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Tackling fall armyworm (*Spodoptera frugiperda*) outbreak in Africa: an analysis of farmers' control actions

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ABSTRACT

Since its emergence in Africa in 2016, fall armyworm (FAW) has spread rapidly and poses a severe threat to the food security and livelihood of millions of smallholder farmers in the continent. Using survey data from Ghana and Zambia, we examined FAW prevention and control methods implemented by farm households and their impacts on maize output and household consumption of self-produced maize. The main control methods used included pesticide application and handpicking of larvae, while access to information on FAW was a key driver behind the implementation of the control methods. Results from an endogenous switching regression showed that the implementation of a FAW management strategy significantly enhanced maize yield and households' own maize consumption. When disentangling the impacts of the main control methods, we found that the combination of pesticide application and handpicking of larvae produced the highest yield gain of 125%. We concluded that the current interventions put in place by farmers to tackle FAW infestations are providing positive outcomes, but successful management of the pest will require more actions, including raising awareness to enhance the adoption of control interventions and exploring other control options.

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1. Introduction

Maize is the most widely grown staple food crop in sub-Saharan Africa (SSA), covering 36 million hectares, and providing food and livelihood for about 208 million people in the region (Macauley 2015; FAOSTAT 2018). Unfortunately, the outbreak of fall armyworm [*Spodoptera frugiperda* (J.E. Smith); FAW] in Africa is causing significant damage to maize crops, thereby threatening the livelihood of numerous farmers who rely on maize production for income and food security (Goergen et al. 2016; Abrahams et al. 2017).

FAW is a polyphagous indigenous pest of the Americas (Todd and Poole 1980; Cock et al. 2017). It disperses quickly and can travel as far as 1600 km over a 30-h period (Rose et al. 1975). FAW was first reported in Nigeria, Togo and Benin, and the island of São Tomé (São Tomé and Principe) in 2016 (Goergen et al. 2016). It has subsequently been identified in 44 African states as of February 2018 and recently in Yemen and India in Asia (FAO 2018; Shylesha et al. 2018). A pathway of introduction analysis suggests a successful transfer as a stowaway on a direct flight is the likely cause of its presence in Africa (Cock et al. 2017). Its potential damage to the agricultural production of many countries in Africa is spurring regional and national plant protection organisations to implement local and national scale initiatives.

FAW attacks a wide range of crops (over 80 plant species) (CABI 2018), but is particularly associated with cultivated grasses, including maize (Casmuz et al. 2010; Silva et al. 2017). It destroys young maize plants by attacking their growing points, and burrows into cobs in older plants, thereby adversely affecting the yield quantity and quality (Burkhardt 1952; FAO 2018). A recent study by Abrahams et al. (2017) has shown that in the absence of control methods, FAW has potential to cause about 21% to 53% reduction in annual maize production (or US$2,481 to US$6,187 million economic damage) in 12 maize-producing countries in Africa.[1] Considering that the pest cannot be eradicated (FAO 2018), implementation of control methods is, therefore, critical in curbing these potential negative economic impacts of FAW in Africa.

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There is quite an extensive literature on FAW control in North and South America, where the pest is endemic (Day et al. 2017). Some of the control methods used in the Americas include genetically modified crops, application of chemical and botanical pesticides, agronomic practices (such as early planting, intercropping and crop rotation), and integrated pest management (Abrahams et al. 2017). However, the farming systems, and agro-ecological and socio-economic conditions (such as farm sizes, yields, and access to institutional support services) in Africa are different from that in the Americas; hence, some of these control options may not necessarily be applicable to an African context.

Given that FAW is new to Africa, understanding the types of practices that farmers have adopted in response to the pest attack and their impacts will offer some insights into actions required to ensure successful management of the pest in the continent. Consequently, the objectives of this study were to examine: (1) the methods implemented by farm households to prevent or control FAW infestations on their farms; (2) the factors influencing the implementation of FAW management practices, and (3) the impact of the implementation of FAW management practices on maize output and own maize consumption.

There is a growing interest in investigating farmers' perceptions of FAW and management practices in Africa (Midega et al. 2018; Chimweta et al. 2019; Kansiime et al. 2019; Kumela et al. 2019). For instance, using survey data from Ethiopia and Kenya, Kumela et al. (2019) found that nearly all the farmers in their sample have experienced FAW attacks on their farms and have subsequently adopted control practices, such as the use of synthetic pesticides and plant extracts, handpicking of larvae, and applying soil to maize whorls. Using survey data from Ghana and Zambia, the present study contributes to the existing literature in the following ways. First, unlike previous studies, we go beyond identifying the FAW management practices adopted by farm households to explore their determining factors. Secondly, we estimate the impact of FAW management options on maize yield and consumption.

2. Material and methods

2.1. Empirical framework

As noted above, one of the main objectives of this study was to examine whether farm households that implemented FAW management practices (hereafter, simply termed adopters) are better off (in terms of maize output and own maize consumption) than households who did not take any action to prevent or control FAW attack (hereafter, simply termed non-adopters). Thus, in this study, FAW management adoption is defined as the implementation of FAW management practices, which comprise both prevention and control practices. Our primary outcome variable is maize output, which is measured as the total maize production in kilograms (kg) per hectare. The second outcome variable is maize consumption from households' own production (own maize consumption), which is expressed in kg per capita basis. Maize is the principal staple food for many smallholders in SSA, where it is mostly cultivated to meet household food consumption needs (Shiferaw et al. 2011). Under smallholder farming and incomplete markets, the amount of maize available for household consumption has important implications for household food security (Bezu et al. 2014).

