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Understanding smallholders' responses to fall armyworm (*Spodoptera frugiperda*) invasion: Evidence from five African countries

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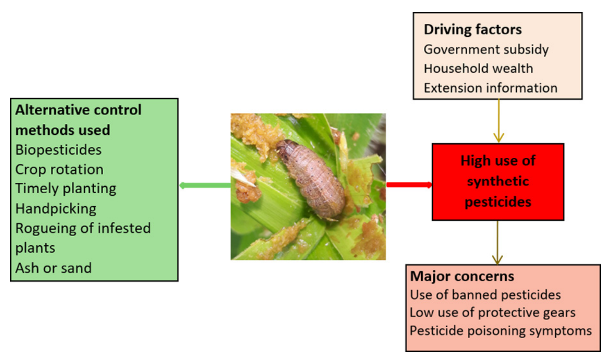
HIGHLIGHTS

- The recent outbreak of fall armyworm in Africa and Asia is threatening livelihoods.
- Many African farmers are using synthetic pesticides, including highly hazardous ones.
- The extensive use of pesticides is largely driven by government-subsidised inputs.
- There is low use of protective clothing, resulting in acute pesticide-related illness.
- Sustainable, safe and environmentally friendly control strategies are required.

GRAPHICAL ABSTRACT



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ABSTRACT

Fall armyworm (FAW) is a new invasive pest that is causing devastating effects on maize production and threatening the livelihoods of millions of poor smallholders across sub-Saharan Africa and Asia. Using unique survey data from 2356 maize-growing households in Ghana, Rwanda, Uganda, Zambia and Zimbabwe, we examined how smallholder farmers are fighting this voracious pest. In particular, we assessed the FAW management strategies used by smallholders, socio-economic factors driving the choice of the management options, the complementarities or tradeoffs among the management options, and the (un)safe pesticide use practices of farmers. Results showed that smallholder farm households have adopted a variety of cultural, physical, chemical and local options to mitigate the effects of FAW, but the use of synthetic pesticides remains the most popular option. Results from multivariate probit regressions indicated that the extensive use of synthetic pesticides is driven by household asset wealth, and access to subsidised farm inputs and extension information. We observed that farm households are using a wide range of pesticides, including highly hazardous and banned products. Unfortunately, a majority of the households do not use personal protective equipment while handling the pesticides, resulting in reports of acute pesticide-related illness. Our findings have important implications for policies and interventions aimed at promoting environmentally friendly and sustainable ways of managing invasive pests in smallholder farming systems.

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1. Introduction

Fall armyworm (FAW), *Spodoptera frugiperda*, is now one of the most devastating crop pests in sub-Saharan Africa. It is indigenous to tropical and subtropical regions of the Americas where farmers have been grappling with the pest for many centuries. It was reported in Central and West Africa for the first time in early 2016 (Goergen et al., 2016) and given its natural distribution capacity (adult moth can travel hundreds of kilometres; Rose et al., 1975) and the increasing levels of international trade, it has spread rapidly across the rest of sub-Saharan Africa. As of March 2019, its presence has been recorded in all sub-Saharan Africa countries, except Lesotho (FAO, 2019). It has subsequently spread to at least 15 Asian countries, including Bangladesh, China, India, Thailand and Yemen (CABI, 2019a), and there is a high likelihood for near global invasion via trade and transportation pathways (Early et al., 2018). It is also projected that Africa will experience the greatest degree of FAW threat in the future (Liu et al., 2020).

The FAW pest reproduces quickly and can reportedly feed on up to 353 different plant species, including staple cereals such as maize, millet, rice, sorghum, wheat and teff (Montezano et al., 2018). In sub-Saharan Africa, it is causing significant damage to maize in particular (Rwomushana et al., 2018). For example, Kumela et al. (2019) reported FAW-induced maize yield reductions of up to 47%, based on a survey of maize farmers in Kenya and Ethiopia. Similarly, based on farm household surveys, Rwomushana et al. (2018) estimated FAW-induced yield losses of 27% and 35%, translating into annual economic losses of US $177 m and US$159 m from maize production in Ghana and Zambia, respectively. In Zimbabwe, Baudron et al. (2019) and Chimweta et al. (2019) also reported maize yield losses of 12% and 58%, based on rigorous field scouting methods and farmers' estimates, respectively. Given the primary importance of maize in the diets of many households in Africa (Shiferaw et al., 2011) and the conditions in sub-Saharan Africa being highly suitable year-round for FAW (Early et al., 2018), the pest poses a significant threat to food security and the attainment of Sustainable Development Goal 2 of ending hunger by 2030.

Since the outbreak of FAW in sub-Saharan Africa, there have been coordinated actions at national and regional levels to mitigate its impact. The emergency response measures taken by most national governments have largely involved the procurement and distribution of pesticides. In 2017, for instance, the government of Ghana allocated US$ 4 million towards pesticide purchase and education; the Zambian government spent US$3 million on subsidised pesticides and protective clothing; US$7 million was reportedly allocated by the Ugandan government for the supply of pesticides; and in Rwanda, the military joined the fight against FAW by helping to distribute pesticides to farmers (Abrahams et al., 2017). The FAW outbreak has also attracted increased research interest in understanding how smallholders can sustainably control the pest. One aspect of research has focused on either field testing or a review of potential accessible agro-ecological (Hailu et al., 2018; Midega et al., 2018; Harrison et al., 2019; Hruska, 2019) and biopesticide options (Bateman et al., 2018; Akutse et al., 2019) for the management of FAW by smallholders. Another aspect of the literature has empirically examined farmers' perceptions of and current practices in managing FAW (e.g., Chimweta et al., 2019; Kansiime et al., 2019; Kumela et al., 2019; Tambo et al., 2019b).

Our study aims to contribute to this emerging body of literature by assessing how smallholder maize-growing households in five sub-Saharan Africa countries are responding to the FAW invasion. The findings from this study can be used to inform policies and interventions aimed at promoting environmentally friendly and sustainable ways of managing FAW in smallholder farming systems. Our paper differs from existing literature in several ways. First, unlike previous studies, we employed unique household survey data from five countries (Ghana, Rwanda, Uganda, Zambia and Zimbabwe) across sub-Saharan Africa. This allowed us to capture the various FAW management strategies used by smallholders across different farming systems and agro-ecological zones. Secondly, we went beyond reporting the FAW management options implemented by smallholders to investigate the factors influencing the choice of the management options. Methodologically, we applied a multivariate probit estimation technique that allowed us to account for possible complementarities and tradeoffs in farmers' FAW management decisions. Finally, given the health and environmental risks associated with pesticides, we examined farmers' pesticide use practices in the context of FAW management, including the type and toxicity of pesticides used, the use of personal protective equipment, and relate this to the incidence of acute pesticide poisoning reported by users.

