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Can plant clinics enhance judicious use of pesticides? Evidence from Rwanda and Zambia

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ABSTRACT

Recent outbreaks of crop pests such as fall armyworm and desert locusts are threatening food security and have spurred increased use of pesticides in sub-Saharan Africa. While pesticides can prevent crop losses, they can also have adverse effects on human health and the environment, if not used judiciously. In this article, we examine whether plant clinics–an innovative extension approach of providing plant health diagnostic and advisory services to smallholder farmers–can enhance judicious use of pesticides, measured by intensity of pesticide use, adoption of alternative and more environmentally friendly pest management practices, safe pesticide use practices, and incidence of pesticide-related illness. We use data from a sample of 1474 farm households in Rwanda and Zambia. Propensity score matching estimates suggest that although plant clinic participants exhibit a higher probability of opting for pesticides for pest control, they do not use pesticides intensively and are more likely to adopt alternatives to chemical pest control. On the other hand, plant clinic users and non-users are equally likely to use restricted pesticides and inappropriate methods of disposing of pesticide wastes, which can lead to pesticide poisoning. Overall, our results imply that the plant clinic extension approach can promote sustainable pest management in smallholder agriculture, but additional training of plant clinic staff and clients on pesticide safety would be necessary.

1. Introduction

It is widely recognised that crop pests are a major limiting factor of agricultural productivity growth worldwide (Oerke, 2006; Savary et al., 2012). Crop losses due to pests are estimated to be between 40% and 60% across sub-Saharan Africa (SSA) (Oerke, 2006). The outbreak and spread of crop pests are likely to increase due to climate and land-use changes as well as increased international trade (Early et al., 2016; Liu et al., 2020). For instance, the invasive fall armyworm (FAW), *Spodoptera frugiperda*, whose outbreak was confirmed in SSA in 2016, has now spread rapidly across all countries in the region, with potential to cause annual maize losses of about 8 to 20 million tonnes in just 12 countries (Day et al., 2017). In addition, a number of East African countries are currently facing a desert locust (*Schistocerca gregaria*) crisis, which is threatening food security and livelihoods in the region (FAO, 2020a). Thus, without appropriate interventions, crop pests can derail efforts towards the achievement of the Sustainable Development Goals of 'no poverty' and 'zero hunger'. This is buttressed by the United Nations declaration of 2020 as the International Year of Plant Health.

Responding to FAW effects on maize (a key food security crop in SSA), most African governments (including Rwanda and Zambia) procured and distributed pesticides to farmers (Day et al., 2017; Stokstad, 2017). Consequently, many farmers in SSA are now routinely applying pesticides to control FAW. Based on an analysis of 2010–2012 nationally representative datasets from six SSA countries, Sheahan and Barrett (2017) observed that only about 16% of households applied pesticides in their farms. However, results from recent surveys of smallholder maize-growing households in SSA suggest high pesticide use, ranging from nearly 50% in Ethiopia and Kenya (Kumela et al., 2019) to 60% in Zambia (Kansiime et al., 2019) and 87% in Rwanda (Tambo et al., 2020a) due to the FAW invasion. Unfortunately, pesticides are expensive and indiscriminate use is associated with negative outcomes, including:

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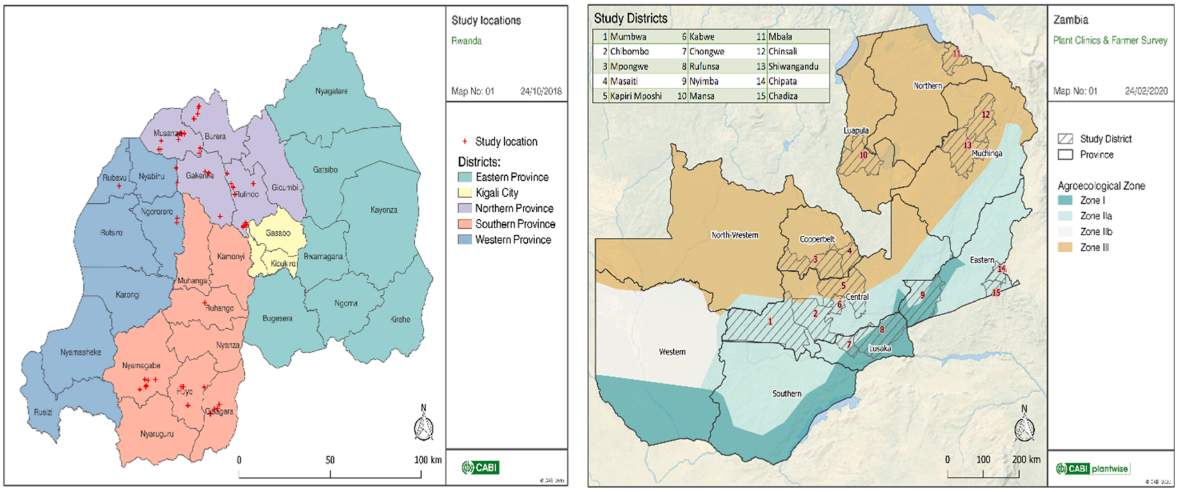

Fig. 1. Maps of Rwanda (left) and Zambia (right) showing locations of the study areas.

insecticide-induced pest outbreaks; pesticide resistance in pests; contamination of food products; soil and groundwater pollution; acute and chronic health problems; and poisoning of non-target (beneficial) organisms, such as pollinators and natural enemies (Pimentel, 2005; Kim et al., 2017; Githiomi et al., 2019). Hence, there have been increased calls for a shift towards the use of integrated pest management (IPM) strategies for FAW management (Day et al., 2017; Prasanna et al., 2018).

The IPM paradigm aims to reduce reliance on pesticides by encouraging the use of a combination of sustainable pest control practices. IPM techniques include judicious use of pesticides, as well as non-chemical pest management practices, such as intensive monitoring, resistant varieties, cultural control, physical or mechanical control and biological control. While IPM practices have proven capacity to reduce crop losses due to pests in an environmentally sustainable manner, implementation at the farm level is limited by information constraints, given that some practices are knowledge-intensive (Dhawan and Peshin, 2009). In this article, we assess whether plant clinics, a novel extension approach that provides plant health diagnostic and information services to farmers, can encourage farmers to use pesticides more judiciously. In particular, we explore the relationship between plant clinic participation and a range of outcomes related to judicious pesticide use, such as intensity of pesticide use, use of toxic or banned pesticides, adoption of alternative and more environmentally friendly pest management practices, proper disposal of pesticide wastes, use of personal protective equipment (PPE), and incidence of pesticide-related illness. We use household survey data from Rwanda and Zambia, where plant clinics have been operating since 2011 and 2013, respectively. We apply the propensity score matching (PSM) estimation method to mitigate potential selection bias due to non-random assignment of plant clinic participants.

The plant clinics are supported by the Centre for Agriculture and Biosciences International (CABI)-led Plantwise programme, which aims to help farmers lose less of their crops to pests and diseases. At the plant clinics, which are set up at public places such as markets and village centres, any farmer can bring a sample of any 'sick' crop and will be attended to by plant doctors who will diagnose the problem and make science-based recommendations free of charge. The plant doctors are local agricultural extension workers who have been trained by the Plantwise programme on pest diagnosis and management, and on how to operate a plant clinic [see Otieno et al. (2021) for a detailed description of the plant clinic extension approach and plant doctors]. In collaboration with national partners, the Plantwise programme has established about 4500 plant clinics in 34 countries across Africa, Asia and Latin America. In Rwanda, there are 66 active plant clinics that are manned by 230 trained plant doctors. Similarly, Zambia has 121 plant clinics that are staffed by 352 plant doctors. As at the time of this study, these plant clinics had attended to 16,130 and 12,000 farmers' queries on about 100 crops in Rwanda and Zambia respectively (POMS, 2020), signifying their growing popularity and importance as a source of plant health information.

Plant clinics are hypothesised to enhance judicious use of pesticides because plant doctors are trained by the Plantwise programme to offer plant health advice to farmers by following the tenets of IPM, which include judicious use of pesticides. In situations where pesticide use is inevitable, plant doctors are advised to recommend only locally-registered pesticides and avoid pesticides that are restricted by international agreements.[1] Furthermore, according to the Plantwise policy on the use of pesticides, "plant doctors are encouraged to give advice that keeps pesticide usage to the lowest effective level and ensures minimal risk to human health and the environment" (Plantwise, 2020). To aid in delivering accurate diagnostic and advisory services, the plant doctors have access to several resources, including pest management decision guides and the Plantwise knowledge bank, which is a repository for pest data and management options.