In order to achieve the objectives of this study, we need to account for the potential endogeneity of FAW management adoption decision. FAW management adoption is not random since farm households self-select whether or not to put in place an intervention against the pest. It is possible that some unobservable characteristics, such as ability, motivation and risk aversion, might influence FAW management adoption decision and the outcomes of interest simultaneously, so that failure to account for these issues may yield biased estimates. In other words, adopting households may be systematically different from non-adopting households, and these differences may mask the effect of FAW management adoption on maize output and own maize consumption. In order to address these issues, we used the endogenous switching regression (ESR) approach.

In the ESR method, separate outcome equations are specified for adopters and non-adopters of FAW management measures, conditional on adoption decision. The adoption decision can be modelled in a random utility framework, in which a utility-maximizing farm household will choose to adopt a FAW management practice provided that the utility gained from adopting exceeds the utility from non-adopting. The net benefit A^* that a farm household i obtains from the adoption of a FAW management option is a latent variable that can be expressed as:

$$A_i^* = \delta X_i + \varepsilon_i \text{ with } A_i = \begin{cases} 1 & \text{if } A_i^* > 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where A is a dummy variable that equals to 1 if a farm household adopts a FAW management strategy and zero otherwise, δ is a vector of parameters to be estimated, X is a vector of explanatory variables, and ε is an error term.

The outcome equations of the ESR model, conditional on adoption, can be specified as:

Table 1. Description of variables in the regression.

Variable	Description	Full sample ($n = 465$)		Adopters ($n = 346$)		Non-adopters ($n = 119$)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Outcome variables							
Maize output	Maize yield (kg/ha)	1286.65	1150.08	1377.68***	1191.28	1018.22	975.04
Own maize consumption	Maize available for home consumption from own production (kg/capita)	81.16	110.24	90.79***	117.77	52.77	77.96
Explanatory variables							
Age	Age of household head (years)	47.27	15.26	47.19	15.38	47.52	14.99
Gender	Gender of household head (1 = male)	0.72		0.74		0.68	
Education	Household head has attained at least secondary education (1 = yes)	0.46		0.49**		0.38	
Household size	Number of household members	7.47	4.08	7.37	3.93	7.76	4.49
Land holding	Total land owned by household (hectares)	4.44	7.59	4.89**	8.25	3.14	5.07
Off-farm activity	Household member has off-farm job (1 = yes)	0.63		0.64		0.60	
Credit access	Household has access to credit (1 = yes)	0.14		0.14		0.13	
Climate shock	Household experienced drought or flood in last cropping season (1 = yes)	0.21		0.18**		0.28	
Pest and disease shock	Household crops were attacked by other pests and diseases (1 = yes)	0.42		0.45**		0.34	
Neighbourhood info on FAW	Household received information on FAW from neighbours and family (1 = yes)	0.39		0.43***		0.28	
Extension info on FAW	Household received information on FAW from extension agents (1 = yes)	0.42		0.48***		0.25	
Maize area	Total area under maize (hectares)	2.34	3.49	2.54**	3.84	1.74	2.05
Country	Location of household (1 = Ghana, 0 = Zambia)	0.26		0.24**		0.34	

Note: *** and ** indicate that the mean values for adopters are significantly different from non-adopters at the 1% and 5% significance levels, respectively. Differences in means were tested using t-test.

$$\text{Regime 1:} \quad y_{1i} = \beta_1 Z_i + \mu_{1i} \qquad \text{if } A = 1 \tag{2}$$

$$\text{Regime 2:} \quad y_{0i} = \beta_0 Z_i + \mu_{0i} \qquad \text{if } A = 0 \tag{3}$$

where y_1 and y_0 represent a vector of outcome variables for adopters and non-adopters of FAW control method, respectively. The terms β_1 and β_0 are parameters to be estimated for the adopters and non-adopters regimes, respectively, and Z denotes a set of explanatory variables. The explanatory variables (X and Z) included in the above three equations are motivated by literature on adoption and impact of agricultural technologies in Africa (Asfaw et al. 2012; Shiferaw et al. 2014; Tambo and Mockshell 2018). The variables include household and farm characteristics (e.g., age, gender, and education of the household head, household size and farm size); institutional and wealth-related factors (e.g., access to credit and off-farm activities); and shock-related variables (i.e., climate, pest and disease shocks). We also include country fixed effects to capture country-specific unobserved heterogeneity. A detailed description of the variables used in the regression is presented in Table 1.

The error terms of the selection equation (ε), and outcome equations (μ_1 and μ_0) are assumed to have a joint-normal distribution with mean vector 0, and a covariance matrix specified as:

$$\operatorname{cov}(\varepsilon, \mu_1, \mu_0) = \begin{pmatrix} \sigma_\varepsilon^2 & \sigma_{\mu_1\varepsilon} & \sigma_{\mu_0\varepsilon} \\ \sigma_{\mu_1\varepsilon} & \sigma_{\mu_1}^2 & \sigma_{\mu_1\mu_0} \\ \sigma_{\mu_0\varepsilon} & \sigma_{\mu_1\mu_0} & \sigma_{\mu_0}^2 \end{pmatrix} \tag{4}$$

where $\operatorname{var}(\varepsilon) = \sigma_\varepsilon^2$, which can be assumed to be 1 since δ is estimable up to a scale factor (Maddala 1983); var $(\mu_1) = \sigma_{\mu_1}^2$, var $(\mu_0) = \sigma_{\mu_0}^2$, cov $(\mu_1, \varepsilon) = \sigma_{\mu_1\varepsilon}$, cov $(\mu_0, \varepsilon) = \sigma_{\mu_0\varepsilon}$, and cov $(\mu_1, \mu_0) = \sigma_{\mu_1\mu_0}$. We have a selection bias problem when $\sigma_{\mu_1\varepsilon} \neq 0$ *or* $\sigma_{\mu_0\varepsilon} \neq 0$. The ESR model addresses the selection bias issue by computing inverse mills ratios (λ_1 and

λ_0) from the selection equation (Equation 1) which are then added to the outcome equations (Equations 2 and 3).

