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Research

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Special Collection: World-Scale Ecology and Management of Fall Armyworm (*Spodoptera frugiperda*)

Reliability of Pheromone Trap Catches and Maize Plant Damage as Criteria for Timing Fall Armyworm Control Interventions in Humid Forest Agroecology of Central Africa

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Abstract

Control of fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) since its invasion of Africa still depends on pesticides. Early detection of adults is considered the key to the success of larvae control in the crop field. However, FAW control thresholds based on current monitoring techniques are not well established in Africa. We investigated the efficacy of moth capture frequencies and FAW incidence levels as decision tools for FAW management. Experiments were conducted over two maize cropping seasons during which FAW incidence, severity, and larvae count were recorded during destructive sampling after the application of a homologated insecticide. During the first season, the FAW incidence ranged from 37.5 ± 5.6% in the 25% incidence threshold treatment to 48.1 ± 8.1% in the control. During the second season, the incidence was significantly lower in the 25% incidence threshold treatment (55.8 ± 5.7%) compared with the control (75.7 ± 3.0%). Over the two seasons, no significant difference in FAW damage severity was recorded between the treatments and control. The highest number of larvae per plant (4.0 ± 0.6) was observed in the 10% incidence threshold treatment. Insecticide application did not consistently contribute to reducing FAW incidence and observed plant damage did not translate into yield loss. FAW control needs further investigation to establish a threshold above which damage translates into yield loss, thus necessitating control intervention.

Key words: FAW monitoring, maize yield, intervention threshold, adult moth capture, insecticide

Maize (*Zea mays* L.) (Cyperales: Poaceae) remains the dominant crop in sub-Saharan Africa, accounting for 70% of households' food consumption (Harashima 2007, Anami et al. 2009, Shiferaw et al. 2011). Major maize production constraints include the decline in soil fertility, a complex of pests, and diseases that are being exacerbated by a changing climate with frequent and prolonged droughts or severe rainfall events (Cairns et al. 2021, Prasanna et al. 2021). In Africa, these production constraints have been compounded by the recent introduction and rapid colonization of the continent by the fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) which has reportedly caused huge losses in maize production throughout the continent (Prasanna et al. 2018).

The fall armyworm is native to the Americas and its first occurrence in Africa was reported in 2016 (Goergen et al. 2016) and in Cameroon in 2017 (Tindo et al. 2017, Fotso et al. 2019). As of now, the pest has been officially confirmed in 44 countries in sub-Saharan Africa (Zhou et al. 2021). FAW larvae are reported to feed on nearly 353 plant species grouped in 76 families (Montezano et al. 2018), with maize and sorghum being the main crops attacked in Africa (Prasanna et al. 2018). Day et al. (2017) reported a loss of 8.3–20.5 million metric tons of maize with a value of $2.5–6.2 billion due to the FAW invasion of Africa. In 2018, an estimated 11.6% of maize yield was lost in two districts in Zimbabwe (Baudron et al. 2019). Yield loss across Africa is reported to range from 22 to 26% in Ghana, 35 to 67% in Zambia (Day et al. 2017), and from 32 to 47% in Ethiopia (Kumela et al. 2018). FAW appears to be much more damaging to maize in West and Central Africa than most other African *Spodoptera* species (IITA 2016). FAW control is largely based on the use of pesticides against larvae although several parasitoids have been reported to attack eggs and larvae (Abang et al. 2020). Several pesticides have been recommended and used in FAW management in other regions of the world (Blanco et al. 2014, Sabri et al. 2016).