Despite efforts to encourage appropriate pesticide use through the plant clinic extension model, there is lack of empirical evidence on whether, and to what extent, plant clinics are achieving this objective. The existing studies on the impact of plant clinics have mostly focussed on outcomes related to technology adoption, crop productivity and household welfare (Bentley et al., 2011; Silvestri et al., 2019; Tambo et al., 2020b; Tambo et al., 2021). The current study attempts to fill this knowledge gap by assessing the effectiveness of plant clinics in ensuring judicious use of pesticides and sustainable pest management. The study also adds to the thin evidence base on the role of agricultural extension in spurring the adoption of pest management strategies. Previous studies have focused on extension approaches such as farmer training (e.g., Schreinemachers et al., 2016; Gautam et al., 2017; Goeb et al., 2020), farmer field schools (e.g., Feder et al., 2004; Waddington et al., 2014), public and private extension (e.g., Wuepper et al., 2020), and ICT-enabled extension services (e.g., Larochelle et al., 2019; Tambo et al., 2019). By contrast, the present study focuses on a demand-led extension approach that provides personalised plant health services to farmers. Insights gained from this study can be useful in informing policy efforts

[1] These include the Montreal Protocol on Substances that Deplete the Ozone Layer, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, the Stockholm Convention on Persistent Organic Pollutants, and pesticides listed as Classes Ia and Ib by the WHO Recommended Classification of Pesticides by Hazard (Plantwise, 2020).

aimed at reducing crop losses due to invasive pests, thereby increasing food production while ensuring environmental sustainability.

The rest of this paper is structured as follows. The next section describes the data and empirical methods. Estimation results are presented and discussed in section three, and section four concludes with some policy implications.

2. Data and methods

2.1. Data and sample characteristics

Our analyses are based on data obtained from surveys of 637 and 837 smallholder maize-growing households in Rwanda (East Africa) and Zambia (Southern Africa), respectively. The data cover the 2017/2018 and 2018/2019 maize cropping seasons in Rwanda and Zambia, respectively. The data were collected with the aim of assessing the role of plant clinics in influencing sustainable pest management in the two countries. In each country, the survey was conducted by trained enumerators using tablet-based questionnaires. The questionnaires captured information on household composition and characteristics, participation in plant clinics, access to institutional services, maize production, FAW infestation and management practices, social capital, risk attitude, household assets, and safe pesticide practices. According to the Plantwise Online Management System (POMS), which is a database of plant clinic users and their queries, the majority of the farmers who visited plant clinics in recent cropping seasons sought advice related to FAW on maize, which is a major food security crop in both countries. Hence, our survey focused on maize-producing households and the FAW pest.

A multi-level stratified sampling approach was used to select sample households. In Rwanda, we first identified three (i.e., Northern, Southern and Western) out of the country's five provinces where maize is an important crop and where there are increased cases of FAW (see Fig. 1). Within each province, we purposively selected 15 sectors where plant clinics have been established and where there are high incidences of FAW, based on the POMS data. We then randomly selected and interviewed around 15 to 20 maize producing households from a list of farmers that visited plant clinics in each sector. In Zambia, the plant clinic users were first stratified based on the three main maize-growing agro-ecological zones (i.e., AEZs I, IIa and III) in the country (Fig. 1). Six, twelve, and seven agricultural camps where plant clinics have been sited were selected from AEZs I, IIa and III respectively, based on the density of plant clinics, the number of queries on FAW, and the importance of maize production. In each selected plant clinic camp, about 15 to 25 plant clinic users were then randomly sampled proportionate to the number of FAW queries. The POMS database was used to confirm that the selected clinic users had actually visited plant clinics to seek advice related to FAW.

In each country, a comparable group of clinic non-users were selected from sectors (in Rwanda) and agricultural camps (in Zambia) that were as similar as possible to the plant clinic sectors and camps, in terms of contextual characteristics such as AEZs, crops grown, incidence of the FAW pest (see Tables A1 and A2 in the appendix). We ensured that a selected plant clinic camp or sector and its comparable non-clinic camp or sector were located within the same AEZ and district but are not geographically adjacent so as to mitigate potential spillover effects.[2] Then in each control camp or sector, between 10 and 20 maize-producing households were randomly selected from household lists and interviewed. Besides using the POMS database to confirm households' clinic participation status, our questionnaires included filter questions to ensure that the selected clinic non-users were maize farmers who had experienced FAW attacks on their maize crops during the past cropping season and had never used plant clinic services. In total, our sample comprises 263 clinic users and 374 non-users in Rwanda, as well as 444 clinic users and 393 non-users in Zambia.

[2] Similarly, the non-clinic users were not selected from the sectors or camps where plant clinics have been established in order to avoid spillover effects.

Table 1
Socio-economic characteristics of sample households.

Variable	Definition	Rwanda		Zambia	
		Mean	SD	Mean	SD
Age	Age of household head (years)	49.59	13.34	50.34	13.23
Gender	Gender of household head (1 = male)	0.77	0.42	0.67	0.47
Education	No. of years of formal education of household head	4.99	3.29	7.69	3.44
Household size	Number of household members	5.18	1.93	7.08	3.21
Dependency ratio	Household dependency ratio[a]	1.00	0.89	1.26	1.11
Farm size	Amount of land cultivated by household (hectares)	0.59	1.15	2.80	2.81
Livestock holding	No. of livestock owned in tropical livestock unit	0.81	1.04	2.47	4.75
Asset index	Household asset index[b]	0.00	1.43	−0.10	1.62
Farmer group	A household member belongs to a farmer association (1/0)	0.32	0.47	0.87	0.34
Credit access	Household has access to credit (1/0)[c]	0.57	0.50	0.77	0.42
Risk preference	Risk attitude of household (0–10)[d]	6.44	1.76	5.58	2.96
Distance to agro-dealer	Distance from household to the nearest input supplier (km)	2.46	2.49	15.11	13.85
Distance to extension	Distance from household to the nearest extension agency (km)	2.54	2.26	9.80	10.15
Northern Province	Household is located in northern province (1/0)	0.45	0.50		
Western Province	Household is located in western province (1/0)	0.12	0.32		
Southern Province	Household is located in southern province (1/0)	0.43	0.50		
AEZ I	Household is located in AEZ I (1/0)			0.17	0.38
AEZ IIa	Household is located in AEZ IIa (1/0)			0.43	0.50
AEZ III	Household is located in AEZ III (1/0)			0.39	0.49
	Number of observations	637		837	

[a] This is measured by the number of household members under 15 years of age plus the number of members over 64 years of age divided by the total number of household members. It reflects pressure on the productive household members, and thus time constraints for participating in plant clinics.
[b] The asset index is based on household ownership of 11 durable assets. It was constructed using principal component analysis.
[c] Measured by whether the household used any of the following sources of credit during the past year: bank, microcredit, family or friends, input providers, and cooperatives or farmer association. Access to credit can help to relax a household's liquidity constraint.
[d] We applied the survey-based risk preference measure proposed by Dohmen et al. (2011), where 0 means not at all willing to take risks and 10 means fully prepared to take risks.

Table 1 compares the socio-economic characteristics of the farm households in our sample across the two study countries. A typical household is headed by a moderately risk averse male farmer who is 50 years of age, with limited educational attainment, especially in Rwanda where the head has attained only 5 years of formal education. On average, households consist of five to seven members with a very high dependency ratio (100% in Rwanda and 126% in Zambia). Average farm size ranges from as low as 0.60 ha in Rwanda to nearly 3 ha in Zambia. Proportionally more households have access to credit and participate in farmer associations in Zambia than in Rwanda. The high (87%)

membership in farmer associations in Zambia is potentially due to the fact that cooperative or farmer group membership is one of the eligibility criteria for participating in the country's input subsidy programme (Mason et al., 2013). The Zambian households have to travel about 10 km and 15 km to access agricultural inputs or advisory services from extension agencies and ago-input dealers, respectively. By contrast, the Rwandan households live in closer proximity (2.5 km) to these two sources of advisory services. This huge difference in proximity to institutional services is partly due to the fact that Zambia is sparsely populated and occupies a land area that is almost 30 times that of Rwanda. Tests of mean differences in these variables between users and non-users of plant clinics are presented in Tables A3 and A4 in the appendix.