The coefficients from the ESR model can then be used to estimate the average treatment effect on the treated (ATT). The ATT compares the outcomes of adopters with and without the adoption of a FAW management strategy. For a FAW management adopting household, the expected value of maize output or own maize consumption is given as:

$$E(y_1|A=1) = \beta_1 Z + \sigma_{\mu_1\varepsilon}\lambda_1 \tag{5}$$

The expected value of maize output or own maize consumption of the same household had it chosen not to adopt a FAW management strategy is:

$$E(y_0|A=1) = \beta_0 Z + \sigma_{\mu_0\varepsilon}\lambda_1 \tag{6}$$

Thus, the change in maize output or own maize consumption as a result of FAW management adoption is the difference between Equations 5 and 6:

$$ATT = E(y_1|A=1) - E(y_0|A=1) \;\; = Z(\beta_1 - \beta_0) + \lambda_1(\sigma_{\mu_1\varepsilon} - \sigma_{\mu_0\varepsilon}) \tag{7}$$

We estimated the ESR model using the full information maximum likelihood (FIML) estimation approach (Lokshin and Sajaia 2004). For the ESR model to be well identified, the selection equation should have at least one variable that is excluded in the outcome equations in addition to those generated by the non-linearities of λ_1 and λ_0. Thus, we need at least one variable that affects FAW management adoption decision, but does not directly affect any of the outcome variables. Inspired by the agricultural innovation literature on the significance of information in farm households' adoption decisions, we used two sources of information on FAW as our selection instruments. These sources included: information on FAW from extension officers (1 = yes) and information on FAW from neighbours and friends (1 = yes). A number of studies (e.g., Di Falco et al. 2011; Asfaw et al. 2012; Shiferaw et al. 2014; Khonje et al. 2015) that also employed the ESR framework to assess the impact of adoption of agricultural technologies and adaptation to shocks in Africa have also used various information sources as identifying instruments.

Besides estimating the impact of FAW management adoption on our outcomes of interest, we also attempted to differentiate the impact estimates based on the stage of maize growth at which the farmers observed FAW infestations in their maize fields. During the survey, the sample households were shown pictures of eight stages of maize growth and asked to indicate the stage at which their plants were affected. Due to the limited sample, we merged the eight growth stages into three growth stages, i.e., 1 = early vegetative growth stage (0 to 2 leaves fully emerged); 2 = mid vegetative growth stage (5 to 8 leaves fully emerged); and 3 = late vegetative growth stage (12 to 16 leaves fully emerged). We thus analysed heterogenous effects according to these three growth stages of maize.

2.2. Data

The data used in this paper were collected between July and August 2017 for a study commissioned by the Department for International Development (DFID) that aimed at developing an evidence note on the spread and potential impacts of FAW in Africa. To this end, household surveys were conducted in Ghana and Zambia using an electronic data collection tool (i.e., Open Data Kit). The households were interviewed face-to-face by enumerators, who were trained and supervised by the research team. The survey tool captured information on household composition and farming activities, FAW control practices, information sources, external shocks and access to credit. It also contained information on farmers' perceptions of the severity of FAW damage on their maize plots, measured as minor infestation (less than 40% of maize plants affected), moderate infestation (40–60% of maize plants affected), and major infestation (more than 60% of maize plants affected). Our sample consisted of 465 (123 in Ghana and 342 in Zambia) farm households that had experienced FAW attack on their maize plots during the 2016/2017 cropping season.

In Ghana, the survey was conducted across all ten administrative regions of the country. Each region was divided into four blocks, with the exception of two regions (i.e., Northern and Brong Ahafo regions), which were divided into eight blocks. Each block consisted of a number of districts, out of which three were randomly selected. Within a selected district, communities were selected randomly, followed by a random selection of the interviewed households. Similarly, in Zambia, the farm households were surveyed across all ten provinces in the country. First, six districts were purposively selected per province based on high maize production and high prevalence of FAW infestation. Then, in consultation with district agricultural officers, three camps were selected in each district based on the level of maize production.[2] Within each camp, about three households were selected randomly at roughly 20 km apart in distance and interviewed. The first part of the survey tool contained screening questions to ensure that the sample households were involved in maize cultivation and have observed

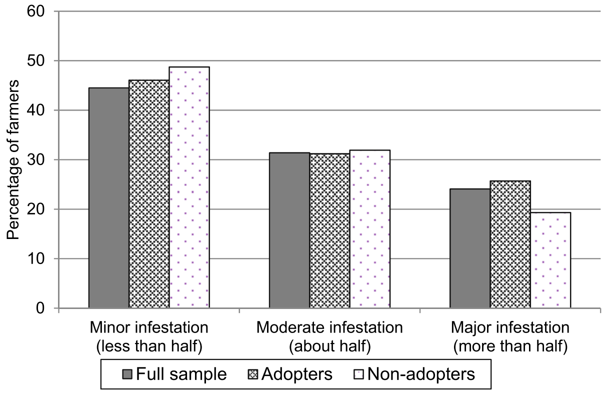

Figure 1. Proportion of maize plants affected by FAW.

FAW on their farms. Thus, the sample is not representative of maize farmers in the two countries, but it is useful as a case study to understand farmers' control actions against FAW pest that is wreaking havoc across SSA.