2. Materials and methods

2.1. Data

We used survey data from 2356 smallholder maize-growing households in five countries across sub-Saharan Africa. The countries include Ghana (West Africa); Rwanda and Uganda (East Africa); and Zambia and Zimbabwe (Southern Africa). Thus, our sample reflects a diverse range of agro-ecological conditions and smallholder maize production systems in sub-Saharan Africa (Fig. S.1). The data were collected in 2018 with the aim of understanding farmers' knowledge, attitudes and practices related to FAW. In each country, the survey was conducted by trained enumerators using tablet-based questionnaires.[1]

In Ghana, the survey was conducted across seven out of the ten administrative regions of the country (Table S.1).[2] These regions represent the major maize production areas of the country. Two districts were selected from each region on the basis of intensity of maize production and severity of FAW infestations. Then villages were randomly chosen from the selected districts, followed by a random selection of the interviewed farmers.

The Rwanda sample comes from three out of the country's five provinces where maize is an important crop and where there are increased incidences of maize pests, particularly FAW. Three or four districts were selected from each province (Table S.1), and within each district, we randomly sampled and interviewed maize-producing households whose farms have been attacked by FAW during the 2017/2018 cropping season.

The Uganda data is based on a survey of 607 maize farmers in Western Uganda, where a FAW information campaign has been implemented. A multi-stage sampling approach, involving purposive sampling of districts and sub-counties, and random sampling of villages and farm households was adopted in the survey. The selected sub-counties include Bwijanga, Mirya and Pakanyi in Masindi district, and Biiso, Kihungya and Ngwedo in Buliisa district. Within each sub-county, we randomly selected between four to eight villages proportional to the size of the sub-county. Finally, we randomly selected and interviewed around 10 to 20 farm households per village based on the size of the village.

In Zambia, the household survey was carried out in nine out of the ten administrative provinces, which also cover the three major maize-growing agro-ecological zones (I, IIA and III) of the country. One to three representative districts were selected from each province (Table S.1), followed by systematic random sampling of every fourth household in an enumeration area. The sample size across the nine provinces was determined based on probability proportional to size.

Similarly, in Zimbabwe, the surveyed households were selected from six out of the country's 10 provinces (Table S.1). Three major maize production and FAW affected districts were then sampled from

[1] The questionnaires and datasets are available at https://ckan.cabi.org/data/dataset/fall-armyworm-evidence-note-2018. Accessed in October 2019.

[2] Six new regions have since been carved out of the 10 regions, making a total of 16 regions in the country.

each of the six provinces, followed by a random sampling of maize-growing households.

2.2. Sample characteristics

The farmers in our study were middle-aged, with an average age of between 40 and 50 years (Table S.2). In all the countries, over three-quarters of the farmers belonged to male-headed households, except in Zimbabwe where one-third were female-headed households. The household heads had attained limited level of education, particularly in Ghana and Rwanda where only about a quarter of them had had secondary education. With average maize plot sizes of less than three hectares, the farm households can be characterised as typical smallholders.

Access to credit and off-farm income earning opportunities were generally low, but varied largely across the study countries. For example, roughly 80% of the sample households in Southern Africa (Zambia and Zimbabwe) were credit-constrained while slightly more than half of the households in East Africa (Rwanda and Uganda) had access to credit facilities (Table S.2). Households in Ghana, Zambia and Zimbabwe had to travel at least about 7 km to access agricultural inputs or advisory services from extension agencies and ago-input dealers. Rwanda has relatively smaller land area, which could partly explain the comparatively closer proximity (2.5 km) to these two sources of agricultural information. In terms of membership in a farmers' organisation, which is an important source of information and social network, we found a high degree of heterogeneity ranging from 18% in Zimbabwe to 74% in Zambia.

Very few (between 2% to 41%) of the sample households were using plant clinics as a source of agricultural advisory services (Table S.2). Plant clinics are a meeting place where farmers can send a sample of any ailing crop for diagnostic and plant health advisory services by trained extension officers, who are normally called ‘plant doctors’. The plant clinic extension model is currently operating in over 30 countries worldwide, including Ghana, Rwanda, Uganda and Zambia (CABI, 2019b). There is at least one plant clinic in each of the 30 districts in Rwanda, hence the relatively high number of plant clinic users in this country. With the exception of Uganda, only a small share of the households received agricultural information (including pest information) through the media in the respective countries. As mentioned above, the farmers in the Uganda sample were surveyed from a region where a mass media campaign on FAW had been implemented; hence, this explains why a high proportion (76%) of the farmers in this country mentioned media as a source of agricultural information. Finally, Table S.2 shows that during the last cropping season, only 9% of the sample households in Zimbabwe (compared to 36% in Ghana and 76% in Rwanda) received free or discounted pesticides.

2.3. Estimation methods

We used a combination of descriptive and econometric techniques to address our research objectives. Descriptive statistics were used to highlight farmers' choice of FAW management practices and perceptions of their effectiveness, as well as safe pesticide practices, including the type of pesticides, use of protective clothing, and self-reported experience of pesticide-related health symptoms.

To tackle FAW infestation, farmers tend to adopt a mix of pest management strategies (Rwomushana et al., 2018; Tambo et al., 2019b). The decision to adopt a specific FAW management strategy or practice depends on the expected utility it yields, which is an unobservable (latent) variable y_{im}^*. The higher the utility, the greater the likelihood of adoption. Given that we do not observe the latent variable y_{im}^*, estimation is based on observable binary variables y_{im}, which denote whether or not a farm household used a particular management strategy. This binary decision variable can be estimated using univariate models such as probit or logit, where the response probability depends on a set of explanatory variables. However, the adoption of one FAW management practice is not independent of other available options. There are potential substitutabilities and complementarities among the management options. Hence, using a univariate technique to model each of the management practices individually would yield biased results since the estimates ignore the interdependence between the different FAW management options. Consequently, to analyse the determinants of farmers' choice of FAW management options, we used the multivariate probit (MVP) model.

The MVP simultaneously models the influence of a set of covariates and each of the different FAW management practices, while allowing for possibility that the decisions on the use of any particular management practice could be jointly made with the decision to use other practices. Besides, the error term correlation matrix generated from an MVP model is informative. A positive (negative) correlation coefficient between the error terms of two management options suggests that they are complements (substitutes) to each other. Thus, results from the MVP correlation matrix are also reported and discussed. The MVP model can be expressed as (Cappellari and Jenkins, 2003):

$$y_{im}^* = \left[\beta_m X'_{im} + \varepsilon_{im}\right]; m = 1, 2, \ldots, n$$

$$y_{im} = 1 \ \text{ if } y_{im}^* > 0 \text{ and 0 otherwise}$$

where y_{im}^* represents farm household i's latent propensity to use FAW management option m, and y_{im} indicates the actual use of management option m by household i. We estimate country-specific MVP models; hence, m denotes the main FAW management practices employed by the sample households in a particular country. β_m is a vector of parameters to be estimated. X_{im} is the vector of explanatory variables, which includes household, institutional and geographic characteristics that are hypothesised to influence farmers' choice of the FAW management options (Table S.2). The choice of these covariates was guided by previous research on the determinants of adoption of pest management techniques (e.g., McNamara et al., 1991; Murage et al., 2015; Tambo et al., 2020). It should be noted that some of the covariates are potentially endogenous; hence, we are not attempting to infer causal relationships based on our MVP estimations. Instead, our analysis seeks to understand the correlates of farmers' choice of FAW management practices. ε_{im} is a vector of error terms with a multivariate normal distribution. We estimated the MVP models in Stata using the conditional recursive-mixed process (cmp) command by Roodman (2011) based on the Geweke-Hajivassiliou-Keane (GHK) smooth recursive conditioning simulator.

