Received: 15 February 2022 | Revised: 7 July 2022 | Accepted: 23 July 2022

DOI: 10.1002/fes3.414

ORIGINAL ARTICLE

Food and Energy Security Open Access WILEY

Sustainable management of fall armyworm in smallholder farming: The role of a multi-channel information campaign in Rwanda

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Funding information
International Fund for Agricultural Development (IFAD); Ministry of Agriculture of the People's Republic of China; Irish Aid; Australian Centre for International Agricultural Research (ACIAR); Swiss Agency for Development and Cooperation (SDC); the European Commission (DG DEVCO); Directorate-General for International Cooperation (DGIS); Foreign, Commonwealth & Development Office (FCDO); CABI-led Plantwise programme

Abstract

In recent years, fall armyworm (FAW), *Spodoptera frugiperda,* has emerged as one of the most serious invasive species in many countries across Africa, Asia and Oceania. The pest is causing extensive damage to maize production and the intensification of pesticide use. In this paper, we examined the effectiveness of three mass-extension channels (plant health rallies, radio drama and SMS) in enhancing farmers' knowledge and management of FAW and in increasing maize productivity. Applying matching techniques to data from 720 smallholder farmers and 1077 maize plots in Eastern Rwanda, we found that exposure to the information channels is significantly associated with increased knowledge outcomes, including knowledge of the correct identification of FAW and the use of cultural practices as the first resort to pest management. Moreover, the information channels showed positive effects on the adoption of environmentally friendly management practices. Generally, the treatment effects are larger for households exposed to multiple (especially all) channels, indicating complementary effects of the channels. We also found suggestive evidence that the information channels are associated with maize yield increases ranging from 10% to 34%, depending on the channel. Overall, the results imply that multi-channel information campaigns can be effective in enhancing farmers' knowledge on how to identify and sustainably manage the FAW pest. Our findings also suggest that while there is a growing popularity in the use of digital extension approaches to deliver timely information to farmers in a cost-effective manner, much greater gains can be achieved if they are combined with other low-cost face-to-face extension methods, such as plant health rallies.

KEYWORDS

agricultural extension, fall armyworm, ICT, integrated pest management, Rwanda

1 | INTRODUCTION

Invasive alien species continue to cause great economic losses and pose a significant threat to global food security, human health and biodiversity. In Africa, for instance, the annual cost of invasive species to agriculture (due to production losses and costs of control) is estimated to be USD 65.58 billion (Eschen et al., 2021). One of the most damaging invasive species to have emerged in Africa in recent years is fall armyworm (FAW), *Spodoptera frugiperda*. Originating from the Americas, FAW was first detected in Central and West Africa in 2016 (Goergen et al., 2016) and has since spread rapidly to over 80 countries across Africa, Asia and Oceania (CABI, 2021). The pest is causing severe damage to maize crops, resulting in economic losses, worsened food security and intensive pesticide usage among smallholder maize farmers (Botha et al., 2020; Tambo et al., 2021; Yang et al., 2021). A study by Rwomushana et al. (2018) has shown that if not well managed, the FAW pest has the potential to cause annual maize production losses of up to 17.70 million tonnes (equivalent to USD 4.66 billion) in 12 maize-producing African countries alone.

In Rwanda, the FAW pest was first reported in Nyamagabe district in February 2017, and within 2 months, its presence was recorded in all of the country's 30 districts (Uzayisenga et al., 2018, 2020). As in most African countries, the initial reaction of the Rwandan government was to procure and distribute pesticides to farmers. Community actions against FAW were also initiated, and even the country's army was deployed to halt the spread of the pest through the distribution of pesticides and the hand-picking of FAW caterpillars on farmers' fields (Rukundo et al., 2020). Recent evidence suggests that the FAW outbreak in Rwanda has led to extensive spraying of pesticides, including the use of prohibited and wrong type of pesticides (Tambo et al., 2020; Uzayisenga et al., 2020). With limited knowledge and in desperate attempts to fight the pest, many farmers also experimented with indigenous pest control practices, such as the use of cattle urine, and mixtures of ash and hot pepper (Rukundo et al., 2020). Unfortunately, the likelihood of FAW infestation in Rwanda continues to be high because of favourable climatic conditions and the presence of a wide host range (FAO, 2020; Rukundo et al., 2020).

The outbreak of a new serious pest such as FAW tends to attract inaccurate, sensationalised or inconsistent information from various sources (CABI, 2019), but farmers and decision-makers need reliable and timely information to be able to adequately respond to the pest. For example, without accurate information, FAW can easily be mistaken for other related but less severe caterpillar pests, such as maize stalk borer (Tambo et al., 2019; Toepfer et al., 2019). This may lead to the uptake of ineffective management strategies, thereby resulting in severe yield and economic losses. To respond to this challenge, the Centre for Agriculture and Biosciences International (CABI) in partnership with the Rwanda Agriculture and Animal Resources Development Board (RAB) implemented a multi-channel information campaign in Rwanda with the aim of providing farmers with consistent and accurate information on FAW, in order to enhance knowledge of the pest and encourage the adoption of environmentally-friendly management practices. The campaign used three complementary mass-extension channels, namely plant health rallies (PHRs), radio drama (RD) and mobile short message service (SMS).