3. Results and discussion

3.1. Descriptive analysis

Table 1 presents the summary statistics for the studied variables. Nearly three quarters of the farm households in our sample had implemented a FAW management strategy, while about a quarter of them did not put in place an intervention to manage FAW infestations on their maize farms. The results indicated that the average yields obtained by adopters of FAW management practices were significantly higher than that of non-adopters. The average maize yield was about 1.38 and 1.01 tons per hectare for adopters and non-adopters, respectively. This range of yield is much lower than the average annual yields of maize obtained by farmers in the two study countries in the past five years prior to FAW invasion (FAOSTAT 2018).[3] We also found a significant difference between adopters and non-adopters in terms of per capita own maize consumption. The average amount of maize consumed from self-production was about 91 kg and 52 kg per capita for adopters and non-adopters of FAW management options, respectively. The statistically significant differences in the outcome variables suggest that adopters of a FAW management strategy achieved better farm outcomes relative to non-adopters. However, these are only mean comparisons and cannot be interpreted as impact of FAW management adoption. Such deductions can be made from the econometric analysis in Section 3.2, where we accounted for systematic differences between adopters and non-adopters of FAW management options.

Looking at the household socio-economic variables, the results showed that adopters had significantly higher secondary education attainment, cultivated larger areas, and allocated more land for maize production than non-adopters of FAW management options. Additionally, significantly more adopters received information on FAW from neighbours and extension workers than non-adopters. On average, the farm households in our sample were middle-aged male-headed households, had large family sizes, and cultivated small plot areas. Nearly two-thirds of the households were involved in other income-generating activities aside farming, while only a paltry 13% had access to credit. In the past cropping season, about 42% of them experienced crop losses due to pests and diseases other than FAW and 21% experienced drought and flood-related shocks. Finally, 39% and 42% of the sampled households received information on FAW from neighbours and extension officers, respectively.

Figure 1 displays the results of farmers' perceptions of the proportion of their maize plants that was affected by FAW. Overall, almost a quarter of the sampled farmers reported that a large share of their maize plants was attacked by FAW. We found that about 55% of the households had at least half of their maize plants affected by FAW. There were no statistical significant differences in the level of FAW infestations reported by adopters and non-adopters of FAW management strategy. However, it should be noted that among the adopters the implementation of FAW prevention strategies may have already contributed to a lower incidence of FAW infestation. This potential problem of reverse causality precludes us from controlling for the level of FAW infestation in our regression models.

Table 2 reports FAW management options applied by the sampled farm households, disaggregated by study countries. The various management options can be categorised into chemical control (e.g., application of botanical and synthetic pesticides), physical control (such as handpicking of egg masses and larvae), cultural practices (e.g., early planting, intercropping with non-host plants, crop rotation, frequent weeding, push-pull approach), biocontrol, and local remedies (e.g., application of ash and detergents). The most commonly used control measure in both countries was the application of synthetic pesticides. Consistent with Kumela et al. (2019), we found that almost half of the households applied pesticides for the management of FAW on their maize fields. The survey data showed that the most popular pesticides used by the households for tackling FAW infestations include cypermethrin, lambda cyhalothrin, chlorpyrifos, and emamectin benzoate. Less than 1% of the farm households used botanical insecticides for FAW control. The second most important FAW control method adopted by the households (particularly in Zambia) involved

Table 2. FAW management practices implemented by farm households.

Practice	Percentage of households[a]		
	Total sample ($n = 465$)	Ghana ($n = 123$)	Zambia ($n = 342$)
Application of pesticides	49.25	51.22	48.54
Handpicking of egg masses and larvae	23.23	5.69	29.53
Frequent weeding	7.96	16.26	4.97
Removal and burning of infected plants	6.45	5.69	6.73
Application of ash on larvae	4.09	0.81	5.26
Early planting	3.23	8.94	1.17
Application of detergents	2.8	0.81	3.51
Crop rotation	1.51	4.88	0.29
Intercropping maize with non-host crops	1.29	3.26	0.58
Application of neem-based products	0.86	2.44	0.29
Push-pull	0.43	1.62	0
Biological control	0.22	0	0.29

[a]Multiple responses recorded as some households implemented more than one management practices.

handpicking and crushing of egg masses and larvae. The picking and crushing of egg masses and young larvae reduce pest build-up, but are labour demanding and are only effective for early larval stages before larvae enter the maize stem. However, they are easier and less costly than dealing with several grown larvae few days later (FAO 2018).

To manage FAW infestation, few farmers implemented cultural practices and these included timely planting so that maize plants are well established before the pest attacks and thus have more chances to survive; constant weeding to remove alternative host plants; rotation and intercropping of maize with non-host plants; and uprooting and burning of infected plants to destroy larvae and pupae. In an attempt to save costs on pesticides, local farmers were noted to use indigenous techniques such as household detergents and ash to control pests (Tambo 2018). Hence, it is not surprising to see that few farmers tried to control FAW by applying ash on larvae or by placing ash in maize whorls and by using soaps and detergents. Only two of the households in our sample practised push-pull strategy to combat FAW, which was expected, as the push-pull approach for controlling pests has been deployed mainly in East Africa. This technique involves using a trap plant as a border crop to attract pests and an intercrop to repel pests. A recent study by Midega et al. (2018) has shown that the push-pull strategy is effective in controlling FAW. None of the farmers in our sample reported the use of resistant or tolerant maize varieties as a FAW management strategy, which was also expected, since such varieties are currently not available in the two study countries. We also found that only one household in the sample chose to control FAW with a biological control option, which involves introducing or encouraging natural enemies (predators and parasites) into the field.