3. Results and discussion

3.1. FAW management practices

Similar to Rwomushana et al. (2018), Kumela et al. (2019) and Tambo et al. (2019b), we found that the most popular FAW management option across the five countries was the use of synthetic pesticides, ranging from 33% in Zimbabwe to as much as 87% in Rwanda (Table 1). The relatively high usage of synthetic pesticides in Rwanda could be related to the greater access to free or subsidised farm inputs (Table S.2). Given the lack of knowledge and experience related to FAW, the rapid build-up of the pest, the devastating havoc it is wreaking on farms and the absence of resistant varieties, there is a tendency of farmers to opt for pesticides, which are generally effective against most pests and offer rapid control. Recognising the negative effects of synthetic pesticides on humans and the environment, biopesticides have been recommended as an appropriate alternative option (Bateman et al., 2018). The results however showed that other than Ghana where 22% of the farmers used biopesticides, there was very limited use (< 5%) of this control option in the other four countries.[3]

[3] Biopesticides, as used here, refers to microbial pesticides (e.g., *Bacillus thuringiensis*) or extracts of plants such as neem (*Azadirachta indica*).

Table 1
FAW management methods used by the sample households (%).

FAW management practice	Ghana (n = 488)	Rwanda (n = 637)	Uganda (n = 607)	Zambia (n = 439)	Zimbabwe (n = 185)
Timely planting	19.26	11.46	56.01	5.49	7.03
Crop rotation	2.66	25.43	23.89	2.29	0.54
Intercropping	0.41	0.31	10.05	0.69	0.00
Regular weeding	20.29	0.00	32.13	0.46	0.54
Fertilisation	11.68	5.65	17.79	3.20	3.24
Trap cropping	0.20	1.57	2.35	0.00	0.00
Synthetic pesticides	59.84	87.28	70.76	45.10	32.97
Biopesticides	22.34	1.88	3.97	2.06	0.54
Handpicking eggs and caterpillars	20.49	59.65	49.46	26.88	29.73
Uproot and burn infested plants	4.71	43.33	34.12	3.20	6.57
Biocontrol using predators	1.64	0.00	0.54	0.00	0.54
Ash or sand	2.46	3.45	17.69	10.71	15.14
Detergents	0.00	0.00	5.96	0.91	3.78

Table 2
Percentage of farmers who perceived that the management options used worked.[a]

Management practice	Ghana	Uganda	Zambia	Zimbabwe
Timely planting	56.38	96.47	70.83	84.62
Crop rotation	7.69	95.17	20.00	
Intercropping		78.69		
Regular weeding	22.22	90.77		
Fertilisation	43.86	94.44	35.71	83.33
Trap cropping		76.92		
Synthetic pesticides	91.78	95.66	96.97	91.80
Biopesticides	82.56	90.91	87.50	
Handpicking eggs and caterpillars	24.00	79.93	38.14	85.45
Uproot and burn infested plants		79.66	35.71	78.57
Ash or sand	58.33	76.92	53.57	48.48
Detergents		90.91		42.86

Note: this information was not captured in the Rwanda survey.
[a] Percentages are based on the number of farm households that used a particular management practice in the respective countries.

Physical methods such as handpicking of egg masses and caterpillars and destruction of infested maize plants were also important options used by farmers for the control of FAW, particularly in Rwanda and Uganda. As highlighted in Table S.2, farmers in these two East African countries cultivated relatively small maize plots, and this may explain why they were more likely to use labour-intensive physical control options, which are more feasible for small farms. Results also showed that the sample farmers employed a number of cultural methods to prevent or reduce the level of FAW infestation. Such practices included avoiding late or staggered planting; regular weeding to remove alternative host plants such as pasture grasses; applying manure or inorganic fertilizer to support healthy plant growth so that the maize plants can withstand FAW infestations; and intercropping and rotating maize with non-host crops such as cowpea and cassava. A few of the farmers (especially in Uganda, Zambia and Zimbabwe) used local control methods such as placing ash and sand into maize whorls to control the pest. There was almost no adoption of biological control using predators and parasitoids for the management of FAW by the smallholders in our sample.

Overall, the results showed that the farmers in our sample were using various low-cost and locally-available agro-ecological practices that have been suggested as potential options for smallholders' management of FAW (FAO, 2018; Prasanna et al., 2018; Harrison et al., 2019; Hruska, 2019). Application of synthetic pesticides was the most widely used option, followed by handpicking and crushing of egg masses and caterpillars, corroborating the findings of Tambo et al. (2019b). Nonetheless, there was some heterogeneity in the management options used across the five countries. For example, the farm households in Uganda, where a FAW information campaign has been implemented, appeared to be more likely to follow the tenets of integrated pest management (IPM) by using a combination of management options, pointing to the importance of communication campaigns in the sustainable management of FAW (Tambo et al., 2019a; Toepfer et al., 2019).

A majority of the farmers perceived that the practices they implemented were helpful in managing the FAW invasion (Table 2). In each country, over 90% of the pesticide users reported that this method was effective in controlling FAW. Kumela et al. (2019), on the contrary, found that 32% and 60% of sampled farmers in Ethiopia and Kenya, respectively, perceived that pesticides were not effective in controlling FAW. A plausible explanation for this differential finding is that the Kumela et al. (2019) study used data that were collected in the early years following the FAW outbreak during which there may have been limited information on pesticide application, while we relied on data collected at a time when many countries had produced technical guidelines, including the recommended pesticides for FAW control and the application methods. We also found that a large share of the biopesticide users perceived that this method worked effectively. The perceived success of some of the methods such as handpicking and crop rotation differ largely across the countries. It should be stressed that the self-ratings of the success of the various management interventions were likely to be influenced by several factors such as the stage of growth at which the maize plants were attacked, the level of infestation, the duration of infestation before the application of the intervention, the quality and correct application of the intervention (particularly in the case of pesticides), the use of multiple pest management strategies, climate and the growing conditions in the field.

3.2. Factors influencing the choice of FAW management options

This section describes the results of the country-specific MVP estimators on the factors influencing farmers' choice of FAW management options, focussing on the main management options used in each country.

3.2.1. Ghana

We observed some notable differences in how the covariates affect the choice of management options (Table 3). Farmers that cultivate large plots of maize are more likely to use synthetic pesticides, probably because they are relatively wealthy and can afford to invest in external inputs. However, households that cultivate larger plots are less likely to engage in the handpicking and killing larvae of FAW, which supports arguments that this method would not be effective on large plots due to its labour-intensiveness (Harrison et al., 2019; Kansiime et al., 2019). Farmers living in close proximity to extension offices, where they can access agricultural information, are more likely to use biopesticides and engage in handpicking and early planting but are less likely to spray synthetic pesticides. As expected, proximity to agro-input dealers is associated with an increase in the adoption of synthetic pesticides (Table 3). This may be related to reduced transaction cost in accessing pesticides as well as better information on the type of pesticide to use, given that agro-dealers are a key source of plant health information for many farmers in developing countries (Sones et al., 2015). Membership in a farmers' organisation and access to agricultural information via media positively influence timely planting of maize, further confirming the significant role of information in FAW management.