In this article, we aim to examine whether and what to extent the information campaign has contributed to improved FAW management outcomes in Eastern Rwanda. Specifically, we measure the combined and separate effects of two media-based mass extension approaches (RD and SMS) and one face-to-face approach (PHR) on outcomes related to farmer knowledge on FAW, adoption of recommended management practices and maize productivity. In doing so, we contribute to the empirical literature on FAW management in smallholder farming systems and the use of information and communication technologies (ICTs) in agricultural extension.

With the proliferation of ICTs in recent decades, ICT-enabled extension approaches are becoming increasingly important in complementing traditional in-person agricultural extension methods in developing countries (Aker, 2011; Nakasone et al., 2014; Spielman et al., 2021). Numerous studies have been undertaken to examine the impact of ICT-mediated channels, such as radio programming (Hudson et al., 2017; Ragasa et al., 2021; Rware et al., 2021); video messages (Abate et al., 2019; Areal et al., 2020; Vandevelde et al., 2021) and mobile phone-based services (Fabregas et al., 2019; Fu & Akter, 2016; Larochelle et al., 2019), with mixed results on their effectiveness. We add to a small but growing body of literature on the separate and combined effects of alternative ICT-enabled extension approaches (Dzanku et al., 2022; Tambo et al., 2019; Van Campenhout et al., 2021). Unlike these previous studies, we assess the relative effectiveness of two ICT-based extension channels versus the combination with one face-to-face channel of communication. This is important because not all ICT-based extension approaches are equally effective in improving agricultural and development outcomes (Baumüller, 2018; Fabregas et al., 2019; Spielman et al., 2021). Moreover, while ICT-based channels such as radio and SMS can be used to disseminate new information and provide reminders to a large number of farmers in a timely and cost-effective manner, they may be less effective in conveying complex information and are often limited by the lack of interactivity and visual communication, as compared with face-to-face extension approaches, such as PHRs. A multi-channel mass extension campaign, such as the one implemented in Rwanda, offers an opportunity to exploit the advantages of both ICT and in-person extension approaches and reinforce the campaign messages.

The study most related to our work is Tambo et al. (2019), who evaluated the impacts of three ICT-mediated channels (radio, SMS and video) on farmer knowledge and management of FAW in Uganda. They found that exposure to the campaign channels increased farmers' knowledge on how to identify and manage FAW and triggered behavioural changes, with some evidence of additive effects from exposure to multiple channels. Apart from testing the external validity of the findings of Tambo et al. (2019), we extend the scope of their study by examining the effects of a combination of ICT and face-to-face channels, and by going beyond knowledge and adoption outcomes to also look at productivity effects of the information channels.

2 | MATERIALS AND METHODS

2.1 | Data

The study was conducted in two major maize-growing districts of Rwanda (i.e., Bugesera and Rwamagana districts), where the three channels described above were used complementarily in the FAW information campaign (See Appendix S1 in the Supporting Information for an overview of the FAW information campaign). These two districts (located in the Eastern province of Rwanda) are predominantly rural, with higher poverty rates in Bugesera (40%) than in Rwamagana (<20%) (NISR, 2018). Small-scale agriculture is the main economic activity for households in the study districts. Most households (70% in Bugesera and 78% in Rwamagana) cultivate less than 0.9 ha of land (NISR, 2012). The important staple crops grown in the districts include maize, beans, sweet potato, cooking banana and cassava. A majority of the inhabitants also rear livestock, particularly cattle, goats and chicken.

In each district, we selected four main maize-producing sectors.[1] The selected sectors include Gashora, Juru, Mayange and Nyamata in Bugesera district and Fumbwe, Gahengeri, Gishari and Mwulire in Rwamagana district. Five villages were then selected from each sector, involving a purposive sampling of one village where a PHR has been held, and a random sampling of four villages. Within each village, 15–20 households were randomly selected to be included in the study. Overall, the sample consists of 720 households (360 per district) operating 1077 maize plots.

The data were collected in March 2021 through face-to-face interviews conducted by 20 local enumerators. The enumerators used a pre-tested tablet-based questionnaire to collect information on household composition, awareness and knowledge of FAW, exposure to FAW information channels, maize production activities, adoption of FAW management practices, access to institutional services and household asset endowment. The data covered the 2021A agricultural season of Rwanda.

2.2 | Estimation method

As previously mentioned, the goal of this study is to evaluate the impact of a FAW information campaign on outcomes related to farmers' knowledge and management of the pest, as well as maize productivity. Given that three complementary information channels were used in the campaign, there are eight possible groups of households depending on the channel(s) through which they received the FAW messages. These include (1) households that did not receive FAW information via any of the three channels, which will serve as the comparison group; and households that received FAW information through either: (2) PHR only; (3) RD only; (4) SMS only; (5) PHR + RD; (6) PHR + SMS; (7) RD + SMS or (8) PHR + RD + SMS. Thus, we can estimate the differential effects of the three campaign channels by comparing the outcomes of households in treatment groups (2) to (8) with the outcomes of the households in the comparison group (1).

However, we recognise that households in the treatment groups may differ systematically from those in the comparison group; hence, a simple comparison of average outcomes between the treatment and comparison groups may produce biased results. To reduce such bias in our impact estimates, we use the propensity score matching (PSM) estimation approach (Rosenbaum & Rubin, 1983). The PSM method involves matching the treatment and comparison groups based on observable characteristics. In the first step of the PSM approach, propensity scores are generated using a logit regression. Following Tambo et al. (2019), the covariates in the logit regression consist of important pre-treatment variables that could affect access to the information channels and the outcome variables. The covariates include household socio-demographic characteristics (such as age, gender and education of household head, household size and access to off-farm income); access to information and institutional-related variables (e.g., ownership of radio and mobile phones, proximity to extension services and agro-input dealers, access to credit, and farmer group membership); as well as a geographic location dummy. Table 1 provides a detailed description of the covariates.