Table 2 also shows that there were some discernible differences in FAW management practices employed by the sampled farmers across the two countries. We found that physical and local control methods, such as handpicking of caterpillars and application of ash and detergents, were mostly utilised in Zambia, while cultural practices such as frequent weeding, early planting and crop rotation were more popular among farmers in Ghana. The results, however, showed that the application of pesticides for the control of FAW was important in both countries, as about 51% and 49% of the sampled households in Ghana and Zambia, respectively, used this control measure.

3.2. Econometric analysis

3.2.1. Determinants of adopting a FAW management strategy

Table 3 presents the first-stage probit results of the factors influencing the adoption of FAW management practices, and this was jointly estimated with the outcome equations using the ESR method. For consistency checks, we also report estimates from an independent probit model. We found consistent results across the two estimation procedures.

Age and gender of household heads did not significantly affect adoption decisions, signifying that both male- and female-headed households as well as young and older farmers were equally likely to adopt FAW management practices. There was a significant positive association between education and adoption of FAW management measures, suggesting that household heads that had attained at least secondary education were more likely to implement FAW management strategies. This is probably because education enhances farmers' access to information as well as their ability to decipher information about pest management options more quickly and efficiently (Foster and Rosenzweig 2010). Households with large land holdings were found to have a higher probability of adopting a FAW management strategy. A plausible explanation is that such households have large cultivated areas affected by FAW, hence may be more inclined to take actions to manage the pest. Alternatively, large land holdings may reflect a higher wealth status, and

Table 3. Determinants of implementing FAW management practices.

	Independent probit[a]	Jointly estimated probit[b]
Age	−0.001	−0.001
	(0.001)	(0.005)
Gender	0.043	0.165
	(0.045)	(0.156)
Education	0.081**	0.287**
	(0.040)	(0.138)
Household size	−0.004	−0.013
	(0.005)	(0.017)
Land holding	0.006*	0.020*
	(0.003)	(0.012)
Off-farm activity	0.043	0.182
	(0.042)	(0.146)
Credit access	0.037	0.129
	(0.061)	(0.213)
Climate shock	−0.101**	−0.358**
	(0.049)	(0.173)
Pest and disease shock	0.080*	0.268*
	(0.043)	(0.149)
Neighbourhood info on FAW	0.101**	0.347***
	(0.041)	(0.132)
Extension info on FAW	0.163***	0.582***
	(0.040)	(0.134)
Country	−0.125**	−0.430**
	(0.050)	(0.174)
Constant		−0.758*
		(0.446)
Number of observations	461	461

[a]Marginal effects reported.
[b]This selection equation is jointly estimated with the outcome equations shown in Table A1 in the appendix.
Note: ***, **, * denote 1%, 5%, and 10% significance level, respectively.

thus a higher propensity to adopt agricultural technologies (Abay et al. 2018). The climate shock variable was negatively and significantly related to adoption decision, indicating that households that had suffered from droughts or floods had a lower likelihood of investing in FAW management. This is intuitive as the adoption of FAW management practices will not help to tackle crop losses resulting from drought and flood shocks. Conversely, we found that farm households that suffered from other pests and diseases (aside FAW) were more likely to adopt FAW management practices. This was expected, since FAW control measures (e.g., application of pesticides) could indirectly help in controlling other pests of maize such as maize stalk borer. Relative to the sampled households in Ghana, those in Zambia were more likely to adopt FAW management practices. Our data showed that proportionally more households in Zambia reported that a large share of their maize plants was affected by FAW; hence, this may partly explain why they were more likely to implement management strategies.

We found that households that were informed about FAW were more likely to put in place interventions to manage the pest. Specifically, households that received information on FAW from neighbours, and family were 10% more likely to adopt management measures, while access to extension information on FAW increased the probability of adopting a management strategy by 16%. The statistical significance of the two information-related variables also confirmed the validity of our excluded instruments. Our findings also support numerous studies (e.g., Di Falco et al. 2011; Kabunga et al. 2012; Tambo and Abdoulaye 2012) that showed that information is pivotal to the adoption of agricultural technologies as well as adaptation to stresses among farm households.

3.2.2. Impact of FAW management adoption

The estimated coefficients for the second stage of FIML ESR model are reported in Table A1 in the appendix. The table shows the determinants of maize output and own maize consumption for households that did and did not adopt a FAW management strategy. These results are not discussed here as they were not primary objectives of this study. However, it is worth mentioning that there were differences in the outcome equation coefficients between adopters and non-adopters, and this justifies our use of the ESR method. Of particular interest is also the statistical significance of the correlation coefficients between the error terms of the selection and outcome equations (ρ_1 and ρ_0), which indicates that self-selection occurs in the adoption of a FAW management strategy. For instance, the correlation coefficients for non-adopters (ρ_0) in maize output equation is negative and statistically significant, suggesting that there is self-selection among non-adopters of FAW management practices, and this would have caused a bias in our results if not accounted for.

Table 4 presents the expected outcomes (i.e., maize output and own maize consumption) under

Table 4. Average treatment effects of FAW management adoption.

Outcome	Adoption decision		ATT	ATT in %
	Adopting	Not-adopting		
Maize output (log [kg/ha])	7.52	5.25	2.27***	43.24
Own maize consumption (log [kg/capita])	4.30	2.84	1.46***	51.41

Note: *** denotes 1% significance level.

Table 5. Impact of FAW control adoption, disaggregated by stage of maize growth.