Results showed that access to free or discounted farm inputs significantly enhances the use of pesticides. In particular, farmers that have access to free or discounted inputs have a 10% and 5% higher likelihood of spraying synthetic pesticides and biopesticides, respectively (Table 3). This is expected as many African governments, including Ghana distributed free or subsidised pesticides in the early days of the invasion in efforts to curb the FAW menace (Abrahams et al., 2017; Rwomushana et al., 2018). Finally, we found significant differences in

Table 3
Correlates of farmers' choice of FAW management options in Ghana.

	Synthetic pesticide	Bio-pesticide	Hand-picking	Frequent weeding	Timely planting
Age	−0.001**	0.001	0.000	0.000	0.001
	(0.001)	(0.001)	(0.001)	(0.000)	(0.001)
Gender	0.027	0.014	−0.016	−0.021	0.022
	(0.020)	(0.020)	(0.024)	(0.017)	(0.022)
Education	0.019	0.014	0.020	0.004	−0.017
	(0.015)	(0.016)	(0.017)	(0.011)	(0.016)
Household size	0.001	0.002	0.001	0.000	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Maize area	0.003***	−0.001	−0.002**	0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Off-farm activity	−0.007	0.010	−0.026*	0.021	−0.009
	(0.016)	(0.016)	(0.015)	(0.013)	(0.017)
Credit access	0.014	−0.005	0.009	0.014	−0.002
	(0.015)	(0.015)	(0.014)	(0.011)	(0.015)
Asset index	−0.001	0.010*	0.000	0.003	0.003
	(0.005)	(0.005)	(0.005)	(0.003)	(0.005)
Distance to agro-dealer	−0.003**	0.001	0.002*	0.001	0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Distance to extension	0.002***	−0.002*	−0.003***	−0.001	−0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Farmer group	0.003	−0.016	0.011	0.017	0.039***
	(0.015)	(0.015)	(0.015)	(0.010)	(0.015)
Plant clinic access	−0.001	−0.014	−0.019	−0.003	0.003
	(0.022)	(0.024)	(0.025)	(0.018)	(0.028)
Media information	0.027*	0.018	0.021	−0.009	0.026*
	(0.015)	(0.017)	(0.015)	(0.010)	(0.015)
Free or subsidised input	0.098***	0.050***	−0.011	−0.019**	−0.028
	(0.014)	(0.016)	(0.014)	(0.009)	(0.015)
Brong Ahafo region[a]	0.104***	0.072**	0.052**	0.020	0.109***
	(0.030)	(0.032)	(0.021)	(0.018)	(0.027)
Ashanti region	0.195***	0.046	0.163***	0.073***	0.138***
	(0.028)	(0.031)	(0.027)	(0.023)	(0.028)
Central region	0.201***	−0.017	0.005	−0.027*	−0.011
	(0.034)	(0.034)	(0.022)	(0.015)	(0.021)
Volta region	0.170***	−0.013	0.242***	0.030	0.059**
	(0.031)	(0.031)	(0.029)	(0.021)	(0.028)
Eastern region	0.155***	−0.047*	0.102***	0.290***	0.150***
	(0.029)	(0.027)	(0.027)	(0.018)	(0.028)
Upper west region	0.027	0.110***	0.071***	−0.003	0.052**
	(0.032)	(0.030)	(0.024)	(0.013)	(0.021)
No. of observations	488	488	488	488	488

Note: marginal effects reported. Robust standard errors in parentheses.
[a] Base region = Northern.
*** p < 0.01.
** p < 0.05.
* p < 0.1.

the choice of management options across the surveyed regions in Ghana. For example, farmers located in all the regions (with the exception of Upper West) are more likely to use synthetic pesticides than those in Northern region (the base category). This could be due to spatial differences in climatic conditions (higher likelihood of investment in costly inputs in favourable climates that guarantee higher returns); poverty incidence (which can affect purchasing power to invest in external inputs); and infrastructure development or proximity to the capital city (and thus timely access to farm inputs).

3.2.2. Rwanda

We found that male-headed households are 6% more likely than female-headed households to adopt synthetic pesticides for FAW control (Table 4). This may be related to the well-known gender differences in access to and use of farm inputs and resources (World Bank, 2008). Conversely, female-headed households are about 13% more likely to be involved in the handpicking and crushing of egg masses and caterpillars than male-head households, lending credence to the notion that this physical method of FAW control may increase women's labour burden (Harrison et al., 2019). Household size is positively correlated with handpicking, which is not surprising as the members can provide the labour needed to implement this control activity. Similar to the Ghana results, we observed that maize area cultivated is positively and significantly correlated with the use of synthetic pesticides. Asset-rich households also have a higher propensity to adopt synthetic pesticides, suggesting that capital constraints inhibit investment in modern crop protection products.

Results also showed that access to plant clinics is positively correlated with the five main control measures used in the country, but the coefficients are statistically significant only in the case of synthetic pesticides and handpicking (Table 4). Specifically, farmers that use plant clinic services have a 18% and 12% higher probability of spraying pesticides and engaging in handpicking in attempts to tackle FAW in their maize fields. Farmers always take diseased crops to plant clinics; hence, it is logical that the plant doctors will prescribe curative rather than preventive measures. We also found that in Rwanda, access to media information is significantly associated with 5%, 10% and 16% higher likelihood of preventing or controlling FAW through synthetic pesticide application, crop rotation and the removal of infested plants, respectively. Consistent with our expectations, farmers that receive free or subsidised inputs are more likely to apply synthetic pesticides and also use other methods such as handpicking and crop rotation for FAW management.

3.2.3. Uganda

The estimation results for Uganda (Table 5) showed that younger farmers and large households are more inclined to control weeds on their farm regularly in efforts to prevent FAW invasion, which is intuitive as this management option can be arduous for older farmers and households with fewer members who may be labour-constrained. Similarly, we found that a higher level of education is significantly

Table 4
Correlates of farmers' choice of FAW management options in Rwanda.