2.2. Empirical approach

We examine the effects of plant clinics on several outcome measures regarding judicious use of pesticides. The first set of outcome variables relate to adoption and intensity of use of pesticides. These include: (1) a binary variable measuring whether or not a farm household used pesticide to control FAW; (2) the number of pesticide sprays during the cropping season; and (3) the amount spent on pesticide per unit of land area (USD/hectare). Plant doctors are obliged not to recommend pesticides that are restricted or banned by international agreements.[3] To check if this guideline is being followed, we include a binary measure of the use of restricted or banned pesticides as an outcome of interest. In line with the Plantwise programme's emphasis on the use of a combination of pest management strategies, the next outcome variable is measured by the number of prevention and control practices that a household implemented for the management of FAW.

We also include two outcomes that measure the use of PPE: whether a household used at least one standard PPE (i.e., goggles, respirators, coverall, gloves or rubber boots) while mixing or spraying pesticides; and the number of different items of PPE used. Given that exposure to synthetic pesticides poses health risks, we examine if plant clinics, which emphasise on both safe and prudent use of pesticides, can generate positive health outcomes, in terms of reduced incidence of acute pesticide-related health symptoms, such as headache, skin or eye irritation, sneezing, dizziness, stomach cramp, nausea and diarrhoea.[4] This outcome variable is defined as the number of pesticide-related illness reportedly experienced by a household member while working with pesticides. Our final outcome variable relates to safe disposal of pesticide wastes. We examine if plant clinic users are more likely than non-users to dispose of pesticide containers in a manner that does not contaminate the environment or pose a risk to human health. As a minimum requirement, pesticide users are expected to triple-rinse and puncture empty pesticide containers.

In estimating the effects of plant clinics on the aforementioned outcome variables, we recognise that participation in plant clinics is not randomly assigned, and thus farm households may decide whether not to use plant clinic services depending on observed and unobservable characteristics. In other words, plant clinic users may differ systematically from non-users; hence, a simple comparison of mean outcome measures of clinic users and non-users may yield biased results. To attenuate this potential selection bias when estimating the effects of plant clinics, we use the propensity score matching (PSM) technique (Rosenbaum and Rubin, 1983), which involves matching the treatment group (clinic users) and control group (non-users) based on observable characteristics.

It should be emphasised that the PSM method does not account for potential bias due to unobserved heterogeneity. Panel data or instrumental variables (IV) estimators (e.g., endogenous switching regression) would have been more appropriate to correct for this potential source of bias. However, our analysis is based on cross-sectional data, which do not include a variable (instrument) that satisfies exclusion restriction required by the IV estimator. Hence, our choice of the PSM method. Although the PSM method controls for only observable variables, it does not rely on functional form assumptions, as required by alternative estimation methods such as IV regression.

In the first stage of the PSM approach, we use a logit regression to generate propensity scores, which reflect the probability of a farm household participating in plant clinics. The covariates in the logit regression include important pre-treatment variables that could influence plant clinic participation and the outcome variables. Inspired by literature on the determinants and impacts of participation in plant clinics and other extension programmes (e.g., Läpple et al., 2013; Gautam et al., 2017; Silvestri et al., 2019; Tambo et al., 2020b), the conditioning variables include household demographic characteristics (age, gender and education of household head, household size and dependency ratio; household asset endowments (farm size, livestock holding and durable asset index); a measure of risk preference (Dohmen et al., 2011); access to institutional services (farmer group membership, credit access, and distance to agro-dealers and extension service providers); and location characteristics. A detailed description of the conditioning variables is displayed in Table 1.

The propensity scores obtained in the first stage are then used to match clinic users with non-users. The matching algorithm used is kernel matching, with the default bandwidth of 0.06. To check the robustness of our results, we also used two alternative matching routines: radius matching with a calliper of 0.05 and nearest-neighbour matching. We refer readers to Caliendo and Kopeinig (2008) for a detailed description of these three matching routines, including their pros and cons. After confirming that all conditioning variables are balanced between clinic users and non-users, we compute the average treatment effect on the treated (ATT):

$$ATT = E\{Y(1) - Y(0) | P_{pc} = 1\} = E\{Y(1) | P_{pc} = 1\} - E\{Y(0) | P_{pc} = 1\} \quad (1)$$

where $Y(1)$ and $Y(0)$ denote the outcomes for the participants and non-participants of plant clinics, respectively; P_{pc} represents participating in plant clinics; and $E\{\ \}$is the expected value operator. The ATT is estimated in the region of common support between clinic users and non-users, and it tells us how plant clinics affect the outcomes of interest for participating households.

The PSM results rely on the conditional independence or unconfoundedness assumption, which states that conditional on observable variables, potential outcomes are independent of treatment assignment (Imbens, 2004). We use the Rosenbaum bounds test (Rosenbaum, 2002) to check the sensitivity of our ATT estimates against the violation of this assumption.

3. Results and discussion

3.1. Descriptive results

Table 2 presents the summary statistics of our outcome variables. It shows that in attempts to combat FAW, the farmers in our sample sprayed pesticides two and three times during the course of a cropping season in Rwanda and Zambia, respectively. We observe that in both countries, plant clinic users spent less on pesticides per unit of land area compared to non-users, with a statistically significant difference in the case of Zambia. We also see discernible differences in the amount spent on pesticide across the two countries. The per hectare pesticide expenditure incurred by Rwandan farmers is about 5 to 6 times that reported by their counterparts in Zambia. Besides differences in the type and cost of pesticides, the small farm size and the relatively higher number of

[3] A list of the restricted and banned pesticides can be found at plantwise.org/pesticide-restrictions/. Accessed on 10 April 2020.

[4] The questions on the pesticide-related health symptoms can be found in Appendix B.

Table 2
Descriptive statistics for outcome variables.

Variable	Rwanda		Zambia	
	Clinic users (n = 260)	Non-users (n = 309)	Clinic users (n = 325)	Non-users (n = 180)
No. of pesticide sprays per season	3.13	2.94	1.82*	2.07
Pesticide cost (USD/ha)	20.58	23.71	3.29**	4.84
Used banned or restricted pesticide (%)	5.00	8.09	5.23	5.56
No. of FAW management practices used	2.78***	2.14	3.72**	3.31
Used at least one PPE item (%)	75.00***	56.96	88.92	86.11
Number of items of PPE used	1.53***	0.85	2.59	2.36
Experienced pesticide symptoms (%)	21.15	21.36	23.08	20.56
No. of acute pesticide symptoms	0.45	0.39	0.54	0.55

Note: n = number of households that used pesticides for FAW control. ***, ** and * denote that the mean values for plant clinic users are significantly different from non-users at the 1%, 5% and 10% significance levels, respectively.

Table 3
Types of pesticide used for FAW control in Rwanda (%).

Trade name	Active ingredients	WHO toxicity class[a]	Clinic users (n = 260)	Non-users (n = 309)
Rocket	Profenofos + Cypermethrin	II	94.23***	86.41
Sumicombi	Fenitrothion + Fenvalerate	II	6.15***	13.27
Dithane M45	Mancozeb[c]	U	8.08	7.44
Thiodan[b]	Endosulfan	II	5.00	7.12
Ridomil	Metalaxyl-M[c]	II	3.08	3.24
Cypermetrin	Cypermethrin	II	3.46	0.32
Benlate[b]	Benomyl[c]	U	0.00	0.97
Pyrethrum	Pyrethrins	II	0.77	0.32

Note: *** denote that the mean difference between clinic users and non-users is statistically significant at the 1% level.
[a] II = moderately hazardous; U = unlikely to present acute hazard in normal use.
[b] These are banned or restricted pesticides. [c]These are fungicides; the rest are insecticides.

sprays per season in Rwanda may explain the huge disparity in the per hectare pesticide expenditures between the two countries.

Tables 3 and 4 list the trade names and active ingredients of the pesticides used by clinic users and non-users for FAW control in the study countries. We find that the sample farmers used a wide range of pesticides, particularly in Zambia. Cypermethrin-based insecticides were commonly used for FAW control in both countries. The most popular pesticide used in Rwanda is rocket (profenofos + cypermethrin). Only a paltry 1% of the farmers in Rwanda used biopesticide (pyrethrins). In contrast, the most widely used pesticide in Zambia is nimbecidine (azadirachtin), which is a biopesticide. GS-omega/kappa-Hxtx-Hv1a is another biopesticide used in Zambia. Biopesticides are safer, low-toxicity products; hence, there have been calls to promote their usage for FAW control (Bateman et al., 2018). Based on the World Health Organization (WHO) classification of pesticides (WHO, 2010), the majority of the pesticides used fall under class II (moderately hazardous). Due to lack of training on safe pesticide handling practices, the Food and Agriculture Organization of the United Nations (FAO) recommends the avoidance of pesticides classified as Ia, Ib and, preferably,

Table 4
Types of pesticide used for FAW control in Zambia (%).