Efforts are being made to develop environment-friendly control methods in a context where chemical control can lead to resistance to pesticides. The occurrence of insecticide resistance is related to the continuous spraying and at high doses coupled with FAW's high adaptative capacity (Giraudo et al. 2015, Carvalho et al. 2018, Flagel et al. 2018). Because FAW is an invasive and recent pest in Africa, current efforts are based on pesticide products sprayed to keep the pest below economic injury levels. However, informed decisions on whether pesticide interventions are necessary, and their timing could be more effective to avoid unnecessary applications and minimize the risk of pesticide resistance (Cruz et al. 2010a,b). These decisions should be based on recommended control thresholds for the FAW. Previous reports indicated that the application of insecticides is more effective in young larval stages (Prasanna et al. 2018). Therefore, early detection is a key component in any control strategy to be developed against FAW. Early detection and monitoring using pheromones have been a useful tool for insect monitoring and pest management since they can help to determine the optimal timing of pesticide applications (Cruz et al. 2010b), reduce plant damage, and avoid unnecessary pesticide applications (Cruz et al. 2012). According to Cruz et al. (2010b), between initiation of oviposition and ten days after, the resulting third and fourth instar larvae have not caused irreversible damage, and eggs and small larvae can be eliminated by natural enemies hence avoiding the need to spray during that period. Cruz et al. (2012) recommend insecticide application 10 d after the threshold of three moth capture in pheromone traps is reached with a repeat application recommended if the threshold is again reached, following the initial application. Other studies suggest insecticide application when 10 or 20% of plants have shot hole or pin hole injury (Cruz et al. 2010a,b). Bessin (2004) and Steffey et al. (1999) recommend pesticide application when more than 5% of the plants have egg masses or when 25% of the plants have leaf damage and feeding larvae present as a threshold level. While these FAW thresholds were adopted based on studies outside Africa, no studies have been conducted to assess their use in sub-Saharan Africa. Most of these studies were conducted in the Americas. In contrast, Sub-saharan Africa consists of wet tropical rainforests and grasslands in parts of central Africa and semi-arid climates to deserts in the northern and southern areas.

The objective of this research is to evaluate the applicability of the currently used FAW damage and moth capture threshold in the sub-Saharan Africa context. We tested 2 criteria for timing and frequency of insecticide applications: (1) A pre-determined number of moths captured in a FAW sex pheromone trap and (2) the level of foliar damage caused by FAW. Pheromone traps are considered the best means to monitor FAW adults and for deciding on pesticide applications to control the pest in maize (Cruz et al. 2010b) while the level of maize foliage damage by FAW is the most commonly used and simplest method for farmers to determine the need for insecticide treatments (Andrews 1980).

Materials and Methods

Experimental Site and Field Design

Two experiments were conducted in 2017 at the IITA Cameroon experimental farm (03°51.791'N; 011°27.706′E; 747 m). The first (season 1) was conducted from April to August and the second (season 2) was conducted from September to December. The average daily temperature ranged from 22.4 to 24.6°C (season1) and 23.0 to 24.6°C (season 2), average daily relative humidity ranged from 84.5 to 89.9 % (season 1) and 82.7 to 88.2 % (season 2). Total rainfall was 1025 mm (season 1) and 805 mm (season 2) (Fig. 1). Historical rainfall data of the study area collected at the IITA-Cameroon weather station showed a 10-year average of 1767 mm before the study year and 1947 mm for the 4 yr after the study. This supports the little variation in environmental conditions, mainly rainfall in the study areas over the years. The high-yielding IITA maize variety pro-vitamin A (PVA) Syn6 (Badu-Apraku et al. 2020) was sown at 25 cm within rows and 50 cm between rows, with 3 grains per hole, and thinned to two plants per stand, 10 d after sowing. Buffer zones (space between plots and blocks) were planted with 2 rows of maize which were not samples during evaluations while the remaining plants were available for sampling, making a total of 192 plants per plot of size 6 m^2. Poultry manure composed of nitrogen (0.01%), phosphorus (1.82%), and potassium (1.16%), was applied at approximately four metric tons per hectare 2 wk before sowing. A completely randomized block design was used with four insecticide treatment decision criteria and untreated control, all replicated four times with a 1 m distance between replicates. The experiments were subsequently fertilized twice with the granular form of chemical fertilizer as a side-dress: (1) nitrogen (20 %), phosphorus (10 %), potassium (10 %) at 11 g/plant, two weeks after planting (after thinning) and (2) urea (46%) at the rate of 11 g/plant, four weeks after planting (after weeding).

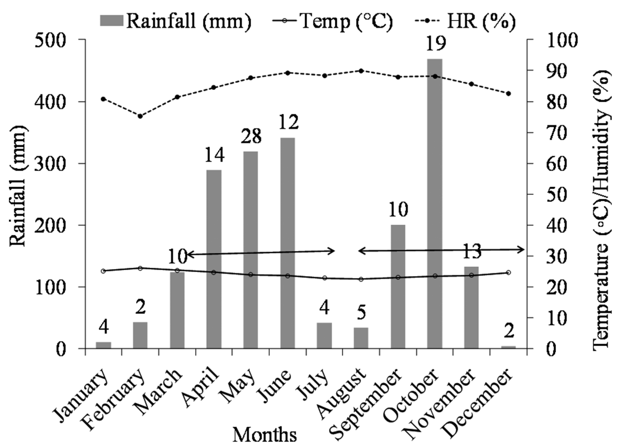

Fig. 1. Monthly mean temperature and relative humidity and total monthly rainfall at the experimental site across season 1 and season 2. Horizontal bars represent the duration of each experiment and figures on the bars represent the number of rainy days.