	Synthetic pesticide	Hand-picking	Uproot and burn	Crop rotation	Timely planting
Age	−0.001	0.000	0.000	−0.001	−0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Gender	0.061**	−0.128***	−0.002	−0.030	−0.024
	(0.029)	(0.046)	(0.050)	(0.043)	(0.032)
Education	−0.011	0.031	0.115**	0.002	−0.012
	(0.037)	(0.047)	(0.050)	(0.044)	(0.031)
Household size	−0.004	0.034***	0.006	0.014	0.009
	(0.007)	(0.010)	(0.011)	(0.009)	(0.007)
Maize area	0.255**	0.010	0.010	0.029	−0.088*
	(0.118)	(0.028)	(0.029)	(0.023)	(0.047)
Off-farm activity	−0.045	−0.015	−0.075	−0.003	−0.014
	(0.029)	(0.043)	(0.046)	(0.040)	(0.030)
Credit access	0.018	−0.043	−0.039	−0.035	−0.010
	(0.025)	(0.038)	(0.041)	(0.036)	(0.026)
Asset index	0.027**	0.005	0.015	−0.015	−0.001
	(0.013)	(0.015)	(0.016)	(0.014)	(0.010)
Distance to agro-dealer	−0.003	0.001	0.003	−0.003	−0.025***
	(0.006)	(0.009)	(0.010)	(0.008)	(0.007)
Distance to extension	−0.007	0.019*	−0.009	−0.006	0.018***
	(0.007)	(0.010)	(0.011)	(0.009)	(0.006)
Farmer group	0.056*	0.079*	−0.072*	0.017	0.082***
	(0.032)	(0.041)	(0.043)	(0.038)	(0.026)
Plant clinic access	0.175***	0.119***	0.032	0.059	0.030
	(0.037)	(0.039)	(0.044)	(0.038)	(0.028)
Media information	0.047*	0.010	0.159***	0.101***	0.010
	(0.028)	(0.038)	(0.040)	(0.035)	(0.026)
Free or subsidised input	0.060**	0.074*	0.037	0.092**	0.034
	(0.025)	(0.039)	(0.043)	(0.039)	(0.028)
Western province[a]	0.027	0.333***	0.064	0.133**	0.096*
	(0.066)	(0.063)	(0.070)	(0.065)	(0.051)
Southern province	−0.014	0.228***	0.092**	0.064*	0.025
	(0.027)	(0.041)	(0.042)	(0.036)	(0.026)
No. of observations	636	636	636	636	636

Note: marginal effects reported. Robust standard errors in parentheses.
*** p < 0.01.
** p < 0.05.
* p < 0.1.
[a] Base province = Northern.

correlated with about a 10% decrease in the choice of labour-intensive control methods of handpicking of larvae and rogueing of infested plants. Households with access to credit, which helps to relax liquidity constraints, are more likely to practice handpicking and various cultural techniques including early planting, crop rotation and constant weeding in order to prevent or reduce FAW infestation. Here again we observed that the use of the more costly option of spraying synthetic pesticides increases with household wealth. Two sources of agricultural information, farmer group and media are significantly associated with an 8% likelihood of the application of synthetic pesticide, and the latter also exerts a significant positive effect on the uptake of handpicking and the cultural practices (Table 5). Finally, access to subsidised inputs increases the use of pesticide by 11%, and decreases the probability of practicing handpicking by 9%, which is possibly because the use of pesticides reduces the need to engage in handpicking.

3.2.4. Zambia

The regression results for Zambia showed that female-headed households are more likely to opt for timely planting as a FAW preventive method (Table 6). Similar to the above results for Rwanda, better educated household heads are less inclined to engage in handpicking and crushing of eggs and larvae. Households with off-farm income sources have a higher probability of investing in early planting and handpicking. Consistent with the findings above, we see here that investment in synthetic pesticides for FAW control is more appealing to asset-rich households who are more likely to afford it. The positive relationship between plant clinics and use of synthetic pesticides observed in the Rwanda data is also confirmed here as Table 6 indicates that farmers who seek advice from plant clinics are 7% more likely to apply synthetic pesticides. Results further showed that using mass media to disseminate agricultural information is significantly correlated with a higher likelihood of timely planting, and the picking and crushing of FAW larvae. Access to discounted farm inputs is positively correlated with synthetic pesticides, but it is negatively correlated with the other management options. This suggests that while providing Zambian farmers with subsidised inputs through the Farmer Input Subsidy Programme will encourage the use of synthetic pesticides, it may inadvertently lead to a decrease in the adoption of non-chemical control options, thereby undermining efforts to promote IPM strategies.

3.2.5. Zimbabwe

Finally, looking at the regression results for Zimbabwe (Table 7), we observed that households with more members, and who are thus less likely to be labour-constrained, have a higher likelihood to engage in handpicking and crushing of egg masses and larvae. This is consistent with the result for Rwanda (Table 4). Better educated households are less inclined to use the traditional pest control practice of pouring ash or sand into maize whorls. We also found that proximity to extension offices and access to information via media are significantly related to a lower probability of using ash or sand of FAW control, possibly because these information sources are likely to desist from informing farmers about locally untested methods of pest control. Lastly, access to free or subsidised inputs is significantly associated with a 30% increase in the likelihood of using synthetic pesticides against FAW.

Taken together, the MVP estimation results suggest that the factors driving the choice of FAW management options vary considerably across the five countries, but we observed a few commonalities. Access to free or subsidised inputs and household wealth are consistently associated with the choice of synthetic pesticides for FAW control. Media campaigns are important in stimulating the uptake of most of the control options. Human capital is important in terms of adoption of considerably more labour-intensive management options. On average, better educated households tend to be less inclined to use more tedious methods of controlling FAW.

Table 5
Correlates of farmers' choice of FAW management options in Uganda.

	Synthetic pesticide	Hand-picking	Timely planting	Frequent weeding	Uproot and burn	Crop rotation
Age	0.001	−0.001	−0.002	−0.003**	0.000	0.003*
	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)	(0.001)
Gender	0.049	0.068	−0.056	−0.036	−0.027	0.194***
	(0.049)	(0.059)	(0.055)	(0.053)	(0.057)	(0.052)
Education	−0.030	−0.105**	−0.054	0.035	−0.096**	−0.024
	(0.041)	(0.046)	(0.043)	(0.040)	(0.044)	(0.037)
Household size	−0.006	−0.004	0.002	0.020***	−0.004	−0.003
	(0.005)	(0.007)	(0.006)	(0.006)	(0.006)	(0.005)
Maize area	0.003	0.010*	0.037**	0.008	−0.012	0.001
	(0.009)	(0.006)	(0.017)	(0.009)	(0.009)	(0.007)
Off-farm activity	−0.032	−0.089**	−0.006	−0.016	0.036	−0.002
	(0.038)	(0.043)	(0.041)	(0.039)	(0.042)	(0.035)
Credit access	0.030	0.168***	0.178***	0.074**	0.011	0.125***
	(0.036)	(0.041)	(0.039)	(0.037)	(0.042)	(0.034)
Asset index	0.046***	−0.022	0.008	0.005	0.026*	0.007
	(0.014)	(0.016)	(0.015)	(0.014)	(0.016)	(0.013)
Distance to agro-dealer	−0.003	0.008*	0.002	−0.002	0.006	0.003
	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)
Distance to extension	0.005	−0.011***	−0.003	0.002	−0.001	0.001
	(0.004)	(0.004)	(0.004)	(0.003)	(0.004)	(0.003)
Farmer group	0.085**	−0.070	−0.107**	−0.033	−0.002	0.002
	(0.043)	(0.048)	(0.046)	(0.042)	(0.047)	(0.038)
Media information	0.080**	0.194***	0.203***	0.221***	0.068	0.125***
	(0.040)	(0.049)	(0.045)	(0.047)	(0.050)	(0.044)
Free or subsidised input	0.105**	−0.087*	0.051	0.009	−0.007	0.042
	(0.045)	(0.053)	(0.050)	(0.048)	(0.052)	(0.045)
Masindi district[a]	0.208***	−0.002	−0.019	0.038	0.014	0.075*
	(0.041)	(0.053)	(0.050)	(0.047)	(0.051)	(0.045)
No. of observations	607	607	607	607	607	607

Note: marginal effects reported. Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.
[a] Base district = Buliisa.

Table 6
Correlates of farmers' choice of FAW management options in Zambia.