Trade name	Active ingredients	WHO toxicity class[a]	Clinic users (n = 325)	Non-users (n = 180)
Nimbecidine	Azadirachtin	N	45.23	38.33
Cypermethrin or Cyrux	Cypermethrin	II	34.15	33.33
Karate, Judo or Boxer	Lambda-cyhalothrin	II	9.23	11.11
Abamectin	Abamectin	II	6.46	5.56
Phoskil[b]	Monocrotophos	Ib	4.92	3.33
Rocket, Agro-Cypro or Supa profenofos	Profenofos + Cypermethrin	II	4.31	1.67
Rogor	Dimethoate	II	2.46	1.67
Cyclone	Chlorpyrifos + Cypermethrin	II	2.15	2.22
Striker	Lambda-cyhalothrin + Thiamethoxam	III	2.46	1.11
Bravo	Chlorothalonil	U	1.54	1.67
Benzo	Emamectin Benzoate	N	0.92	2.78
Spear	GS-omega/kappa-Hxtx-Hv1a	N	0.92	2.22
Snow Cron	Profenofos	II	1.23	1.11
Alpha Gold	Alpha-cypermethrin	II	0.92	1.11
Belt	Flubendiamide	N	1.23	0.56
Atrazine	Atrazine[c]	III	0.31	1.67
Ampligo	Chlorantraniliprole + Lambda-cyhalothrin	II	1.23	0.00
Dichlorvos[b]	Dichlorvos	Ib	0.31*	1.67
Denim Fit	Emamectin Benzoate	N	0.62	0.56
Malathion	Malathion	III	0.62	0.56
Methamidophos[b]	Methamidophos	Ib	0.00	0.01

Note: * denote that the mean difference between clinic users and non-users is significant at the 10% level.
[a] Ib = highly hazardous; II = moderately hazardous; III = slightly hazardous; U = unlikely to present acute hazard in normal use; and N = not classified.
[b] These are banned or restricted pesticides.
[c] These is a herbicide; the rest are insecticides.

II by farmers in developing countries (FAO, 2020b).

Most of the pesticides listed in Tables 3 and 4 have been registered or are recommended for use against FAW in the study countries. However, there are a few exceptions. For example, some of the Rwandan farmers used endosulfan and benomyl, which are restricted pesticides. Similarly, a few of the farmers in Zambia used banned or highly hazardous insecticides such as monocrotophos, dichlorvos and methamidophos. Disturbingly, these banned or restricted pesticides are used by both clinic users and non-users. Table 2 indicates that about 5% each of clinic users in the two countries applied unapproved pesticides compared to 6–8% of clinic non-users. Surprisingly, we find that roughly 11% of the Rwandan farmers opted to control FAW using fungicides such as benomyl, mancozeb and metalaxyl-M, although FAW is not a fungus. Moreover, a few of the farmers in Zambia tried out atrazine, which is a herbicide. This wrong choice of pesticides is possibly driven by desperate attempts of farmers to curb the devastating effects of an unfamiliar pest, or limited knowledge and unavailability of appropriate options.

Table 2 also shows that the sample households used multiple measures to manage FAW, with a statistically significant difference between clinic users and non-users. In Rwanda, clinic users adopted about 2.78 different technologies or practices to manage FAW compared to 2.14 for non-users. The average number of FAW management methods adopted by clinic users and non-users in Zambia are 3.72 and 3.31, respectively. Thus, in both countries, plant clinic users put in place about an extra intervention to manage FAW relative to clinic non-users. The management practices used in addition to biopesticides and synthetic pesticides are presented in Table 5. This includes mechanical methods such as handpicking of egg masses and caterpillars, and rogueing of infested

Table 5
Adoption of FAW management technologies and practices (%).

FAW management practice	Rwanda	Zambia
Timely planting	11.74	34.81
Crop rotation	26.29	31.11
Intercropping	0.33	5.31
Regular weeding	0.00	41.48
Fertilization	5.94	36.20
Trap cropping	1.68	1.35
Synthetic pesticides	88.84	35.67
Biopesticides	2.40	30.93
Handpicking eggs and caterpillars	61.58	44.09
Uproot and burn infested plants	43.90	17.95
Biological control	0.00	0.49
Ash or sand	3.45	18.08
Use of detergents	0.00	10.98

plants; cultural methods such as avoiding late or staggered planting, regular weeding to remove alternative host plants such as pasture grasses, and intercropping and rotating maize with non-host crops such as cowpea and cassava; as well as local remedies, including using household detergents or placing ash and sand into maize whorls.

Results show that despite using several moderately and highly hazardous chemicals, some of the farmers did not wear any protective clothing while handling the pesticides (Table 2). This was particularly the case in Rwanda where about 35% of the farmers sprayed pesticides without wearing any PPE. Our data further show that only 5% and 12% of the pesticide applicators in Rwanda and Zambia, respectively, used the full set of PPE. Similar low use of PPE has been reported among vegetable farmers in Ghana (Ntow et al., 2006) and Ethiopia (Mengistie et al., 2017), as well as potato farmers in Uganda (Okonya and Kroschel, 2015). The farmers cited unavailability, high cost and lack of awareness of the importance of PPE as the main reasons for the limited use of suitable PPE.

Table 2 also indicates that in Rwanda, significantly more clinic users used at least one PPE item and a greater number of PPE items than clinic non-users. Results regarding the use of specific items of PPE by clinic users and non-users in the two countries are depicted in Fig. 2. First, we find that, on average, proportionally more farmers in Zambia than Rwanda used the standard PPE, which includes goggles, mask, gloves, coverall and rubber boots. This is possibly due to the supply of publicly subsidised PPE in Zambia in the wake of the FAW outbreak in 2017 (Abrahams et al., 2017). Second, in Rwanda, a significantly higher percentage of clinic participants than non-participants used each PPE item, pointing to potential positive effects of plant clinic participation. Finally, the most highly used PPE in both countries is rubber boots, which is not surprising because farmers usually wear rubber boots while performing farming activities, and thus this PPE is easily accessible compared to the others.

Given the inadequate use of appropriate protective gear, it is not startling to find that roughly 22% of the pesticide users in both Rwanda and Zambia reported having experienced symptoms of acute pesticide poisoning during or after the application of pesticides (Table 2). Table 6 presents the pesticide-related ailments reportedly experienced by the pesticide users. The most common symptoms reported include headache, sneezing, skin and eye irritations, and dizziness. With the exception of diarrhoea in Zambia, we find no statistically significant difference between the percentage of clinic users and non– users who claimed to have experienced the various pesticide-related health effects (see Table 7).

Finally, the pesticide users in our sample were asked what they did with empty pesticide containers after spraying, and their responses are summarised in Fig. 3. Our data show that only two farmers in our sample

Table 6
Percentage of pesticide users reporting pesticide-related health symptoms.

Symptom	Rwanda		Zambia	
	Clinic users (n = 260)	Non-users (n = 309)	Clinic users (n = 325)	Non-users (n = 180)
Headache	8.85	11.33	9.23	8.33
Sneezing	13.46	9.39	11.08	15.56
Nausea / vomiting	1.54	1.94	1.54	0.56
Stomach cramps	0.38	0.97	0.92	1.67
Fatigue	3.08	1.62	5.54	5.56
Skin rash/ irritation	6.92	6.80	8.92	6.67
Dizziness	3.08	1.94	4.92	6.67
Blurred vision	0.77	0.65	1.54	1.11
Diarrhoea	0.38	0.00	0.00*	1.11
Eye irritation	5.77	3.56	6.46	5.00
Excessive sweating	0.38	0.32	3.69	1.67

Note: * denote that the mean difference between clinic users and non-users is significant at the 10% level.