Pheromones and Trapping Setup

The commercial lure Bio Spodoptera was used in paper Delta traps composed of lure, paper, and glue cards, all supplied by ChemTica International, Heredia, Costa Rica. The lure is a mixture of (*Z*)-9-tetradecen-1-ol acetate (*Z*9-14: Ac); (*Z*)-7-dodecen-1-ol acetate (*Z*7-12: Ac); (*Z*)-9-dodecen-1-ol acetate, (*Z*9-12: Ac) and (*Z*)-11-hexadecen-1-of acetate (*Z*11-16: Ac) in the ratio of 81: 0.5: 0.5: 18. Two traps with the pheromone were installed within the experimental field 25-m apart, after plant emergence. The traps were fastened by a wooden post at an initial height of 1 m above the soil surface. Pheromones and sticky cards were replaced every 2 wk, and the trap was maintained above the plant's canopy.

Decision Tools and Insecticide Applications

The decision to apply an insecticide was based on the level of infestations by FAW (Cruz et al. 2012). Five FAW control decision thresholds were evaluated: (1) a control where no pesticide was applied; (2) a 3 moth trap count threshold with a single pesticide application 10 d after the threshold is reached; (3) a 3 moth trap count threshold with a pesticide applied 10 d after the threshold is reached as in the previous treatment, and another application when the threshold of 3 moth capture is met again, starting the counting from the 4th day after the first insecticide application; (4) 10% leaf damage treatment and (5) 25% leaf damage treatment; with pesticide applied one time when the leaf damage threshold is reached (Chinwada 2021). The insecticide emamectin benzoate, sold in Cameroon under the trade name Emacot 50 WG (Horizon Phyto Plus, Douala, Cameroon), was used. Emacot is widely used in Cameroon for FAW control (Fotso et al. 2019) and in other African countries, America, and Asia (Wan et al. 2021). When a threshold was reached, the insecticide was applied at the recommended dose of 10 g for 15 liter of water using a knapsack sprayer. Treatment (2) represents the calendar application (or positive control) recommended by the extension services (Ministry of Agriculture and Rural Development 2017).

Sampling Procedure and Data Collection

The traps were inspected daily and the maize plants were inspected at 3-d intervals for the first six weeks to evaluate FAW incidence using one or more of the symptoms that are characteristic of FAW damage including leaf 'windowpanes', irregularly shaped leaf holes, chewed-up whorl leaves, leaf tattering, and presence of dried larval frass. Generally circular and smaller leaf holes were attributed to maize stem and cob borers (Chinwada 2021). Each time a treatment threshold was reached as described in Table 1, the treatment was applied. All plots were sampled 24 hr after each insecticide application to evaluate larval mortality (Cruz et al. 2012) and post-treatment evaluations were conducted at 2-wk intervals after the initial treatment to assess FAW incidence and damage severity.

During each evaluation, the number of FAW larvae was counted on each of 10 plants randomly selected along the 2 plot diagonals. Collected larvae and pupae were maintained in the insectary (at room conditions) on maize leaves until adult emergence to confirm their identity. FAW damage severity was scored for leaf damage on a scale of 1–5 with 1 = absence of damage, 2 = 1–25% plant damage, 3 = 26–50% plant damage, 4 = 51–75% plant damage and 5 > 75% plant defoliation (Tefera et al. 2011, Silva et al. 2015). The maize plant development stage was recorded during each evaluation as described by (Endicott et al. 2014). At harvest, 10 plants were randomly selected to measure plant height, stem diameter, cob length, cob width, and grain weight. Grain yield was converted to metric tons per hectare.