	Synthetic pesticide	Hand-picking	Ash or sand	Timely planting
Age	−0.001	0.001	0.000	0.001
	(0.000)	(0.001)	(0.000)	(0.000)
Gender	−0.020	0.025	0.001	−0.032***
	(0.015)	(0.019)	(0.014)	(0.010)
Education	0.014	−0.027*	0.011	−0.006
	(0.013)	(0.016)	(0.012)	(0.009)
Household size	0.001	−0.001	−0.002	−0.001
	(0.002)	(0.002)	(0.001)	(0.001)
Maize area	0.001	−0.001	0.003	0.003
	(0.003)	(0.004)	(0.003)	(0.002)
Off-farm activity	−0.013	0.038**	−0.004	0.024***
	(0.013)	(0.016)	(0.012)	(0.009)
Credit access	0.021	−0.021	0.022	0.006
	(0.017)	(0.021)	(0.015)	(0.011)
Asset index	0.024***	0.007	−0.001	0.002
	(0.005)	(0.006)	(0.004)	(0.003)
Distance to agro-dealer	0.000	−0.001	0.000	−0.001
	(0.000)	(0.000)	(0.000)	(0.000)
Distance to extension	−0.001	−0.001	−0.001	−0.001
	(0.000)	(0.000)	(0.000)	(0.000)
Farmer group	0.007	0.028	−0.007	0.019*
	(0.015)	(0.018)	(0.013)	(0.010)
Plant clinic access	0.071***	−0.011	0.032	−0.023
	(0.028)	(0.035)	(0.025)	(0.019)
Media information	0.016	0.029*	−0.001	0.030***
	(0.014)	(0.017)	(0.013)	(0.009)
Free or subsidised input	0.225***	−0.047**	−0.029**	−0.020**
	(0.014)	(0.018)	(0.013)	(0.010)
Central[a]	0.018	−0.129***	−0.101***	0.035**
	(0.022)	(0.027)	(0.020)	(0.015)
Luapula	−0.024	0.040	−0.076***	0.008
	(0.030)	(0.032)	(0.027)	(0.020)
Southern	0.018	−0.090***	−0.107***	0.001
	(0.021)	(0.025)	(0.019)	(0.014)
Copperbelt	0.057**	−0.175***	−0.066***	0.029*
	(0.024)	(0.031)	(0.023)	(0.017)
North-Western	−0.083***	−0.151***	0.003	0.064***
	(0.023)	(0.028)	(0.020)	(0.015)
Eastern	−0.026	−0.124***	−0.105***	0.006
	(0.022)	(0.026)	(0.019)	(0.015)
No. of observations	436	436	436	436

Note: marginal effects reported. Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.
[a] Base province = Northern.

Table 7
Correlates of farmers' choice of FAW management options in Zimbabwe.

	Synthetic pesticide	Handpicking	Ash or sand
Age	−0.001	0.000	0.000
	(0.000)	(0.000)	(0.000)
Gender	0.017	−0.005	−0.008
	(0.014)	(0.016)	(0.014)
Education	0.009	−0.001	−0.035**
	(0.016)	(0.018)	(0.014)
Household size	0.001	0.003**	−0.001
	(0.001)	(0.002)	(0.001)
Maize area	0.001	−0.001	−0.001
	(0.001)	(0.001)	(0.001)
Off-farm activity	−0.019	−0.006	0.006
	(0.015)	(0.016)	(0.013)
Credit access	0.005	−0.019	0.014
	(0.020)	(0.019)	(0.016)
Asset index	0.007	−0.007	−0.001
	(0.006)	(0.005)	(0.003)
Distance to agro-dealer	−0.001	0.000	−0.001
	(0.000)	(0.001)	(0.000)
Distance to extension	−0.001	−0.002***	−0.001**
	(0.001)	(0.001)	(0.000)
Farmer group	0.063***	−0.014	0.009
	(0.023)	(0.018)	(0.017)
Media information	0.062**	0.103***	−0.038***
	(0.026)	(0.029)	(0.008)
Free or subsidised input	0.293***	0.046	0.000
	(0.018)	(0.044)	(0.028)
Mashonaland East[a]	0.022	−0.033	0.032
	(0.028)	(0.033)	(0.022)
Mashonaland West	0.014	−0.086***	0.013
	(0.024)	(0.026)	(0.016)
Midlands	0.005	−0.068**	−0.005
	(0.024)	(0.030)	(0.015)
Masvingo	0.040	−0.067**	0.033*
	(0.028)	(0.028)	(0.019)
Matabeleland North	−0.009	−0.063**	0.032*
	(0.024)	(0.027)	(0.017)
No. of observations	185	185	185

Note: marginal effects reported. Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.
[a] Base province = Mashonaland Central.

3.3. Complementarities and tradeoffs among FAW management practices

As mentioned earlier, correlation matrices from the MVP estimations are used to check for complementarities and substitutabilities of the FAW management practices used in our five study countries. Some significant correlations were found between the error terms of the FAW management practices equations (Table 8), indicating that the use of the MVP estimations over single-equation probit estimations is justified. The results showed a negative and significant correlation between synthetic pesticides and biopesticides, implying that the farmers perceived tradeoffs in the use of these two groups of pest control products. In other words, households that used biopesticides were less likely to opt for synthetic pesticides, which is expected as both options compete for scarce resources and are used to achieve a similar purpose of immediate control of pests. Thus, the promotion of biopesticides (as currently done in Ghana) is likely to reduce the demand for highly toxic control methods. This is a compelling finding, given the increasing recognition of the need to promote more environmentally-friendly and safe methods of FAW control.

In general, we did not see significant correlations between the application of synthetic pesticides and the use of other control methods, indicating that the promotion of synthetic pesticides for FAW control is less likely to encourage the adoption of IPM solutions. Interestingly, we observed synergies between the use of biopesticides and the practices of regular weeding and handpicking of larvae (Table 8). In most cases, handpicking of egg masses or larvae is positively correlated with the use of cultural control options, signifying complementarities. A plausible explanation is that the cultural methods help to greatly reduce the level of FAW infestation, and complementing them with handpicking of egg masses and larvae may suffice to adequately control the pest. In Uganda, we found strong complementarities in the use of the physical and cultural control methods, which is likely due to the emphasis on IPM techniques during the FAW communication campaign in the country. Results suggest that synthetic pesticides and ash or sand were seen as substitutes by farmers in Zambia but were used complementarily by farmers in Zimbabwe (Table 8), pointing to location-specific differences in the management of FAW.

3.4. Safety of pesticide use

Given that pesticide application was the most preferred FAW control option among the surveyed farmers across the five countries and the well-known negative effects of pesticides on animals, humans and the environment (Kim et al., 2017), we examine in this section the types of pesticide products (including synthetic pesticides and biopesticides) used and whether the farmers observed some safety precautions while handling the pesticides.

Table 8
Correlation matrix from the multivariate probit (MVP) models.