The propensity scores obtained in the first step are then used to match the households in the treatment and comparison groups. The matching method used is kernel matching, with the default bandwidth of 0.06. We also used two alternative matching algorithms (nearest neighbour and radius matching) to check the robustness of our results. Readers are referred to Caliendo and Kopeinig (2008) for a detailed overview of the various matching algorithms. Finally, after confirming that there is successful balancing of the distribution of covariates between treatment and comparison groups, we estimate the average treatment effects on the treated (ATTs) in the region where the propensity score distributions of treatment and comparison groups overlap (i.e., the region of common support).

The ATTs measure how the various information channels affect the outcomes of interest for households who were exposed to the channels. This can be specified as

$$\mathrm{ATT}^{C_a|C_0} = E\left\{Y^{C_a} - Y^{C_0} | D = C_a\right\}$$
$$= E\left\{Y^{C_a} | D = C_a\right\} - E\left\{Y^{C_0} | D = C_a\right\}, D \in \{1, 2 \cdots 8\}$$

where C_a indicates exposure to an information channel, and C_0 represents non-exposure to any of the information channels.[2] Y^{C_a} and Y^{C_0} denote the outcomes for households in group C_a and C_0, respectively, and D indicates an information channel, which ranges from 1 (none of the channels) to 8 (all the three channels, i.e., PHR + RD + SMS).

An important assumption of the PSM estimator is the conditional independent assumption (CIA), meaning that the treatment and comparison groups are assumed to differ only with regards to observable characteristics (Imbens, 2004). Thus, the PSM method does not control for potential selection bias due to unobserved household characteristics. We therefore test the robustness of our impact estimates to the possibility of unobserved selection bias using the Rosenbaum bounds approach (Rosenbaum, 2002). We recognise that experimental, panel data and instrumental variables (IV) techniques are better suited for addressing possible bias stemming from unobserved heterogeneity. Unfortunately, our study is based on non-experimental cross-sectional design, and IV techniques require the identification of valid instruments, which is even more challenging in our case with several treatment groups. Hence, the results are correlations and should not be given causal interpretations.

2.3 | Outcome measures

We examined the effects of the information channels on three set of outcome variables: technical knowledge of

TABLE 1 Summary statistics on household characteristics

Variable	Description	Mean	SD
Age	Age of household head (years)	47.84	12.31
Gender	Gender of household head (1 = male)	0.83	0.37
Education	Years of schooling of household head	4.51	2.68
Household size	Number of household members	5.25	2.00
Maize area	Maize area cultivated (hectares)	0.35	0.42
Off-farm	Household engages in off-farm activities (1/0)	0.20	0.40
Credit	Household has access to credit (1/0)	0.37	0.48
Asset index	Household asset index computed using PCA	−0.01	1.58
Livestock holding	Number of livestock owned (tropical livestock unit)	0.86	1.83
Farmer group	Household is a member of a farmer group (1/0)	0.49	0.50
Radio	Household owns a radio (1/0)	0.69	0.46
Phone	Household owns a mobile phone (1/0)	0.89	0.31
Distance to extension	Distance from household to nearest extension agency (km)	2.17	2.19
Distance to agro-dealer	Distance from household to nearest agro-input shop (km)	2.40	2.21
District	Location of household (1 = Rwamagana; 0 = Bugesera)	0.50	0.50

FAW, practices adopted for the management of the pest and maize productivity. The farmers' knowledge level of FAW were assessed using five multiple-choice test questions, as shown in Appendix S2 in the Supporting Information. The first question was related to how to identify FAW. Here, the farmers were shown photosheets of three caterpillar pests (African armyworm, FAW and maize stalk borer) and were asked to indicate which of them represents FAW. These three pests can be confused with each other, as they share some common features. The distinctive features of the FAW in the photosheets included an inverted Y-shaped mark on the head and four-spots forming a square on the second-to-last body segment of a FAW larvae.

The other four knowledge questions were related to the recommended practices for FAW prevention and control. These included questions on the first resort for FAW management, maize planting practices that can prevent or reduce FAW infestation, the optimal time for scouting maize fields for FAW and the optimal time for pesticide application for improved efficacy against FAW. For each question, the surveyed farmers had to indicate the correct answer from four possible answers that were read to them. The correct answers to the five knowledge test questions were aggregated into one score (which we termed 'overall knowledge score', ranging from 0% to 100%), and this represented our main outcome of interest in terms of FAW knowledge. However, we also presented estimation results for the five individual knowledge questions, as they capture different aspects of the FAW campaign information.

One of the key messages conveyed by the information channels was on the use of a combination of multiple pest management practices to combat FAW, in line with the principles of integrated pest management (IPM). Consequently, we used the number of recommended FAW management practices adopted by a household as one of our main outcome variables. The recommended FAW management practices included (1) regular monitoring of maize fields for early detection of outbreaks of FAW; (2) cultural control methods, such as timely planting of maize; intercropping and rotation of maize with non-host crops, frequent weeding to remove alternative host plants and fertilization to promote healthy plant growth; (3) mechanical control, including destroying of severely infested plants and handpicking of egg masses and larvae and (4) chemical control, which involves the judicious use of pesticides. We also performed separate estimations for these four categories of FAW control options.