Outcome	Adoption decision		ATT	ATT %
	Adopting	Not-adopting		
Maize output (log [kg/ha])				
Early vegetative growth stage	7.34	5.09	2.23***	43.81
Mid vegetative growth stage	7.57	5.34	2.24***	41.95
Late vegetative growth stage	7.55	5.19	2.37***	45.66
Own maize consumption (log [kg/capita])				
Early vegetative growth stage	4.14	2.70	1.44***	53.33
Mid vegetative growth stage	4.37	2.89	1.47***	50.87
Late vegetative growth stage	4.30	2.84	1.45***	51.06

Note: Number of observations = 69, 175, and 91 for early, mid and late development stages, respectively. *** denotes 1% significance level.

actual and counterfactual conditions. The predicted outcomes from the ESR equations were used to compute the treatment effects (ATT) of the adoption of a FAW management strategy. The ATT measures the mean difference between the actual outcomes of adopters and what they would have gained if they had not implemented a FAW management strategy. Results showed that the adoption of a FAW management strategy had a positive and statistically significant impact on maize output. The ATT showed that the implementation of a FAW management strategy produced a significant yield gain of about 43%. Turning to the results for own maize consumption, the ATT estimate suggests that FAW management adoption caused an increase in per capita maize available for household consumption by about 51%, which is statistically significant. Thus, the positive yield gains from FAW management adoption significantly translates into an higher household consumption of maize from own production.

Table 5 shows the differential impact estimates based on stage of maize growth at which farmers observed FAW infestations in their maize fields. For each of the outcome variables, we found very little variation in the magnitudes of the ATT estimates across the three stages of growth. For instance, the results showed that FAW management adoption raised maize output by about 44%, 42%, and 46% depending on whether maize plants were attacked by FAW during the early, mid or late vegetative growth stages, respectively. Overall, the results suggest that implementation of a FAW management strategy is significantly associated with higher maize output and increased consumption of self-produced maize, irrespective of the stage of growth at which the maize plants were affected by FAW.

3.2.3. Treatment heterogeneity

So far, we have analysed the determinants and impacts of FAW management adoption using the ESR estimation technique. In doing so, all households that implemented any of the management practices reported in Table 2 were lumped together as adopters and then compared with non-adopters. However, aggregating the FAW management methods may mask important information about heterogeneity in determinants and performances of the management options. In this section, we try to address this limitation by disentangling determinants and unique effects of the most common control methods, which consist of pesticide application, handpicking of larvae, and the combination of pesticide application and handpicking of larvae. Due to limited observations, all the remaining control methods were grouped together and labelled as “others”.

Similar to the above aggregated analysis of FAW management adoption, households’ adoption decisions regarding specific management options is based on self-selection, and this needs to be taken into account in order to obtain unbiased results. In addition, our treatment variable now assumes a multinomial distribution as farm households can choose between five options (i.e., no adoption, pesticide only, handpicking only, combination of pesticide and handpicking, and others). Hence, we require estimation techniques that can account for selection issues and the multinomial nature of the FAW management adoption variable. Consequently, we employed the multinomial treatment effects model proposed by Deb and Trivedi (2006).[4] The model allows for the estimation of the impacts of an endogenous multinomial treatment variable, while simultaneously controlling for selectivity bias. This model also involves two parts (selection and

Table 6. Factors influencing adoption of FAW control options (MSL first stage).

	Pesticide	Handpicking	Pesticide + handpicking	Others
Age	−0.008	−0.009	−0.005	0.016
	(0.010)	(0.012)	(0.015)	(0.014)
Gender	0.400	0.156	−0.206	0.459
	(0.336)	(0.411)	(0.513)	(0.497)
Education	0.547*	0.013	0.397	0.921**
	(0.293)	(0.388)	(0.474)	(0.416)
Household size	−0.023	−0.028	0.051	−0.091
	(0.036)	(0.055)	(0.059)	(0.057)
Land holding	0.061**	−0.005	0.012	0.032
	(0.027)	(0.041)	(0.040)	(0.036)
Off-farm activity	0.283	−0.172	1.116**	0.881*
	(0.314)	(0.391)	(0.524)	(0.465)
Credit access	0.202	0.036	−1.041	0.897
	(0.440)	(0.657)	(0.900)	(0.562)
Climate shock	−0.850**	−0.404	−0.830	−0.152
	(0.371)	(0.471)	(0.589)	(0.509)
Pest and disease shock	0.366	1.296***	1.151**	−0.272
	(0.324)	(0.413)	(0.487)	(0.455)
Neighbourhood info on FAW	0.213	1.114***	0.945**	0.796*
	(0.309)	(0.386)	(0.465)	(0.420)
Extension info on FAW	1.040***	0.884**	2.034***	0.530
	(0.306)	(0.395)	(0.481)	(0.435)
Country	−0.444	−2.703***	−2.016***	−0.307
	(0.362)	(0.715)	(0.704)	(0.501)
Constant	−1.157	−6.424***	−7.620***	−3.883***
	(0.933)	(1.618)	(1.763)	(1.344)
No. of observations	461	461	461	461

Note: ***, **, * denote 1%, 5%, and 10% significance level, respectively. Base category = non-adoption.

outcome stages) that are jointly estimated. The selection stage comprises applying a multinomial logit selection model to analyse households' choice of FAW management options, and in the outcome stage, ordinary least squares (OLS) is used with selectivity correction to estimate impacts of control options on the three outcome variables. The explanatory, exclusion restriction and outcome variables are similar as in the ESR model.

Table 6 displays parameter estimates of the selection stage of the multinomial treatment effects model and these show the determinants of households' choice of the four FAW management options relative to the base category of non-implementation of control measures against FAW infestation. We focussed on the individual and combined adoption of pesticides and handpicking of larvae, and thus do not discuss the results of the "others" category. We found some noticeable differences in the estimated coefficients across control options, which justify the disaggregated analysis.