Ghana	Synthetic pesticide	Biopesticide	Handpicking	Frequent weeding	Timely planting
Synthetic pesticide	1				
Biopesticide	−0.306 (0.046)***	1			
Handpicking	−0.015 (0.047)	0.126 (0.050)**	1		
Frequent weeding	0.053 (0.042)	0.170 (0.052)***	0.051 (0.055)	1	
Early planting	−0.001 (0.046)	0.006 (0.046)	0.081 (0.052)	0.070 (0.055)	1

Rwanda	Synthetic pesticide	Handpicking	Uproot and burn	Crop rotation	Timely planting
Synthetic pesticide	1				
Handpicking	0.137 (0.097)	1			
Uproot and burn	−0.173 (0.095)*	0.196 (0.069)***	1		
Crop rotation	0.004 (0.103)	0.338 (0.077)***	0.111 (0.071)	1	
Early planting	−0.118 (0.136)	−0.148 (0.090)	−0.206 (0.086)**	0.859 (0.107)***	1

Uganda	Synthetic pesticide	Handpicking	Timely planting	Frequent weeding	Uproot and burn	Crop rotation
Synthetic pesticide	1					
Handpicking	−0.055 (0.076)	1				
Early Planting	0.074 (0.077)	0.363 (0.073)***	1			
Regular weeding	0.139 (0.080)*	0.286 (0.075)***	0.401 (0.074)***	1		
Uproot and burn	0.042 (0.079)	0.215 (0.072)***	0.246 (0.072)***	0.121 (0.073)*	1	
Crop rotation	0.045 (0.084)	0.105 (0.077)	0.190 (0.076)**	0.370 (0.078)***	0.291 (0.079)***	1

Zambia	Synthetic pesticide	Handpicking	Ash or sand	Timely planting
Synthetic pesticide	1			
Handpicking	−0.013 (0.048)	1		
Ash or sand	−0.118 (0.047)**	0.178 (0.046)***	1	
Early Planting	−0.067 (0.048)	0.185 (0.046)***	0.178 (0.046)***	1

Zimbabwe	Synthetic pesticide	Handpicking	Ash or sand
Synthetic pesticide	1		
Handpicking	0.060 (0.053)	1	
Ash or sand	0.104 (0.053)**	0.010 (0.054)	1

Note: standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

We found that *Bacillus thuringiensis*-based biopesticide was the most widely used pesticide among farmers in the Ghana sample (Table 9). This can be explained by policy efforts of the Ghana government to promote biopesticides for FAW control (Rwomushana et al., 2018). On the contrary, very few farmers in the other four countries used biopesticides, which included pyrethrins in Rwanda and GS-omega/kappa-Hxtx-Hv1a in Zambia. The most popular pesticide used by the farmers in East Africa for FAW control was Rocket (profenofos and cypermethrin), which was applied by 92% and 88% of the sample farmers from Rwanda and Uganda, respectively. In the two Southern African countries, lambda-cyhalothrin was the most common option. While most of the pesticides can be found in the list of recommended pesticides for FAW control in the study countries, there are a few exceptions, including the use of highly toxic and prohibited products (Table 9). For instance, 16 of the Zambian farmers used monocrotophos, a highly hazardous chemical according to the World Health Organisation (WHO) classification of pesticides (WHO, 2010). Other highly hazardous pesticides in our data include dichlorvos in Uganda and Zambia, methomyl in Zambia, and methamidophos in Zimbabwe. This confirms a report by Chimweta et al. (2019) that some Zimbabwean farmers were controlling FAW using methamidophos, which is a banned product. Results also showed that 35 farmers in Rwanda sprayed endosulfan, despite the prohibition of its use in the country (Government of Rwanda, 2016). In attempts to curb the deleterious effects of FAW and given the limited knowledge of the pest, some of the maize farmers tried out several pesticides including fungicides such as mancozeb and benomyl, though FAW is not a fungus. This points to the need to intensify education on the recommended chemicals for FAW control and enforce pesticide regulations so that resource-poor smallholders do not spend their meagre income on ineffective, banned or hazardous products in desperate attempts to control this new invasive pest.

Fig. 1 shows that despite using a number of moderately and highly hazardous pesticides, some of the pesticide users did not wear any standard protective apparel when mixing or spraying the pesticides. This ranges from 15% in Uganda to as high as almost 50% of the pesticide users in Ghana. In all the five study countries, less than half of the pesticide users wore coverall, goggles, gloves and masks while working with synthetic pesticides. Such a low use of protective clothing among smallholders has been observed in several studies (e.g., Okonya and Kroschel, 2015; Kwakye et al., 2018; Sharifzadeh et al., 2019), and this is alarming particularly in the context of the FAW invasion as most governments and farmers have so far opted for pesticide options for rapid control of the pest.

Given the low use of personal protective equipment, it is not surprising that some of the pesticide users reported having experienced symptoms of acute pesticide poisoning (Table 10). For example, in Ghana where half of the farmers did not use a protective gear, 20% of the pesticide users experienced skin irritations and dizziness, and almost 30% of them reported suffering from headache after working with pesticides. In Uganda and Zambia, slightly more than half of the pesticide users reported some form of illness after exposure to synthetic pesticides.

4. Conclusion

In this study, we have investigated how smallholder farmers in five sub-Saharan African countries are fighting FAW, a new invasive pest that is causing devastating effects on maize. We used data from 2356 smallholder maize-growing households across Ghana, Rwanda,

Table 9
Most common pesticide products used by the surveyed farmers.

Country	Trade name	Active ingredient	No. of farmers	% of farmers[a]	WHO toxicity class[b]
Ghana (n = 359)	Agoo	*Bacillus thuringiensis* (Bt) + Monosultap	81	22.56	N
	Bypel	Bt + Pieris rapae granulosis virus	29	8.08	N
	Sunpyrifos	Chlorpyrifos ethyl	29	8.08	II
	Attack	Emamectin Benzoate	55	15.32	N
	EmaStar	Emamectin Benzoate+Acetamiprid	26	7.24	II
	Adepa	Ethyl palmitate	54	15.04	U
	Super top or K-Optimal	Lambda-cyhalothrin+Acetamiprid	38	10.58	II
	Lambda Super	Lambda-cyhalothrin	43	11.98	II
	Eradicoat T	Maltodextrin	16	4.46	III
	Efforia	Lambda-cyhalothrin+Thiamethoxam	15	4.18	II
	Condifor	Imidacloprid	15	4.18	II
Rwanda (n = 556)	Rocket	Profenofos+Cypermethrin	510	91.73	II
	Sumicombi	Fenitrothion+Fenvalerate	57	10.25	II
	Dithane M45	Mancozeb	44	7.91	U
	Thiodan	Endosulfan	35	6.29	II
	Ridomil	Metalaxyl-M	18	3.24	II
	Cypermetrin	Cypermethrin	10	1.80	II
	Benlate	Benomyl	3	0.54	U
	Pyrethrum	Pyrethrins[c]	3	0.54	II
Uganda (n = 392)	Rocket	Profenofos+Cypermethrin	343	87.50	II
	Striker	Lambda-cyhalothrin+Thiamethoxam	114	29.08	III
	Dudu Fenos	Profenofos+Cypermethrin	57	14.54	II
	Larvet	Cypermethrin+Profenofos	33	8.42	II
	Supa profenofos	Profenofos+Cypermethrin	33	8.42	II
	Profecron	Profenofos+Cypermethrin	13	3.32	II
	Ambush	Cypermethrin	12	3.06	II
	Tafgor	Dimethoate	6	1.53	II
	Dudu-Cyper	Cypermethrin	6	1.53	II
	Lava	Dichlorvos	6	1.53	Ib
Zambia[d] (n = 198)	Karate or Lambda	Lambda-cyhalothrin	55	27.78	II
	Cypermethrin	Cypermethrin	41	20.71	II
	Phoskill	Monocrotophos	16	8.08	Ib
	Emamectin	Emamactin benzoate	10	5.05	N
	Malathion	Malathion	9	4.55	III
	Spear	GS-omega/kappa-Hxtx-Hv1a[c]	6	3.03	N
	Profenofos	Profenofos	4	2.02	II
Zimbabwe (n = 61)	Karate or Lambda	Lambda-cyhalothrin	16	26.23	II
	Cabaryl	Carbaryl 85%	15	24.59	II
	Nemesis or Superdash	Emmamectin Benzoate+Acetamiprid	7	11.48	N
	Tamaron	Methamidophos	2	3.28	Ib
	Belt	Flubendiamide	2	3.28	N
	Dimethoate	Dimethoate	2	3.28	II
	Dipterex	Trichlorfon	2	3.28	II