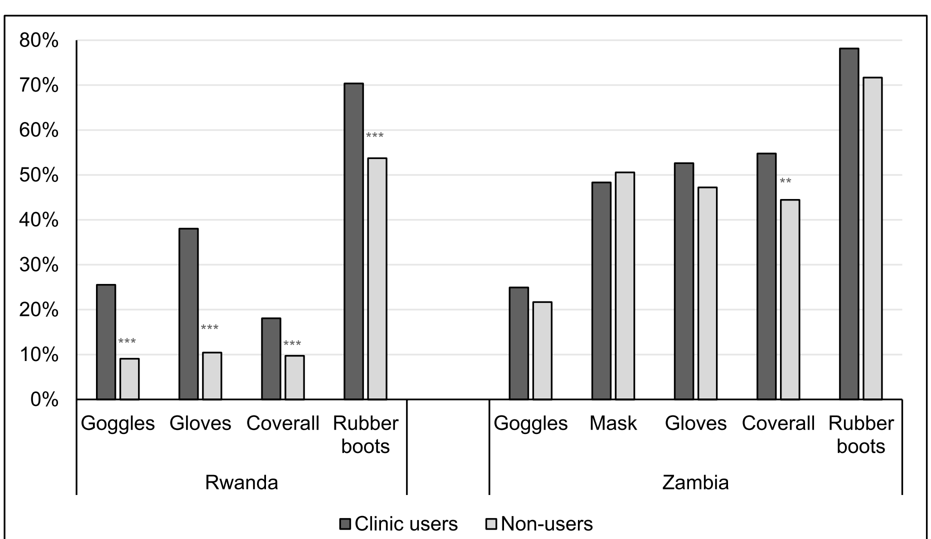

Fig. 2. Percentage of clinic users and non-users who used PPE while handling pesticides Note: ** and *** denote that the mean values for clinic users are significantly different from non-users at the 5% and 1% significance levels, respectively.

Table 7
Factors determining plant clinic participation.

	Rwanda		Zambia	
	Marginal effect	Standard error	Marginal effect	Standard error
Age	0.001	0.001	−0.001	0.001
Gender	−0.059	0.044	0.134***	0.039
Education	0.012**	0.006	−0.003	0.006
Household size	−0.007	0.010	−0.007	0.006
Dependency ratio	0.014	0.019	0.027*	0.015
Farm size	0.032*	0.017	0.005	0.007
Livestock holding	0.014	0.022	0.009**	0.004
Asset index	0.024	0.015	0.000	0.013
Farmer group	0.044	0.039	0.070	0.051
Credit access	0.050	0.036	−0.002	0.042
Risk preference	0.017*	0.010	0.009	0.006
Distance to agro-dealer	0.032***	0.010	0.003**	0.001
Distance to extension	0.023**	0.009	−0.001	0.002
Western Province	0.588***	0.044		
Southern Province	0.017	0.040		
AEZ IIa			0.199***	0.049
AEZ III			0.229***	0.049
No. of observations	637		837	

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

(from Zambia) were practicing the disposal method of triple-rinsing and puncturing of empty containers. The mostly widely used disposal method in both countries, particularly in Zambia, is to throw the containers into pit latrines. Other common methods include dumping on the farm and burning in Rwanda, and burning and burying in Zambia. This may be explained by reports showing that in several developing countries, national authorities and extension workers tend to recommend burning or burying of empty pesticide containers, partly due to the absence of local container collection systems (Dougoud et al., 2018; FAO, 2020b). More worrying is the finding that a small percentage of both clinic users and non-users in Rwanda re-used pesticide containers for household purposes, including storing condiments, which can result in acute and chronic health effects as empty containers may have residues of harmful chemicals.

Such unsafe pesticide container disposal methods have been reported in the literature (e.g., Macharia et al., 2013; Dougoud et al., 2018). Most of these improper disposal practices pose a risk to human health, animals and the environment. For instance, burying or discarding into pit latrines can contaminate soils and groundwater. Burning of empty containers can release toxic fumes; thereby, putting the health of the population at risk. There is also the threat of pesticide poisoning, particularly for children and livestock when pesticide containers are dumped on the farm, given that most of the sample farmers cultivate near the homestead. Fig. 3 shows that both clinic users and non-users are equally guilty in using inappropriate methods to get rid of empty pesticide containers. Besides the lack of proper pesticide waste disposal mechanisms, it is possible that the plant doctors' recommendations on pesticide use are not complemented with information on proper discarding of pesticide wastes, or the farmers do not follow the advice regarding the disposal of pesticide wastes.

3.2. Econometric results

3.2.1. Determinants of plant clinic participation

Table 3 presents the results for the logit model of the probability of plant clinic participation, which is the first-stage of the PSM estimator. We observe heterogeneity in the factors determining participation in plant clinics across the two study countries. The results show that gender exerts a significant effect on plant clinic participation, but only in Zambia. Specifically, male-headed households in Zambia are 13 percentage point more likely to attend plant clinic sessions than female-headed households, reflecting gender bias in access to agricultural extension services (Quisumbing et al., 2019).

We find that higher level of education is positively and significantly associated with participation in plant clinics in Rwanda. This is plausible, because educated farmers tend to have better access to information and are also able to decode agricultural information more quickly and effectively (Foster and Rosenzweig, 2010). Livestock holding (a

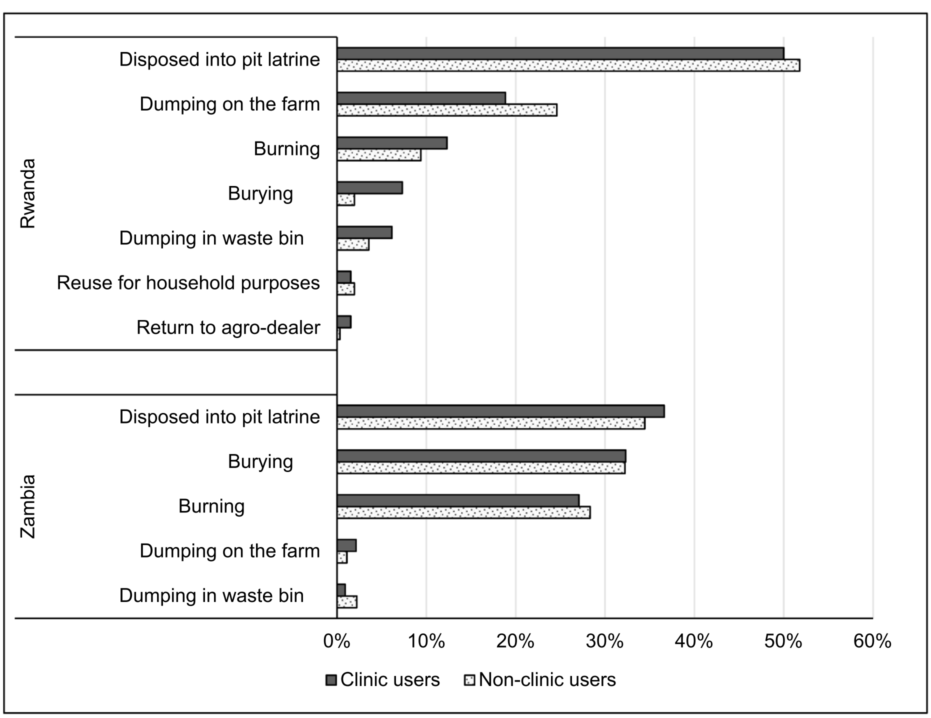

Fig. 3. Disposal mechanisms for empty pesticide containers.

Table 8
Kernel matching estimates of the impacts of plant clinics.

Outcome	Rwanda				Zambia			
	ATT	SE	ATT in %	Γ	ATT	SE	ATT in %	Γ
Use of pesticides	0.12***	0.03	14	5.6–5.7	0.29***	0.04	66.28	5.5–5.6
Pesticide cost (USD/ha)	−1.06	4.79	−4.66		−0.69	1.13	−17.28	
No. of pesticide sprays per season	0.17	0.19	5.72		−0.20	0.21	−9.82	
No. of FAW mgt. practices used	0.43***	0.11	19.20	1.6–1.7	0.48**	0.19	14.99	1.2–1.3
Use of banned/restricted pesticide	−0.03	0.02	−42.59		0.01	0.03	18.26	
Used at least one PPE item	0.15***	0.05	24.95	1.6–1.7	0.03	0.04	4.02	
No. of items of PPE used	0.49***	0.11	51.61	1.9–2.0	0.33*	0.18	14.35	1.3–1.4
Experienced health symptoms	0.01	0.04	4.58		0.01	0.05	2.22	
No. of acute pesticide symptoms	0.07	0.09	23.46		−0.02	0.16	−3.24	

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Γ = Critical level of hidden bias.

proxy for household wealth) has a significant positive effect on clinic participation in Zambia, corroborating the findings of Läpple et al. (2013) that farmers with large livestock units are more likely to participate in agricultural extension programmes.

The results also indicate that households in close proximity to agro-input shops and extension offices have a lower probability of seeking plant health advice from plant clinics. This is unsurprising given that agro-dealers and extension workers are important traditional sources of agricultural information for many farm households in SSA (Sones et al., 2015). This finding suggests that plant clinic services are more likely to be used by farm households who have limited access to alternative sources of agricultural advisory services. Finally, the province and AEZ dummies are statistically significant, indicating within-country spatial heterogeneity in plant clinic participation.