Maize yield and income were used as indicators for maize productivity. Maize yield was measured as the total quantity of maize harvested in kilogram per hectare of maize area, while maize income was computed by deducting the variable costs incurred in maize production from gross maize income.

3 | RESULTS AND DISCUSSION

3.1 | Descriptive statistics

Figure 1 reports the percentage of households exposed to the three channels used in the FAW campaign. We find that nearly 73% of the households received the FAW messages through at least one of the communication channels. Thus, roughly one-fourth of the households were not exposed to any of the campaign channels, and this group will serve as the comparison group in the ensuing analysis of the impact of the campaign. Radio drama was by far the most common channel through which majority of the farmers received the FAW campaign messages. In particular, about 27% households followed the campaign through RD only, while about 30% participated in the campaign through RD in addition to either PHR, SMS or both. This is expected, because unlike the other two channels, the radio drama covered all the communities in the study regions. This also lends additional support to arguments and evidence that radio programming is a key source of agricultural information among African smallholders because of its ubiquitousness (Hudson et al., 2017; Ragasa et al., 2021; Tambo et al., 2019). We also see that almost 33% of the households were exposed to multiple channels, compared to 40% that were exposed to only one channel. The results further show that only about 7% of households were exposed to all the three information channels.

Note that given the small percentage of households that received the FAW messages via SMS only and PHR + SMS, these two categories of campaign participants were excluded from the PSM analysis of the differential effects of the campaign channels. This is necessary to avoid problems of insufficient statistical power and poor overlap between the campaign participants and the comparison group.

Table 2 reports the summary statistics for the three categories of outcome variables, including a disaggregation by the campaign channels. Focusing first on the knowledge outcomes, a number of points can be drawn from the results. First, more than three quarters of the farmers were able to correctly identify FAW. This is noteworthy, given that correct pest identification is crucial for the application of appropriate management practices. Results indicate that less than half of the farmers responded correctly to two of the FAW knowledge questions. In particular, only 40% of farmers considered cultural methods as the first resort to FAW management, implying that a majority of them regarded pesticide

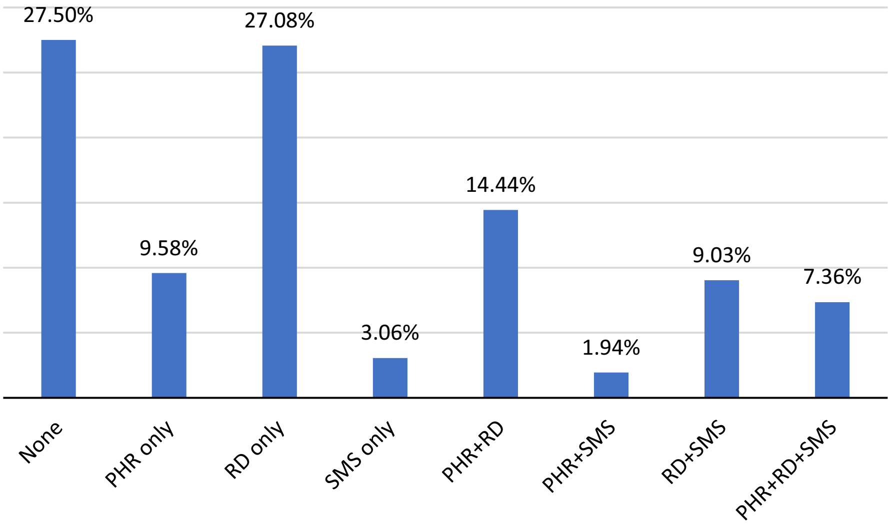

FIGURE 1 Percentage of farmers receiving FAW information via different channels.

application as necessary as soon as FAW infestation is observed. Similarly, only 35% of the farmers had correct knowledge about the time at which the spraying of pesticides is most effective against FAW. Taken together, these results may be suggestive of the need for further awareness-raising about rational use of pesticides in the study region. We find that on average, farmers who received the FAW information, irrespective of the channel, outperformed their counterparts who were not exposed to any of the campaign channels, in terms of knowledge on how to identify and manage FAW. However, the knowledge gain was significantly higher for only those exposed to multiple campaign channels, especially all three channels.

Turning to the descriptive results for the practices adopted for the management of FAW, Table 2 shows that 58% of the farmers engaged in regular monitoring, compared to 88% and 72% who adopted chemical and mechanical control methods. This means that several of the farmers applied control measures against FAW without regularly scouting their fields, which is in contrast to the principles of IPM. On the positive side, we find that proportionally more of the campaign participants than non-participants regularly monitored their maize fields for FAW infestation. Additionally, they used significantly more cultural control practices than their non-participants counterparts. Lastly, the average number of FAW management practices applied by the sample households was six, with the campaign participants adopting significantly higher number of practices relative to the non-participants.

The lower panel of Table 2 provides the descriptive statistics for the maize productivity outcome variables. The average maize yield was about 2.3 tonnes per hectare. Once again, we observe that the campaign participants achieved higher maize yield and income than their non-participant counterparts. However, it should be emphasised that Table 2 reports unconditional summary statistics and tests, which do not account for systematic differences between the treatment and comparison groups. In the next section, we will examine the results for the impact of the campaign conditional on observable confounders.