[a] Percentages are based on households that used pesticides for FAW control.
[b] Ib = highly hazardous; II = moderately hazardous; III = slightly hazardous; U = unlikely to present acute hazard in normal use; and N = not classified.
[c] These are biopesticides.
[d] Dichlorvos and methomyl, which are both WHO class Ib pesticides, were used by one farmer each in this country.

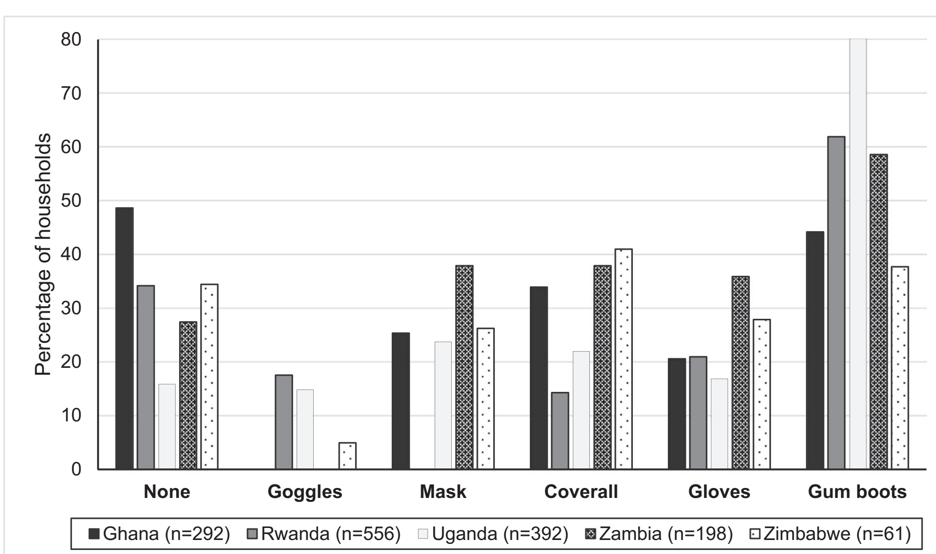

Fig. 1. Use of personal protective equipment (PPE) during pesticide application.

Table 10
Pesticide-related health symptoms (%).[a]

	Ghana (n = 292)	Rwanda (n = 556)	Uganda (n = 392)	Zambia (n = 198)	Zimbabwe (n = 61)
Headache	28.77	10.07	15.05	15.74	13.11
Sneezing	0.00	11.15	17.60	3.54	0.00
Skin rash/irritation	19.86	6.65	26.28	22.34	9.84
Dizziness	20.21	2.52	5.87	12.69	6.56
Eye irritation	0.34	4.68	13.52	2.03	4.92
Stomach cramps	6.85	0.72	4.08	2.03	0.00
Nausea	0.68	1.80	3.83	1.52	0.00
None	54.79	78.40	49.87	47.72	68.85

[a] Percentages are based on households that used synthetic pesticides for FAW control.

Uganda, Zambia and Zimbabwe. Results showed that smallholders are pursuing a wide range of options to tackle FAW, including agronomic practices, such as crop rotation, timely planting, and regular weeding of farms; chemical controls such as the use of synthetic pesticides and biopesticides; physical methods involving handpicking and crushing of egg masses and caterpillars, and removal and destruction of infested maize plants; as well as local controls such as pouring of ash and sand into maize whorls to kill the larvae. Nonetheless, the use of synthetic pesticides remains the most popular control option. We observed a relatively high use of biopesticides in Ghana, where there is an ongoing national effort to promote this option for FAW control.

Results from multivariate probit regressions showed that access to free or subsided inputs and household wealth are positive and significant determinants of pesticide use. In each country, a large share of the farmers used moderately hazardous chemicals (WHO toxicity class II pesticides). More worrying is the evidence that a few of the farmers used pesticides such as endosulfan, monocrotophos, dichlorvos and methamidophos that are highly toxic or prohibited in the study countries. Alarmingly, most of the farmers did not use personal protective equipment while spraying pesticides, resulting in reports of acute pesticide-related illness such as headache, dizziness, skin rashes and stomach cramps.

We found complementarities between various cultural control methods, but tradeoffs between synthetic pesticides and biopesticides, implying that policy efforts towards the promotion of low-risk products can generate positive spillover effects in terms of a reduction in the use of toxic chemicals. Given our findings on the significant role of free and discounted inputs in spurring the adoption of synthetic pesticides and the substitutabilities between biopesticides and synthetic pesticides, governments keen on supporting their farmers with subsidised pesticides for FAW control should consider using the subsidies to foster the adoption of low-risk control options (such as biopesticides) instead of synthetic pesticides. As shown by Bateman et al. (2018), there are several registered biopesticides that smallholder farmers in sub-Saharan Africa could potentially use to tackle the pest.

Our findings also suggest the need to enforce pesticide regulations to curb the use of highly toxic and banned products. Additionally, mass media campaigns and training of plant health advisory service providers (such as plant doctors, agro-input dealers and extension agents) would be essential in informing farmers about the recommended pesticides for FAW control, risks and safety precautions, as well as alternative and more sustainable management options. Moreover, government distribution of free or subsidised pesticides will need to be accompanied by subsidised PPE and the necessary training. Finally, it would be necessary to test the effectiveness of the various FAW management practices identified in this study, and also intensify research efforts into other low-cost and low-risk IPM options such as resistant varieties and biological control, which have shown great potential for FAW control elsewhere but are currently not options for farmers in our study countries (Prasanna et al., 2018; Kenis et al., 2019).

CRediT authorship contribution statement

Justice A. Tambo: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Monica K. Kansiime:** Data curation, Investigation, Writing - review & editing. **Idah Mugambi:** Data curation, Software, Investigation. **Ivan Rwomushana:** Investigation, Writing - review & editing. **Marc Kenis:** Writing - review & editing, Funding acquisition. **Roger K. Day:** Writing - review & editing, Funding acquisition, Supervision. **Julien Lamontagne-Godwin:** Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140015.

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