Similar to the aggregated analysis, we found that age and gender of household head did not significantly affect the implementation of FAW control methods. Attainment of secondary education was positively and significantly related with pesticide application, but not with handpicking of larvae or implementation of the two practices jointly. A plausible reason is that pesticide application is a more knowledge-intensive practice than handpicking of larvae. Hence, educated farmers, who are more likely to have better information, including awareness of appropriate safety procedures, are more inclined to use pesticides to control FAW. Household land holding was negatively related to handpicking (albeit not statistically significant), which is expected as handpicking will be tedious to implement on large farms. Conversely, a large land holding was positively and significantly associated with adoption of pesticide for FAW control. Households with off-farm income generating activities had a higher probability of combining pesticide application with handpicking of larvae. A joint adoption of pesticide and handpicking requires more investment, so that the income obtained from off-farm activities can help to relax household liquidity constraints. Climate shock was negatively related to all the control options, but was statistically significant in the adoption of pesticides only. This finding suggests that households whose maize plants have been affected by climatic shocks were less inclined to invest in the control of FAW. By contrast, households that experienced other pest and disease attack (other than FAW) were more likely to carry out handpicking only or in combination with pesticide application. Agricultural extension agents are key sources of information for farmers; hence, it is not surprising that access to extension information on FAW was positively and significantly associated with the adoption of pesticide and handpicking, either in isolation or in combination. Similarly, households that received FAW-related information from neighbours and family had a high likelihood of adopting control options, but the result was not statistically significant in the case of pesticide use only, which may be related to the knowledge intensive nature of pesticide application. Finally, we found that the sampled households in

Table 7. Differential impacts of FAW control options.

	Maize output	Own maize consumption
Pesticide application	0.634***	0.592***
	(0.192)	(0.209)
Handpicking of larvae	0.134	−0.244
	(0.234)	(0.227)
Pesticide + handpicking	0.809***	0.914***
	(0.244)	(0.265)
Others	0.507**	0.596**
	(0.261)	(0.262)
Age	−0.005	−0.003
	(0.004)	(0.004)
Gender	0.219*	0.140
	(0.133)	(0.148)
Education	−0.043	−0.049
	(0.117)	(0.128)
Household size	−0.028*	−0.033*
	(0.015)	(0.018)
Land holding	0.008	0.035***
	(0.008)	(0.009)
Off-farm activity	−0.092	−0.312**
	(0.126)	(0.140)
Credit access	−0.201	−0.150
	(0.174)	(0.204)
Climate shock	−0.370**	−0.076
	(0.147)	(0.162)
Pest and disease shock	−0.236*	0.050
	(0.126)	(0.139)
Country	−0.443***	0.163
	(0.149)	(0.164)
Constant	6.780***	3.520***
	(0.379)	(0.412)
λ(Pesticide)	−0.480***	−0.517***
	(0.156)	(0.167)
λ(Handpicking)	0.261	0.951***
	(0.169)	(0.142)
λ(Pesticide + handpicking)	−0.443***	−0.341**
	(0.149)	(0.137)
λ(Others)	0.261	0.172
	(0.169)	(0.163)
No. of observations	461	461

Note: ***, **, * denote 1%, 5%, and 10% significance level, respectively.

Ghana and Zambia were equally likely to use pesticide for FAW control, but the sampled households in Zambia had a higher propensity to engage in handpicking of larvae and to combine it with pesticide application than those in Zambia.

The results of the outcome stages of the multinomial treatment effects estimates, which show the differential impacts of FAW management options on our outcome variables, are presented in Table 7. We found that households that applied pesticides only for FAW control significantly increased their maize output by almost 90% relative to households that did not adopt any of the FAW control options.[5] Handpicking of larvae alone did not have a significant impact on maize output. However, households that combined handpicking and pesticide application obtained a significant yield gain of 125% compared to households that did not adopt any control practice. Thus, a higher yield is achieved when households adopt pesticide and handpicking in combination rather than in isolation. Pesticides and handpicking of larvae have some distinct advantages for FAW management, and thus a combination of the two creates positive synergies. For instance, pesticide application alone may not be able to successfully deal with concealed larvae, but combining it with handpicking of larvae may help in doing so.

In terms of own maize consumption, the results showed that the adoption of pesticide application in isolation increased the consumption of self-produced maize by roughly 80%, while a combination of pesticide application and handpicking of larvae enhanced households' own maize consumption by almost 150%. Overall, our findings suggest that irrespective of the two outcome variables used in this study, the joint adoption of pesticide application and handpicking of larvae provided the largest benefit in the face of FAW infestation. This reinforces suggestions to combine different control methods to tackle FAW infestations (Day et al., 2017). This is also consistent with other studies (Teklewold et al. 2013; Tambo and Mockshell 2018) that have shown that agricultural technologies and practices generate higher gains when adopted in combination rather than in isolation.

The results concerning the coefficients on the other variables in Table 7 are informative. The sign and statistical significance of the sample selection bias correction terms (λs) in the lower part of Table 7 give an indication of the presence of unobserved heterogeneity bias in our estimates. For instance, the λ(Pesticide) and $\lambda(Pesticide + handpicking)$ variables in maize output result had statistically significant negative coefficients, suggesting that without accounting for selection bias, the estimated impacts of the adoption of pesticide alone or in combination with handpicking would have been downwardly biased. This finding also indicates that unobserved characteristics, which increase the likelihood of adopting these two FAW control options, also lead to lower maize output. Results also indicate that compared to female-headed households, male-headed households obtained higher maize yields, and this may be due to differences in access to and use of resources (World Bank et al. 2009). Consistent with our expectations, we found that climate and other pest and disease shocks were significantly associated with decreases in maize yield. Finally, in the context of FAW infestation, the sampled households in Zambia benefit significantly more than those in Ghana in terms of maize yield and own maize consumption. This could be explained by the earlier finding in Table 6 that households in Zambia have a higher probability of using FAW control option that provides the highest gain (i.e., the combination of pesticide and handpicking).