3.2.2. Impacts of plant clinic participation

We now present the PSM results regarding the effects of plant clinic participation on pesticide use practices after correcting for selection bias due to observable differences between clinic users and non– users. Before turning to the ATT estimates, we first examine the results for the tests of matching quality, including whether or not the common support and covariate balancing conditions are fulfilled. Figs. A1 and A2 in the appendix show that there are substantial overlaps in the propensity score distributions for clinic users and non-users after matching, confirming that the common condition is well satisfied. Tables A3 and A4 in the appendix present the test of mean differences in all conditioning variables between clinic users and non-users before and after matching. The results demonstrate that unlike the unmatched sample, there are no statistically significant differences in covariates between the clinic users and non-users after matching, suggesting that the matching procedure was successful in reducing differences in characteristics between the clinic users and non-users. Moreover, the lower parts of Tables A3 and A4 in the appendix indicate low pseudo-R^2, reduced mean bias and insignificant log-likelihood values after matching, which all confirm that our matched sample is well balanced with respect to the covariates included in the PSM model (Caliendo and Kopeinig, 2008).

Table 8 displays the treatment effects of plant clinics, based on kernel matching routine.[5] We find that in both countries, participation in plant clinics is significantly associated with a higher likelihood of using pesticides, corroborating findings of previous studies (e.g., Tambo et al., 2020b). In particular, plant clinic users are 14 and 29 percentage points (or 17% and 66%) more likely to spray pesticides for FAW control relative to matched non-users in Rwanda in Zambia, respectively. Farmers tend to visit plant clinics when their crops are highly infested; hence, plant doctors may be likely to recommend pesticide usage among any array of control options. As mentioned earlier, pesticide per se is not necessarily bad if it is used judiciously in combination with other pest management options. After matching on observable covariates, we find no statistically significant differences between clinic users and non-users in terms of per hectare expenditure on pesticide and the number of pesticide applications during the cropping cycle in the two countries. This suggests that despite having a higher tendency to opt for chemical control, clinic participants do not overuse pesticides compared to non-clinic participants. This is a positive finding given that overuse of pesticides poses health and environmental risks.

Table 8 also shows that clinic users have a significantly higher probability of adopting multiple FAW management practices than clinic non-users. In other words, clinic users are more likely to use other pest management techniques besides pesticides. The ATT estimates indicate that clinic users in Zambia and Rwanda respectively adopt nearly 15% and 20% more FAW management interventions than their matched non-clinic user counterparts. This is expected because plant doctors are trained to make IPM-based recommendations to their clients. The ATT results reported in Table A5 in the appendix indicate that the FAW management practices that are significantly associated with participation in plant clinics include the use of synthetic pesticides and bio-pesticides, as well as the handpicking of eggs and larvae.

We find heterogenous results across the two countries with respect to the use of PPE. In Rwanda, using plant clinic services leads to a significantly higher likelihood of using at least one item of PPE and a significantly greater likelihood of using multiple items of PPE (25% and 52% higher, respectively). Conversely, we find no significant difference between clinic users and non-users in Zambia when it comes to whether or not to use PPE while working with pesticides. This is consistent with the recent findings of Goeb et al. (2020), who also found no effect of agricultural extension (farmer training) on the demand for PPE in Zambia. Perhaps this is due to differences in the availability and affordability of PPE, given that the Zambian government offered subsidised PPE to farmers in the early years following the FAW outbreak (Abrahams et al., 2017).[6] It could also be that plant doctors in Rwanda are more likely than those in Zambia to inform farmers about PPE, but this will require further investigation.

Similar to the descriptive results presented earlier, we find no significant difference between clinic users and non-users in terms of the use of banned or restricted pesticides even after controlling for a number of observable differences between the two groups (Table 8). Thus, both clinic users and non-users have similar likelihoods of using prohibited and more harmful pesticides. Finally, we find no significant health benefits in terms of reductions in the incidence of acute pesticide-related illnesses from participating in plant clinics. This is possibly because both clinic and non-clinic participants generally use similar types of

[5] Note that given the above results indicating that almost all farmers in our sample used improper methods to disposed of empty pesticide containers, we do not estimate the treatment effects of plant clinics on safe disposal of pesticide wastes.

[6] In fact, our data show that 97% of the pesticide users in Rwanda (compared to 83% in Zambia) mentioned either unavailability or high cost as the main barrier to the use of PPE.

pesticides.

3.2.3. Robustness checks

As mentioned earlier, the robustness of our ATT estimates was examined using two alternative matching procedures: nearest neighbour (NN) matching and radius matching with a calliper of 0.05. Tables A6 and A7 in the appendix display the estimation results for these two matching routines. In general, we find consistent results in terms of the signs and statistical significances of the estimated ATTs across the three matching methods. We however observe slight differences in the magnitudes of the ATT estimates. For instance, participation in plant clinics significantly increases the use of pesticide (the use of multiple FAW management practices) in Rwanda by 17% (19%), 21% (11%), and 17% (20%) based on kernel, radius and NN matching routines, respectively. Another noticeable difference is the statistical significance (albeit weakly) of the estimated ATT on pesticide cost in Rwanda in only the case of NN matching. This result indicates that expenditure on pesticide per hectare is 38% less for clinic users compared to non-users. Overall, the results from these two algorithms are fairly similar to those of the kernel matching, suggesting that our impact estimates are robust to the matching routine employed.

As also noted earlier, PSM relies on a selection-on-observables or unconfoundedness assumption, and thus our results would be biased if there are unobserved differences (hidden bias) between clinic users and non-users that affect our outcome variables. We check the sensitivity of the estimated ATTs to hidden bias by computing the Rosenbaum bounds (critical gamma levels, Γ), which measure how large the difference in unobserved characteristics that influence the decision to use plant clinic services would have to be in order to affect the ATT estimates. For example, the Γ values of 5.60–5.70 and 5.50–5.60 in Table 8 indicate that the significant effect of plant clinic participation on the use of pesticides would be questionable only if farm households with the same conditioning factors differ in their odds of participating in plant clinics by a factor of 460–470% and 450–460% in Rwanda and Zambia, respectively. Overall, the Γ values for the significant ATT estimates in Table 8 as well as in Tables A6 and A7 in the appendix suggest that the estimated significant effects of plant clinics are fairly insensitive to hidden bias.

We also carried out robustness checks by including an additional variable (receipt of subsidised inputs) in the first-stage logit model to generate the propensity scores. Recent evidence has shown that participation in input subsidy programmes affects farmers' adoption of sustainable intensification practices (e.g., Morgan et al., 2019), including some of the FAW management practices identified in our study.[7] Note that we did not control for this variable in our primary model because participation in plant clinics is likely to influence the demand for subsidised inputs, and this can bias the treatment effect estimates (Caliendo and Kopeinig, 2008; Garrido et al., 2014). The ATT results in Table A8 in the appendix show that our primary results on the impacts of plant clinics remain qualitatively unchanged even after the inclusion of the potentially endogenous input subsidy variable.[8]

4. Conclusion and policy implications

The increasing incidence and devastating effects of crop pests, such as the invasive fall armyworm (FAW), has spurred increased use of pesticides among smallholder farmers in sub-Saharan Africa. Pesticides can provide rapid means of controlling pests and prevent crop losses, but they can also pose a major risk to humans, animals and the environment, if not used judiciously. In this article, we investigated whether plant clinics, which provide plant health diagnostic and advisory services to smallholder farmers, can enhance judicious use of pesticides, in terms of reduced use of highly toxic or banned pesticides, adoption of alternative and environmentally friendly pest management practices, proper disposal of pesticide wastes, use of personal protective equipment (PPE), and the implications for incidence of pesticide-related ill-health. We applied descriptive and propensity score methods to survey data from representative samples of clinic users and non-users in Rwanda and Zambia.

Our analysis showed that although plant clinic participants exhibit a higher probability of opting for pesticides for FAW control, they do not overuse pesticides in terms of frequency of application and per hectare pesticide expenditure relative to non-clinic participants. Moreover, clinic users are more likely than non-users to use pesticides in combination with other non-chemical methods of pest control, including cultural and physical methods such as crop rotation and handpicking of egg masses and larvae. In particular, our treatment effect estimates indicated that clinic users adopt significantly more FAW management options than their matched non-clinic user counterparts (15% and 20% more in Zambia and Rwanda, respectively).