3.2 | Impact on FAW knowledge and management

The descriptive statistics in Table S1 point to some systematic differences between households that were exposed to the various campaign channels (treatment groups) and the non-exposed households (comparison group). We used the PSM procedure to estimate the effects of the information channels on the outcome indicators by controlling for observable differences between the treatment and comparison groups. Before presenting the PSM estimation results, we first check whether the common support or overlap and covariate balancing conditions (matching quality tests) have been fulfilled or violated.

A visual inspection of the propensity score overlaps in Figure S1 show substantial overlaps in the propensity score distributions for the treatment and comparison groups after matching, suggesting that the common support condition is well fulfilled. The matching diagnostic tests results presented in Table S2 suggest low pseudo-R^2, reduced mean bias and insignificant log-likelihood values after matching, indicating that the covariates used in the PSM analysis are well balanced between the matched treatment and comparison groups (Caliendo & Kopeinig, 2008). In addition, tests of mean differences between treatment and comparison groups on all covariates after matching were conducted. The results show no statistically significant differences in covariates between the treatment and comparison groups after matching, further confirming the satisfaction of the covariate balancing conditions.[3]

TABLE 2 Descriptive statistics for outcome variables

Outcomes	Full sample	PHR only	RD only	PHR + RD	RD + SMS	PHR + RD + SMS	None
FAW knowledge outcomes							
FAW dentification (%)	78.47	71.01	76.41	93.26***	83.08**	90.57***	69.70
First management decision (%)	40.00	39.13	45.13***	42.30**	49.23**	52.83***	29.29
Timing of planting (%)	81.94	88.41	76.41	82.69	84.62	88.68	80.30
Timing of scouting (%)	61.67	60.87	54.36	61.54	63.08	77.36**	61.11
Timing of spraying (%)	35.14	33.33	27.18	43.27	30.77	49.06*	34.85
Overall knowledge score (%)	59.44	58.55	55.90	64.62***	62.15**	71.70***	55.05
FAW management outcomes							
Monitoring (1/0)	0.58	0.65***	0.50	0.68***	0.58	0.85***	0.49
Chemical control (1/0)	0.88	0.85	0.91***	0.93***	0.92***	0.99***	0.79
Mechanical control (1/0)	0.72	0.78***	0.73***	0.79***	0.68	0.83***	0.62
Cultural control (#)	3.20	3.08**	3.29***	3.22***	3.81***	3.75***	2.71
No of FAW mgt practice (#)	5.90	5.90***	5.89***	6.10***	6.70***	7.19***	5.00
Productivity outcomes							
Maize yield (kg/ha)	2270.24 (1818.06)	2445.83** (2016.21)	2254.31* (1780.42)	2476.86*** (1975.67)	2580.35*** (1771.87)	2402.63 (2304.92)	1982.93 (1635.39)
Maize income (1000 RWF/ha)	5497.24 (7506.96)	7334.34*** (8840.15)	5304.22 (7798.82)	6029.58* (7842.36)	5629.32 (7330.30)	5226.53 (7651.17)	4675.13 (6312.98)
No. of observations	1077	100	297	150	113	75	284

Note: ***, ** and * denote that the mean values for household exposed to the various information channels are significantly different from non-exposed households at the 1%, 5% and 10% significance levels, respectively.

Table 3 displays the results for the effects of the campaign channels on FAW knowledge outcomes. While the various campaign channels are associated with improved knowledge on FAW identification, the effects are only statistically significant for households that were exposed to either PHR + RD or all the three channels. In particular, the receipt of information through PHR + RD and PHR + RD + SMS is, respectively, associated with about 17 and 25 percentage points higher probability of correctly identifying FAW, compared to the comparison group. Interestingly, exposure to only one campaign channel or multiple ICT-mediated channels alone (RD + SMS) does not result in a significant increase in the likelihood of correctly identifying FAW. This implies that using face-to-face channels to complement mass media channels could be helpful in improving farmers' ability to identify FAW.

The results also indicate that exposure to the campaign channels (whether singly or in combination) is significantly correlated with improved knowledge of using cultural methods (rather than pesticides) as the first resort for managing FAW. We also see that none of the information channels is significantly associated with increased knowledge on the appropriate time to scout for FAW. Additionally, only the exposure to all three channels exerts a significant effect (25 percentage points) on improved knowledge on timely planting of maize to help prevent or reduce FAW infestation. Looking at the overall knowledge test scores, we find FAW knowledge increases of about 8, 9 and 22 percentage points for households exposed to RD + SMS, PHR + RD and PHR + RD + SMS, respectively. Thus, only the exposure to multiple channels has significant effects on FAW knowledge, and the greatest knowledge gain seems to be achieved when a household is exposed to all the three channels. Our findings are consistent with those of Tambo et al. (2019) who found that farmer knowledge of FAW is greatly enhanced when exposed to multiple ICT-mediated extension channels. The findings also buttress arguments about the critical role of communication campaigns in providing timely and relevant information during the outbreak of new invasive pests, such as FAW (CABI, 2019; Toepfer et al., 2019).