Data Analysis

Average FAW incidence at each sampling date was calculated as the percentage of sampled plants with FAW damage, and the severity as the percentage of plant defoliation. Mortality was calculated as a percentage corrected using the Abbot formula (Shamseldem et al. 2014). The effect of insecticide treatments was analyzed separately for each season with a generalized linear model with quasi-Binomial error for FAW incidence, severity, and mortality, quasi-Poisson error for larval counts, and Gaussian error for maize plant height, stem diameter, cob length, and grain yield. Where the F-test indicated a significant effect ($P < 0.05$), the Tukey's HSD multiple comparisons test ($P = 0.05$) was used to compare pairs of treatment means. A separate mixed model GLM was used to test the interactions between treatment and season with the season as a fixed effect and treatment as a random effect. The RStudio software version 4.0.2 was used for all analyses.

Results

FAW Adult Population Dynamics and Treatment Application

During season 1, pesticide application for the first 3 moth threshold was applied at 25 d after sowing (DAS), and the second application for the second 3 moth threshold at 85 DAS (Fig. 2). Spraying using the condition of 10% plant damage threshold occurred l8 DAS while that of 25% plant damage occurred 25 DAS. Moth capture peak was observed at 70 DAS while maize plants were in the 20th leaf collar stage (V20).

During season 2, the first capture of three moths occurred 10 d earlier compared with season 1 which triggered the single spray treatment 16 DAS. The treatments for 10 and 25% incidence were applied at 16 DAS (Fig. 2). The second capture of three moths took place 20 d after the first and the second pesticide application was applied at 36 DAS in the corresponding treatment.

Table 1. Summary of treatment decision criteria and timing of insecticide applications

Treatment decision criterion	Treatment description	Frequency of application	Treatments
Adult capture	Spray at 10 DAC of 3 adults (F1)	Once	Single spray
	F1 + Spray at 10 DAC of 3 adults	Twice	Double spray
FAW incidence	Spray at 10% of plants damaged	Once	Spray at 10% incidence
	Spray at 25% of plants damaged	Once	Spray at 25% incidence
	Control	Control	Control

Days After Moth Capture (DAC).

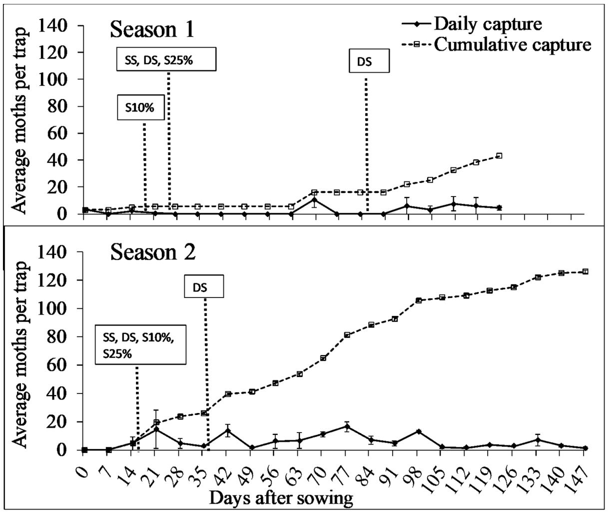

Fig. 2. Average number of moths (Mean ± SE) per pheromone trap during the 2 maize cropping seasons. Dotted bars represent the time of application for the respective treatment: Single spray (SS), Double spray (DS) Spray at 10% incidence (S10%), Spray at 25% incidence (S25%).

FAW Abundance, Incidence, and Severity

Larval Abundance

In season 1, the initial FAW larval infestation was low for all treatments (<0.25 larvae per plant) including the control and did not increase beyond 0.5 larvae per plant, while some treatments did not have any larvae after treatment (Fig. 3A). Results did not show significant differences among treatments at any of the crop stages (Fig. 4).

In season 2, the number of larvae per plant increased to 3.3 which occurred very early but dropped to one or fewer larvae per plant within two days. The control remained at a low level and dropped below 0.3 larvae per plant two weeks later (Fig. 3B). Analysis of key crop stages in season 2 did not show differences among treatments in FAW infestations at any of the stages (Fig. 4).