The present study is not without limitations. For instance, our data do not allow us to analyse the impact of FAW management options on the profitability of maize production. Chemical pesticides are costly and handpicking of caterpillars is labour intensive, and thus has cost implications. Hence, it would be relevant to find out if the yield gains from adoption of these FAW management practices are worthwhile considering the costs involved, and we leave this issue for future research.

4. Conclusion

We analysed the adoption and impacts of fall armyworm (FAW) management practices using recent survey data from 465 maize growing households whose farms were attacked by FAW in Ghana and Zambia. The endogenous switching regression (ESR) technique was used to account for selection bias and estimate determinants and impacts of adoption of a FAW control intervention. We also employed the multinomial treatment regression estimator to disaggregate the impacts of the most common control measures adopted by the sampled households to cope with FAW menace.

Results showed that almost three-quarters of the sampled households adopted at least one FAW management practice, and the common control methods included pesticide application, and handpicking of egg masses and caterpillars. We found that the adoption of a FAW management strategy produced a significant positive impact on maize output and own maize consumption. The ESR results showed that households that adopted a FAW management practice would have obtained 43% less maize yield had they not adopted. We also found that the positive yield effects translated to increased consumption of self-produced maize, which has important food security implications considering that maize is a major staple food in the two countries of the study. Disaggregating control methods, we found that in the context of FAW attack, the adoption of pesticides and handpicking of larvae in combination was strongly associated with increases in both maize yield and household's own maize consumption than the adoption of the two practices in isolation. In particular, households that combined pesticide application with handpicking of larvae and larvae obtained a yield gain of 125%.

Our results provide evidence that the current interventions put in place by farmers to tackle FAW invasion provide positive outcomes. Nevertheless, successful management of the pest will require more actions. As shown by our findings, information about FAW is important in the management of the pest. Thus, policy efforts are needed to sensitise farmers about the pest and the appropriate control practices. For instance, massive roll-out of communication campaigns and training programmes on FAW will be necessary. Furthermore, it is worthy of note that nearly 50% of the households in our sample used synthetic chemical pesticides to control FAW [as did the households in Ethiopia and Kenya (Kumela et al. 2019)], with low level of use of non-chemical methods. In the wake of FAW invasion in Africa and given the limited knowledge of the pest among farmers, there may be a tendency of some households to opt for pesticides. However, some of these pesticides may not be effective in controlling the pest or may have negative health and environmental effects. Hence, farmers need to be advised on rational use of pesticides, including compliance with re-entry intervals following the application of pesticides. In addition, extensive research efforts are needed to assess the effectiveness of the various pesticides in controlling FAW as well as their environmental and health implications and to explore other control options, such as integrated pest management techniques (Van Huis and Meerman 1997).

Notes

1. The countries include Benin, Cameroon, Democratic Republic of Congo, Ethiopia, Ghana, Malawi, Mozambique, Nigeria, Uganda, Tanzania, Zambia and Zimbabwe.
2. A camp is the lowest agricultural division in Zambia (i.e. from national, province, district, block to camp).
3. Between 2011 and 2016, the average annual maize yields ranged from 1.6 to 2 tons/ ha in Ghana, and 2.5 to 3 tons/ha in Zambia (FAOSTAT 2018).
4. This was estimated in Stata using the Maximum Simulated Likelihood approach (Deb, 2009).
5. Following Halvorsen and Palmquist (1980), the percentage effects of dummy coefficients in models with a log-dependent variable are given by $100\{\exp(c) - 1\}$, where c denotes the dummy coefficients.

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Appendix

Table A1. ESR estimates of the determinants of the outcome variables.

	Maize output		Own maize consumption	
	Adopters	Non-adopters	Adopters	Non-adopters
Age	−0.002	−0.014	−0.003	−0.011
	(0.004)	(0.010)	(0.006)	(0.009)
Gender	0.185	0.321	0.034	−0.044
	(0.136)	(0.330)	(0.225)	(0.295)
Education	−0.059	−0.118	−0.170	−0.604**
	(0.121)	(0.311)	(0.194)	(0.291)
Household size	0.012	−0.083**	−0.001	−0.094***
	(0.015)	(0.036)	(0.025)	(0.032)
Land holding	0.001	0.024	−0.003	0.054
	(0.008)	(0.030)	(0.013)	(0.029)
Off-farm activity	0.028	−0.203	−0.594***	0.453
	(0.126)	(0.316)	(0.210)	(0.277)
Credit access	0.021	−0.795*	−0.291	−0.324
	(0.172)	(0.456)	(0.291)	(0.399)
Climate shock	−0.199	−0.349	0.213	−0.100
	(0.158)	(0.351)	(0.253)	(0.322)
Pest and disease shock	−0.389***	−0.140	−0.308	−0.385
	(0.129)	(0.338)	(0.206)	(0.311)
Country	−0.593***	0.467	0.245	0.222
	(0.156)	(0.376)	(0.252)	(0.332)
Constant	7.740***	7.008***	5.768***	4.323***
	(0.290)	(0.705)	(0.406)	(0.684)
σ_1, σ_0	1.017***	1.760***	1.887	1.429
	(0.039)	(0.227)	(0.083)	(0.194)
ρ_1, ρ_0	0.053	−0.727***	−0.969***	−0.483*
	(0.292)	(0.130)	(0.012)	(0.275)
LR test of indep. eqns.	5.81*		69.04***	
No. of observations	461		459	

Note: ***, **, * denote 1%, 5%, and 10% significance level, respectively.