Recall that the PSM estimator only controls for selection bias due to observables, and thus our impact estimates would be biased if the treatment and comparison groups differ in unobserved characteristics (hidden bias) 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). In Table 3, the Γ values for the statistically significant ATTs indicate that the estimated percentage effects of the information channels on FAW knowledge are robust to hidden bias. For instance, the Γ values of 4.2–4.3 and 2.9–3.0 for PHR + RD and PHR + RD + SMS in Table 3 signify that the significant effects of these two treatments on farmers ability to correctly identify FAW would be questionable only if the treatment and comparison groups differ in their odds of exposure to the campaign channels by a factor of 320–330% and 190–200%, respectively.

TABLE 3 Effects of information channels on FAW knowledge

Knowledge outcomes	PHR only	RD only	PHR + RD	RD + SMS	PHR + RD + SMS
FAW identification	0.004	0.057	0.165***	0.089	0.252***
	(0.066)	(0.052)	(0.052)	(0.073)	(0.082)
			[4.2–4.3]		[2.9–3.0]
First management decision	0.119*	0.184***	0.170**	0.240***	0.294***
	(0.071)	(0.056)	(0.067)	(0.083)	(0.100)
	[1.2–1.3]	[1.8–1.9]	[1.4–1.5]	[1.8–1.9]	[1.9–2.0]
Timing of planting	0.074	0.029	0.002	0.081	0.250***
	(0.051)	(0.048)	(0.054)	(0.067)	(0.080)
					[3.5–3.6]
Timing of scouting	−0.002	−0.070	−0.008	0.003	0.141
	(0.072)	(0.058)	(0.068)	(0.086)	(0.100)
Timing of spraying	0.015	−0.067	0.104*	−0.026	0.199*
	(0.070)	(0.055)	(0.062)	(0.083)	(0.103)
			[1.5–1.6]		[1.6–1.7]
Overall knowledge score	0.040	0.026	0.085**	0.077*	0.227***
	(0.038)	(0.030)	(0.034)	(0.043)	(0.051)
			[1.6–1.7]	[1.4–1.5]	[4.3–4.4]

Note: Standard errors are in round brackets, while critical gamma levels (Γ) are in square brackets. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The treatment effect estimates of the impact of the information channels on the adoption of recommended FAW management practices are presented in Table 4. We find that exposure to the channels is significantly related to the adoption of different IPM techniques, with considerable heterogeneity depending on the channel. For example, the probability of practicing regular monitoring increases by 14 percentage points when exposed to RD + SMS to almost 33 percentage points when exposed to all the three channels. The channels are also significantly related to the adoption of chemical and mechanical control options, as well as the use of multiple cultural practices for FAW management. Encouragingly, the effect is less pronounced for chemical control, indicating that the campaign may have stimulated the use of more environmentally-friendly practices for FAW management. This corresponds with the above finding that the campaign participants performed significantly better on a knowledge test regarding the use of cultural methods (rather than pesticides) as the first option for FAW management. This is a positive finding because excessive use of chemical pesticides can have adverse effects on human health and the ecosystem.

Turning to the outcome of interest in the last row of Table 4, we find that all the information channels are significantly associated with the adoption of multiple FAW management practices, in line with recommended IPM approaches and consistent with the content of the campaign messages. In other words, households exposed to the information channels are more likely to adopt one or two additional FAW management techniques than households that did not receive the FAW information. Similar to the results on the knowledge outcomes, the likelihood of adoption of an IPM practice or multiple IPM practices for FAW management is higher for households exposed to multiple information channels, especially all the three channels. We see that there is little to no enhanced effect of adding RD on PHR, but there seems to be an additive effect of RD and SMS, and a greater effect is realised when the two ICT-based channels are combined with the face-to-face PHR intervention, possibly reflecting different complementarities between the channels. These findings corroborate previous reports on the effectiveness of digital and field-based extension approaches in stimulating the adoption of IPM practices (Gautam et al., 2017; Larochelle et al., 2019; Tambo et al., 2019). Here again the sensitivity analysis results (Γ values) suggest that our impact estimates are not likely driven by unobserved heterogeneity.

3.3 | Impact on maize productivity

Finally, we examine if the FAW campaign intervention also have an impact on maize productivity. The PSM estimation results in Table 5 show that exposure to the information channels is associated with up to 34% and 49% gains in maize yields and incomes, respectively, compared to the comparison group. With the exception of RD only, all the campaign channels are associated with significant increases in maize yields and incomes. The results also show that while the highest yield is achieved with the RD + SMS treatment, the PHR + RD + SMS treatment is linked with the greatest gain in terms of maize income. This is due to differences in costs of inputs used in maize production, including the cost of FAW management. We also find that unlike the FAW knowledge and management outcomes, households exposed to a single channel (PHR only) appear to achieve greater maize productivity outcomes than some of their counterparts that were exposed to multiple channels. Overall, these results suggest that the positive effects of the information campaign on farmers knowledge and management of FAW reported above translate into significant increase in maize productivity.

A look at the results for the sensitivity analysis of hidden bias, however, suggest that the impact estimates on the productivity outcomes should be interpreted with some caution. The Γ values are 1.0–1.1, indicating that the ATT estimates are quite sensitive to hidden bias. Thus, the estimated treatment effects are not robust to unobserved household characteristics that may affect exposure to the campaign channels and the productivity outcome variables simultaneously. This notwithstanding, it should be noted that Rosenbaum bounds sensitivity results are worst-case scenarios (Becker & Caliendo, 2007; DiPrete & Gangl, 2004), and that critical Γ of 1.0–1.1 does not imply that there is no true effect of the information channels on maize productivity.