A wide range of (mostly moderately hazardous) pesticides are used by both clinic users and non-users. The pesticides have been registered for use against FAW in the two countries, but we found some exceptions, including the use of restricted, banned or highly hazardous insecticides like endosulfan in Rwanda, and monocrotophos and dichlorvos in Zambia. In addition, we observed a few cases of misuse of pesticides, with respect to the application of the wrong pesticide group against FAW (i.e., fungicide and herbicide instead of insecticide). We also found inadequate use of PPE and, consequently, reports of acute pesticide health symptoms such as eye and skin irritations, dizziness, headache, and sneezing. On average, plant clinic users are significantly more likely than non-users to wear protective clothing while working with pesticides. Finally, we found evidence that a large percentage of both clinic users and non-users in Rwanda and Zambia have been using inappropriate methods to discard empty pesticide containers, which can lead to pesticide poisoning as well as soil and groundwater contamination. These results are consistent across different matching methods, and a sensitivity analysis shows that our impact estimates are robust to unobserved heterogeneity.

Several important policy implications can be drawn from our results. The finding that plant clinic participants are significantly more likely to use multiple pest management strategies concurrently suggests that scaling the plant clinic extension approach would be important in efforts to promote IPM adoption, and by extension, sustainable pest management in smallholder agriculture. Although only a small percentage of clinic participants used banned, restricted or wrong pesticides, this is still a cause for concern, because the plant doctors from whom the clinic users seek advice have been trained not to recommend pesticides that are unregistered or subject to international restrictions. This implies that further trainings are needed to upgrade plant doctors and farmers' knowledge about pesticides and their associated risks. In addition, partnerships between plant doctors and agro-dealers could be established to enhance farmers' access to the recommended pesticides. Moreover, national authorities need to enforce pesticide regulations to curb the supply of unregistered or banned pesticides. Government subsidies for pesticides should be geared towards low-toxicity products such as biopesticides, as well as protective gear, as unavailability and unaffordability were identified as the main obstacles to the use of PPE. Finally, plant doctors, agricultural extension workers and agro-dealers' knowledge about safe disposal of pesticide wastes need to be greatly improved so that they can in turn advise farmers to, at least as a minimum requirement, triple-rinse and puncture or crush empty pesticide containers in order to prevent pesticide poisoning and environmental pollution.

Our study has some limitations. First, we used cross-sectional data and PSM design, which only controls for selection bias due to observable characteristics. While sensitivity analyses suggest that our impact estimates are robust to hidden bias, further research using data collected in

[7] We thank an anonymous reviewer for this insight.

[8] Results for the matching quality tests are also similar to the primary model.

panel or experimental designs would be helpful to properly account for unobserved heterogeneity and confirm our findings. Second, the treatment effects are likely to be heterogeneous across plant clinics, but this was not considered in this study as we used a binary treatment effect approach. For instance, the effects may differ according to plant clinic density and the number and quality of plant doctors. Third, due to data limitations, this study did not examine other important aspects of judicious use of pesticides, such as the dosage of the specific pesticides used, timing of application, and the compliance with re-entry and pre-harvest intervals. Finally, we focused only on FAW pest on maize. Future studies involving other crops requiring high pesticide use (e.g., vegetables) will add to our understanding of the role of plant clinics in the judicious use of pesticides.

CRediT authorship contribution statement

Justice A. Tambo: Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization, Supervision. **Dannie Romney:** Writing - review & editing, Funding acquisition, Project administration. **Idah Mugambi:** Data curation, Software, Writing - review & editing. **Fredrick Mbugua:** Data curation, Software, Writing - review & editing. **Mary Bundi:** Data curation, Investigation. **Bellancile Uzayisenga:** Data curation, Investigation. **Mathews Matimelo:** Data curation, Investigation. **Mathias Ndhlovu:** Data curation, Investigation.

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Appendix A

(See. Figs. A1-A2**).**
(See. Table A1-A8**).**

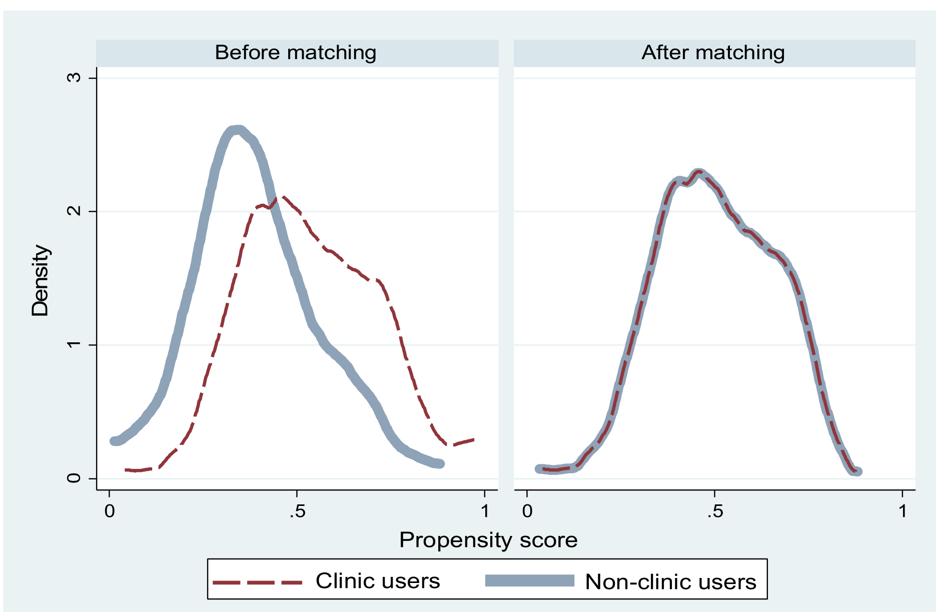

Fig. A1. Propensity score distribution showing overlap and balancing between plant clinic users and non-users in Rwanda.

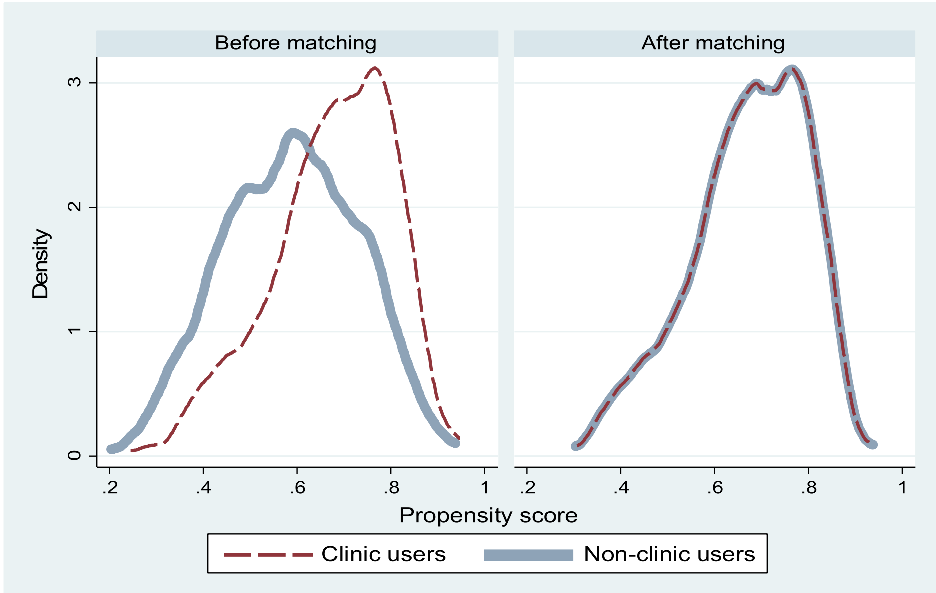

Fig. A2. Propensity score distribution showing overlap and balancing between plant clinic users and non-users in Zambia.

Table A1
Summary statistics for main variables used in selecting households in Rwanda.

Selection variable	Percentage of households	
	Clinic users (n = 263)	Non-users (n = 374)
Main crops grown		
Maize	100	100
Common bean	90.35	93.12
Sweet potato	60.23	63.49
Potato	36.29	41.01
Cassava	35.52	33.86
Agro-ecological zone		
The Cone and High Volcanic Plain	34.23	28.65
Bubereka Highlands	20.00	23.70
Congo Nile Watershed Divide	9.62	10.94
Central Plateau	36.15	36.72
Pest problem		
Experienced fall armyworm attack on maize crops during the 2017–2018 cropping season	100	99.47

Table A2
Summary statistics for main variables used in selecting households in Zambia.

Selection variable	Percentage of households	
	Clinic users (n = 444)	Non-users (n = 393)
Main crops grown		
Maize	100	100
Peanut	74.55	69.47
Common bean	27.25	32.57
Sweet potato	29.50	26.46
Soybean	25.68	22.14
Agro-ecological zone		
I	17.39	22.90
IIa	45.50	41.22
III	37.11	35.88
Pest problem		
Experienced fall armyworm attack on maize crops during the 2018–2019 cropping season	100	100

Table A3
Matching quality tests for Rwanda.

