plot (1/0)	0.042	0.075
	(0.039)	(0.053)
Medium depth plot (1/0)	0.030	0.048
	(0.025)	(0.043)
Medium slope plot (1/0)	-0.023	-0.008
	(0.016)	(0.025)
Steep slope plot (1/0)	-0.076**	-0.044
	(0.030)	(0.049)
Soil color is brown (1/0)	0.003	-0.019
	(0.017)	(0.025)
Soil color is gray (1/0)	-0.006	-0.004
	(0.017)	(0.030)
Soil color is red (1/0)	-0.018	-0.068
	(0.027)	(0.041)
Manure or compost used in the plot (1/0)	0.008	-0.008
	(0.013)	(0.019)
Legume-maize intercropping (1/0)	-0.022	-0.001
	(0.016)	(0.025)
Irrigation used (1/0)	-0.008	0.032
	(0.059)	(0.114)
Plot distance to residence (walking minutes)	0.000	0.000
	(0.000)	(0.000)

	FL-fixed effects	
Variables	Full-sample	Sub-sample
Owned plot by the household (1/0)	0.006	-0.024
	(0.023)	(0.046)
Other FAW control strategies used (1/0)	0.417***	0.408***
	(0.027)	(0.048)
Doyo Chale (1/0)	0.258***	0.349***
	(0.030)	(0.076)
Doyo Otilgho (1/0)	0.291***	0.312**
	(0.043)	(0.153)
Tenkaka Umbulo (1/0)	0.288***	0.355***
	(0.030)	(0.073)
Emoshe Humo (1/0)	0.231***	0.337***
	(0.030)	(0.070)
Udo Wotate (1/0)	0.089**	0.110
	(0.036)	(0.079)
Dore Bafano (1/0)	0.121***	0.248***
	(0.045)	(0.074)
Kajima Umbulo (1/0)	0.151***	0.106
	(0.031)	(0.105)
Umbulo Wacho (1/0)	0.223***	0.172**
	(0.042)	(0.079)
Sama Ejersa (1/0)	0.040	0.173**
	(0.049)	(0.077)
Mekibasa Korke (1/0)	0.047	0.087
	(0.032)	(0.086)
Rukesa Sukie (1/0)	0.074**	-0.188**
	(0.035)	(0.082)
Jara Dado (1/0)	0.222***	0.375***
	(0.032)	(0.081)
Jara Gelelcha (1/0)	0.207***	0.325***
	(0.031)	(0.072)
Jara Kerera (1/0)	0.137***	0.173**
	(0.036)	(0.074)
Galo Hargisa (1/0)	0.114***	0.125
	(0.038)	(0.077)
Lebu Koremo (1/0)	0.099***	0.126
	(0.030)	(0.084)
Mundlak fixed-effects joint signficance (x^2)	102.740***	51.620***
Constant	-2.214***	-2.004**
	(0.610)	(0.819)
Number of plots	2,135	726

Notes: bootstrapped standard errors clustered at the household-level are reported in parentheses. ∗p<0.10, ∗∗p<0.05, ∗∗∗p<0.01.

Table 2A. PPT’s effect on insecticides use (liter/ha) and maize yield (kg/ha): fixed-effects model

Variables	Insecticides use (liter/ha)		Maize yield (kg/ha)	
PPT plot (1/0)	0.035	0.026	0.151***	0.117***
	(0.036)	(0.045)	(0.040)	(0.042)
DAP use (kg/ha)-IHS	-0.011	-0.111	0.049	-0.035
	(0.027)	(0.107)	(0.043)	(0.106)
Urea use (kg/ha)-IHS	0.052*	0.129	0.090**	0.167
	(0.030)	(0.108)	(0.045)	(0.104)
Seed use (kg/ha)-IHS	0.012	0.044	0.441***	0.481***
	(0.035)	(0.067)	(0.050)	(0.071)
Weeding frequency	-0.042	-0.014	-0.008	-0.046
	(0.035)	(0.026)	(0.036)	(0.051)
Ploughing frequency	-0.018	-0.041	-0.014	-0.103
	(0.025)	(0.064)	(0.043)	(0.092)
Hired labour (1/0)	-0.012	-0.076	-0.070	-0.089
	(0.032)	(0.072)	(0.045)	(0.079)
Medium plot fertility (1/0)	-0.000	-0.002	-0.018	-0.058
	(0.033)	(0.080)	(0.036)	(0.069)
Poor plot fertility (1/0)	-0.057	-0.143	0.002	-0.076
	(0.055)	(0.148)	(0.065)	(0.077)
Shallow depth plot (1/0)	0.038	0.057	-0.066	0.095
	(0.028)	(0.089)	(0.058)	(0.119)
Medium depth plot (1/0)	0.052	0.035	0.114**	0.055
	(0.039)	(0.077)	(0.055)	(0.098)
Medium slope plot (1/0)	0.002	0.091	0.005	-0.128
	(0.033)	(0.089)	(0.040)	(0.078)
Steep slope plot (1/0)	-0.112	-0.171	-0.034	-0.010
	(0.081)	(0.104)	(0.082)	(0.172)
Soil color is brown (1/0)	0.030	0.038	-0.001	0.026
	(0.040)	(0.079)	(0.056)	(0.112)
Soil color is gray (1/0)	0.035	0.094**	0.048	0.117
	(0.023)	(0.047)	(0.040)	(0.072)
Soil color is red (1/0)	0.005	0.000	0.040	0.136
	(0.029)	(0.057)	(0.097)	(0.172)
Manure or compost used in the plot (1/0)	0.006	0.017	-0.030	-0.068
	(0.016)	(0.032)	(0.033)	(0.060)
Legume-maize intercropping (1/0)	0.097***	0.186***	0.161***	0.139**
	(0.033)	(0.064)	(0.040)	(0.062)
Irrigation used (1/0)	-0.005	-0.123	-0.160*	-0.348**
	(0.098)	(0.240)	(0.089)	(0.160)
Plot distance to residence (walking minutes)	-0.000**	0.000	0.000	-0.001
	(0.000)	(0.000)	(0.000)	(0.001)

Variables	Insecticides use (liter/ha)		Maize yield (kg/ha)	
Owned plot by the household (1/0)	0.039	0.079	-0.027	-0.079
	(0.043)	(0.131)	(0.039)	(0.081)
Other pest control strategies used (1/0)	-0.158***	-0.191**	0.159***	0.160
	(0.034)	(0.081)	(0.055)	(0.101)
Constant	0.058	0.086	6.191***	6.552***
	(0.199)	(0.415)	(0.240)	(0.403)
R^2	0.107	0.138	0.304	0.380
Number of plots	2,135	726	2,135	726

Notes: robust standard errors clustered at the household-level are reported in parentheses. ∗p<0.10, ∗∗p<0.05, ∗∗∗p<0.01.