3.4 | Robustness checks

As mentioned previously, we analysed the robustness of the kernel matching estimates by using two other matching algorithms: nearest neighbour (NN) and radius matching. The estimation results for these two alternative matching procedures are presented in Tables S3 and S4. While the results are generally consistent across the three matching methods with regard to signs, statistical significances and magnitudes of the estimated ATTs, there are a few noticeable differences. For instance, the kernel matching results indicate that none of the channels has a significant effect on the knowledge score on timely scouting of fields for FAW, but results from the NN and radius matching routines suggest that exposure to all the three campaign channels is significantly associated with a 18–20% increase in farmer knowledge of timely scouting for

TABLE 4 Effects of information channels on FAW management

Adoption outcomes	PHR only	RD only	PHR + RD	RD + SMS	PHR + RD + SMS
Monitoring	0.204***	0.034	0.246***	0.143**	0.325***
	(0.063)	(0.052)	(0.055)	(0.067)	(0.068)
	[2.7–2.8]		[3.4–3.5]	[1.6–1.7]	[2.8–2.9]
Chemical control	0.066	0.067*	0.090**	0.062	0.147***
	(0.049)	(0.039)	(0.039)	(0.046)	(0.042)
		[3.5–3.6]	[4.2–4.2]		[11.2–11.3]
Mechanical control	0.210***	0.098**	0.174***	0.102	0.187***
	(0.057)	(0.048)	(0.051)	(0.064)	(0.065)
	[1.5–1.6]	[1.4–1.5]	[1.3–1.4]		[2.2–2.3]
Cultural control	0.336*	0.552***	0.413***	1.019***	1.002***
	(0.184)	(0.138)	(0.145)	(0.178)	(0.178)
	[1.2–1.3]	[2.2–2.3]	[1.5–1.6]	[4.6–4.7]	[7.8–7.9]
No. of practices adopted	0.978***	0.892***	0.995***	1.674***	2.040***
	(0.264)	(0.193)	(0.202)	(0.254)	(0.264)
	[1.8–1.9]	[2.1–2.2]	[2.5–2.6]	[6.0–6.1]	[16.9–17.0]

Note: Standard errors are in round brackets, while critical gamma levels (Γ) are in square brackets. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 5 Effects of information channels on maize productivity

Productivity outcomes	PHR only	RD only	PHR + RD	RD + SMS	PHR + RD + SMS
Maize yield (kg/ha)	498.288**	212.636	510.841***	655.707***	535.508*
	(226.896)	(150.467)	(192.584)	(197.709)	(310.797)
	25.65%	10.42%	21.48%	34.07%	28.04%
	[1.0–1.1]		[1.0–1.1]	[1.5–1.6]	[1.0–1.1]
Maize income (1000 RWF/ha)	2018.249**	830.460	1647.992**	1450.400*	1918.440*
	(994.724)	(620.765)	(767.479)	(826.244)	(1112.434)
	37.80%	18.56%	36.96%	34.71%	48.56%
	[1.0–1.1]		[1.0–1.1]	[1.0–1.1]	[1.0–1.1]

Note: Standard errors are in round brackets, while critical gamma levels (Γ) are in square brackets. The % values are the percentage gain over the mean outcome for the matched comparison group. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

FAW. Additionally, unlike in the case of kernel matching, the greatest yield gain is obtained from exposure to all the three campaign channels when using the NN and radius matching methods. Overall, the three matching methods yielded fairly similar results, suggesting that our treatment effect estimates are robust to the matching algorithm employed.

As also noted earlier, households exposed to SMS only and PHR + SMS were excluded from the analysis of the differential effects of the campaign channels due to limited observations. However, it could be argued that doing so may result in sample selection bias. Hence, as a robustness check, all the households that were exposed to the campaign (irrespective of the channel) were merged together, and their outcomes were compared to the outcomes of the comparison group (non-exposed households). The PSM estimation results in Table 6 suggest that households that received FAW information (regardless of the information channel) significantly outperformed their counterparts in the comparison group on all of our main outcomes of interest. For example, we find a 7 percentage point increase in FAW knowledge and the adoption of one additional FAW management practice among the FAW information recipients, compared to the comparison group. Table 6 further shows that exposure to any of the FAW information channels significantly associated with maize yield and income gains of about 21% and 42%, respectively. However, once again the results for the critical level of hidden bias (Γ = 1.0–1.1) suggest that some caution is warranted when interpreting the yield and income results.