	Before matching			After matching		
	Clinic users	Non-users	*t*-test	Clinic users	Non-users	*t*-test
Age	49.87	48.55	1.22	50.20	51.05	−0.65
Gender	0.78	0.78	−0.18	0.76	0.75	0.29
Education	5.72	4.66	3.92***	5.46	5.31	0.43
Household size	5.23	5.20	0.23	5.22	5.25	−0.14
Dependency ratio	0.97	1.01	−0.61	1.07	1.05	0.24
Farm size	0.79	0.49	2.97***	0.74	0.70	0.31
Livestock holding	0.98	0.72	2.88***	0.93	0.97	−0.46
Asset index	0.35	−0.17	4.23***	0.24	0.19	0.31
Farmer group	0.40	0.29	2.92***	0.36	0.37	−0.28
Credit access	0.63	0.53	2.43**	0.61	0.60	0.22
Risk preference	6.81	6.37	3.26***	6.65	6.65	0.04
Distance to agro-dealer	2.94	2.15	3.69***	2.62	2.45	0.62
Distance to extension	2.91	2.18	3.97***	2.76	2.66	0.42
Western Province	0.28	0.02	10.19***	0.02	0.03	−0.71
Southern Province	0.36	0.48	−2.84***	0.49	0.52	−0.52
Pseudo R^2		0.207			0.005	
Mean bias		23.9			3.6	
LR χ^2 P-value		0.000			1.000	

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

Table A4
Matching quality tests for Zambia.

	Before matching			After matching		
	Clinic users	Non-users	*t*-test	Clinic users	Non-users	*t*-test
Age	49.72	50.68	−0.81	49.84	49.32	0.52
Gender	0.76	0.63	2.96***	0.76	0.78	−0.75
Education	7.98	8.37	−1.23	8.07	8.35	−1.13
Household size	7.26	7.78	−1.65*	7.30	7.32	−0.08
Dependency ratio	1.21	1.43	−2.05**	1.22	1.20	0.22
Farm size	3.30	2.77	2.06**	3.25	3.30	−0.20
Livestock holding	3.73	3.05	1.32	3.69	4.07	−0.81
Asset index	0.09	0.45	−2.42**	0.09	0.12	−0.22
Farmer group	0.89	0.88	0.31	0.89	0.89	0.31
Credit access	0.76	0.73	0.72	0.76	0.80	−1.14
Risk preference	6.06	5.58	1.77*	6.05	5.92	0.56
Distance to agro-dealer	16.79	14.31	1.81*	16.69	16.35	0.28
Distance to extension	10.71	9.77	0.90	10.62	10.15	0.55
AEZ IIa	0.51	0.42	2.10**	0.52	0.51	0.19
AEZ III	0.34	0.24	2.14**	0.33	0.30	0.82
Pseudo R^2		0.095			0.008	
Mean bias		14.9			4.0	
LR χ^2 P-value		0.000			0.966	

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

Table A5
Kernel matching estimates of plant clinic effects on the adoption of FAW management practices.

Outcome	Rwanda				Zambia			
	ATT	SE	ATT in %	Γ	ATT	SE	ATT in %	Γ
Timely planting	0.20	0.30	21.67		0.02	0.04	5.84	
Crop rotation	0.07*	0.04	34.22		0.02	0.03	6.72	
Intercropping	0.01	0.01	48.57		0.01	0.02	35.52	
Regular weeding					0.01	0.04	0.93	
Fertilization	0.02	0.02	24.28		0.02	0.04	4.44	
Trap cropping	0.02	0.01	20.24		−0.01	0.01	−35.20	
Synthetic pesticides	0.16***	0.03	18.92	11.5–11.6	0.18***	0.04	67.07	1.9–2.0
Biopesticides	0.01	0.02	18.39		0.16***	0.03	68.32	1.4–1.5
Handpicking eggs and caterpillars	0.15***	0.05	28.40	1.2–1.3	0.09**	0.04	23.79	2.3–2.4
Uproot and burn infested plants	0.02	0.05	3.94		−0.02	0.03	−11.17	
Biological control					−0.01	0.01	−39.74	
Ash or sand	−0.01	0.02	–23.65		−0.01	0.03	−5.97	
Use of detergents					0.02	0.02	26.05	

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Γ = Critical level of hidden bias.

Table A6
Nearest neighbour matching estimates of the impacts of plant clinics.

Outcome	Rwanda				Zambia			
	ATT	SE	ATT in %	Γ	ATT	SE	ATT in %	Γ
Use of pesticides	0.17***	0.04	20.87	4.4–4.5	0.27	0.05	59.51	2.6–2.7
Pesticide cost (USD/ha)	−13.71*	7.42	−38.82	1.2–1.3	−0.83	1.62	−19.94	
No. of pesticide sprays per season	0.33	0.26	12.02		−0.60	0.30	−3.15	
No. of FAW mgt. practices used	0.27*	0.14	11.11	1.2–1.3	0.40*	0.24	11.98	1.1–1.2
Use of banned/restricted pesticide	−0.01	0.03	−22.15		0.00	0.05	0.05	
Used at least one PPE item	0.22***	0.06	42.43	1.4–1.5	−0.02	0.04	−2.07	
No. of items of PPE used	0.59***	0.15	71.07	2.1–2.2	0.25	0.21	10.80	
Experienced health symptoms	0.04	0.05	24.12		0.05	0.05	25.01	
No. of acute pesticide symptoms	0.09	0.12	32.71		0.09	0.19	20.42	

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Γ = Critical level of hidden bias.

Table A7
Radius matching estimates of the impacts of plant clinics.

Outcome	Rwanda				Zambia			
	ATT	SE	ATT in %	Γ	ATT	SE	ATT in %	Γ
Use of pesticides	0.14***	0.03	16.97	5.6–5.7	0.29***	0.04	66.47	5.7–5.8
Pesticide cost (USD/ha)	−1.09	4.80	−4.80		−0.72	1.13	−17.87	
No. of pesticide sprays per season	0.17	0.19	5.83		−0.20	0.20	−9.99	
No. of FAW mgt. practices used	0.44***	0.11	19.49	1.7–1.8	0.49***	0.19	15.13	1.2–1.3
Use of banned/restricted pesticide	−0.03	0.02	−42.98		0.01	0.03	17.48	
Used at least one PPE item	0.15***	0.05	24.83	1.6–1.7	0.04	0.04	4.14	
No. of items of PPE used	0.49***	0.11	51.38	1.9–2.0	0.32*	0.18	14.22	1.2–1.3
Experienced health symptoms	0.01	0.04	4.63		0.01	0.05	3.17	
No. of acute pesticide symptoms	0.07	0.09	23.22		−0.01	0.15	−1.43	

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Γ = Critical level of hidden bias.

Table A8
Kernel matching estimates of the impacts of plant clinics (with controls for input subsidies).

Outcome	Rwanda				Zambia			
	ATT	SE	ATT in %	Γ	ATT	SE	ATT in %	Γ
Use of pesticides	0.12***	0.03	14.36	17.0–17.1	0.29***	0.04	65.01	5.6–5.7
Amount spent on pesticides	−0.83	4.78	−3.73		−0.65	1.13	−16.47	
No. of pesticide sprays per season	0.19	0.19	6.51		−0.20	0.20	−9.93	
No. of FAW mgt. practices used	0.36***	0.11	16.51	1.5–1.6	0.50***	0.19	15.70	1.2–1.3
Use of banned/restricted pesticides	−0.03	0.02	−43.13		0.01	0.03	19.24	
Used at least one PPE item	0.15***	0.05	25.52	1.0–1.1	0.03	0.04	3.94	
No. of items of PPE used	0.51***	0.11	53.95	1.9–2.0	0.33*	0.18	14.47	1.3–1.4
Experienced health symptoms	0.01	0.04	3.53		0.01	0.05	1.55	
Number of health symptoms	0.07	0.09	22.76		−0.02	0.15	−2.77	

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Γ = Critical level of hidden bias.

Appendix B:. Question on pesticide-related illness.

In the past cropping season, did you or a household member or a farm worker experience any of the following health symptoms during or after the application of pesticides?

Symptoms	**1 = Yes 0 = No**
Headache	
Sneezing	
Nausea/vomiting	
Stomach cramps	
Fatigue	
Skin rash/irritation	
Dizziness /feeling faint	
Blurred vision	
Diarrhoea	
Eye irritation	
Excessive sweating	
Other (please specify).	

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