TABLE 6 Effects of the FAW campaign (irrespective of the channel)

Outcomes	ATT	SE	Gamma
Knowledge outcomes			
FAW identification	0.088**	0.043	1.7–1.8
First management decision	0.187***	0.045	1.8–1.9
Timing of planting	0.064*	0.038	1.8–1.9
Timing of scouting	0.001	0.048	
Timing of spraying	0.027	0.046	
Overall knowledge score	0.073***	0.024	1.5–1.6
Adoption outcomes			
Monitoring	0.149***	0.040	2.6–2.7
Chemical control	0.073**	0.031	4.3–4.4
Mechanical control	0.118***	0.038	1.2–1.3
Cultural control	0.574***	0.109	2.7–2.8
No. of practices adopted	1.119***	0.151	3.1–3.2
Productivity outcomes			
Maize yield (kg/ha)	408.051***	134.540	1.0–1.1
	20.69%		
Maize income (1000 RWF/ha)	1736.281***	532.223	1.0–1.1
	42.10%		

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

4 | CONCLUSIONS

In this article, we examined the effectiveness of three complementary mass-extension channels in enhancing farmers' knowledge and management of fall armyworm (FAW), an invasive pest that is causing substantial damage to maize production in several countries across Africa, Asia and Oceania. We also assessed the effects of the information channels on maize productivity. The information channels examined include two ICT-mediated channels (radio drama and SMS) and a face-to-face channel (plant health rallies). We used survey data from 720 smallholder farmers in Eastern Rwanda, where these three information channels have been recently used to provide actionable advice to farmers on how to identify, prevent and sustainably control FAW.

Findings from PSM estimators indicated that exposure to the campaign channels is associated with increased knowledge outcomes, including knowledge of the correct identification of FAW, the use of cultural practices as the first resort to FAW management, timely planting to limit infestation and timely spraying for effective control of the pest. However, the treatment effects are statistically significant only when the field-based extension method is combined with digital extension approaches. Moreover, we found that the effects are greater for households that were exposed to all the three channels, suggesting complementary effects of the channels. For instance, the results showed that receiving FAW messages through any of the channels is correlated with in a 7 percentage point increase in farmers' level of knowledge on FAW, but the knowledge gain could increase to up to 23 percentage points when the information is received through all the three channels under study.

Our analysis also showed that the campaign seems to have fostered the adoption of a combination of FAW management practices. Households exposed to the information channels were significantly more likely to regularly monitor their maize fields for FAW, and adopt cultural, chemical, mechanical measures for FAW control than those who did not receive the FAW information. The treatment effect estimates are less pronounced for chemical control than for other management practices, implying that the campaign is associated with the use of more environmentally friendly approaches to FAW management. We also observed that exposure to all the three channels is related to the adoption of two additional FAW management measures, while exposure to single channels is correlated with the uptake of one additional practice, compared to the non-exposed households. These results are robust to hidden bias and to different matching algorithms.

We also found suggestive evidence that the possible FAW knowledge gains from the campaign and the subsequent adoption of recommended management practices could translate into a significant increase in maize productivity. Specifically, exposure to the information channels is associated with maize yield increases of about 10–34%, and maize income of around 19–49%, depending on the channel. However, results from sensitivity analyses of hidden bias suggested that the estimated productivity gains from the information campaign are sensitive to unobserved heterogeneity, and thus some caution is warranted when interpreting these results

Overall, our findings suggest that the information campaign, particularly the use of complementary channels, can be effective in enhancing farmers' knowledge of how to identify and sustainably manage the FAW pest, and in boosting the uptake of environmentally friendly management practices in the study region. Our findings also imply that while there is a growing popularity in the use of digital extension approaches to deliver timely information to farmers in a cost-effective manner, greater gains can be achieved if the digital advisory services are combined with other low-cost face-to-face extension approaches, such as plant health rallies.

Finally, this paper has several limitations that are worth mentioning. First, our study was limited by the use of cross-sectional data and PSM methods, which can only control for selection bias due to observed confounding factors. Thus, we were unable to provide causal evidence on the effectiveness of the information intervention. In addition, there is a likelihood of positive FAW knowledge spillovers from the information recipients to the comparison group; therefore, the exact magnitudes of the treatment effect estimates may have been underestimated. Moreover, we did not explore the intensity of exposure to the information channels. These issues deserve attention in future research. For instance, the use of experimental approaches in future research to properly account for potential unobserved heterogeneity bias and spillover effects would be useful to test the current findings.

ACKNOWLEDGMENTS

This research was funded by the CABI-led Plantwise programme, which is financially supported by the Foreign, Commonwealth & Development Office (FCDO), United Kingdom; the Directorate-General for International Cooperation (DGIS), Netherlands; the Swiss Agency for Development and Cooperation (SDC); the European Commission (DG DEVCO); the Australian Centre for International Agricultural Research (ACIAR); the Ministry of Agriculture of the People's Republic of China; Irish Aid; and the International Fund for Agricultural Development (IFAD). The authors gratefully acknowledge RAB, BK TecHouse Limited, Rwanda Broadcasting Agency, and Rwanda's Ministry of Agriculture and Animal Resources (MINAGRI) for their roles in the implementation of the FAW campaign. We also thank Jean Pierre Kalisa, Jean de Dieu Nsabimana and 20 enumerators for their great efforts in conducting household surveys under COVID-19 restrictions.

CONFLICTS OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions.

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ENDNOTES

[1] A sector is a third tier (i.e., province, district and sector) of government administration in Rwanda.

[2] In this paper, exposure to information channel means that a household reportedly received FAW information through one or more of the three campaign channels, while non-exposure implies that a household reportedly did not receive FAW information through any of the campaign channels.

[3] For reasons of brevity, the detailed results for the balancing of all covariates for each outcome are not presented, but are available upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Tambo, J. A., Uzayisenga, B., Mugambi, I., Onyango, D. O., & Romney, D. (2022). Sustainable management of fall armyworm in smallholder farming: The role of a multi-channel information campaign in Rwanda. *Food and Energy Security*, *00*, e414. https://doi.org/10.1002/fes3.414