FAW Incidence

In season 1, all treatments started at the same level of FAW incidence, except in the control where FAW incidence was higher up to 25 DAS. There was an increasing trend for all the treatments from 25 DAS onwards (Fig. 5A). At V2 (18 DAS), FAW incidence ranged from 15% in the 10 % damage threshold treatment to 25% in the control (F = 0.715; df = 4, 15; P = 0.595). At V5 (25 DAS), the incidence was up to 40% in all the treatments except in the 25% threshold treatment where incidence (16%) did not change within 7 d (Fig. 5A). At V15 (53 DAS), FAW incidence continued to increase and ranged from 30% in the single and double spray treatments to 50% in the control, and in the single spray at 10 and 25% damage threshold treatment. At tasseling, 72 DAS (VT), incidence ranged from 43% in the double spray treatment to 70% in the single spray treatment.

During season 2, FAW incidence was lowest in the control at the beginning of infestations, but after the application of the four insecticide treatments, it displayed a decreasing trend compared with season 1 (Fig. 5B). For most crop growth stages, the initial incidence was about 4-fold higher in season 2 than in season 1 (Fig. 6). Analysis based on major crop stages showed that at V2 (16 DAS), incidence ranged from 60% in the single spray treatment to 80% in the double spray treatment. At V5 (37 DAS), there was a significant difference between all treatments and the control,

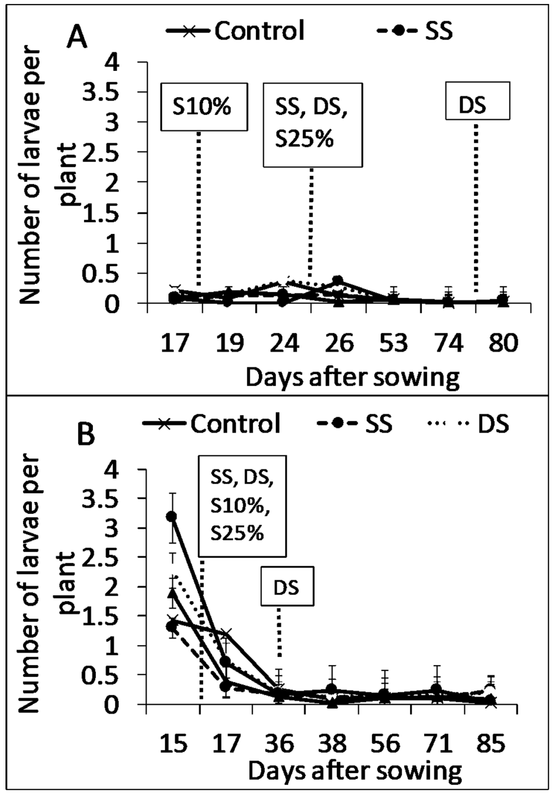

Fig. 3. Changes in FAW larval infestations (Mean ± SE) for the treatments and the control between sampling dates in days after sowing (DAS) during season 1 (A) and season 2 (B) between sampling dates in days after sowing (DAS). Vertical dotted lines correspond to the timing of insecticide applications: Single spray (SS), Double spray (DS) Spray at 10% incidence (S10%), Spray at 25% incidence (S25%).

with the incidence in all treatments decreasing to 50% while it increased to 80% in the control (F = 3.11; df = 4, 15; P = 0.04). At V15 (56 DAS), incidence in all treatments continued to decrease with significant differences among them and ranged from 20% for the double spray treatment to 70% for the control (F = 3.32; df = 4, 15; P = 0.04). At VT (71 DAS), apart from incidence in the single spray treatment that decreased to 30%, it increased in the other treatments but remained lower compared with the incidence in the control which was up to 77% (F = 3.0; df = 4, 15; P = 0.05; Fig. 6). At the last stage R2 (85 DAS), the FAW incidence increased to 75% in the double spray treatment and 85% in the control (Fig. 6).

FAW Damage Severity

During season 1, FAW damage severity increased with DAS (Fig. 7A) and with key growth stages, but at each stage, there were no significant differences between treatments (Fig. 8). Damage severity at V2 (18 DAS) ranged from 28% in the spray at 10% damage threshold treatment to 32% in the double spray treatment. All treatments including the control increased to almost the same level (35%) at V5 (25 DAS) and at V15 (53 DAS), except for the spray at 25% damage threshold treatment where damage severity decreased to 25% and increased to 42% in the spray at 10% incidence treatment (F = 1.073; df = 4, 15; P = 0.404); but at VT (72 DAS), the severity increased in all treatments ranging from 43% in the 10 % damage threshold treatment to 65% in the control (F = 2.93; df = 4, 15; P = 0.06; Fig. 8).

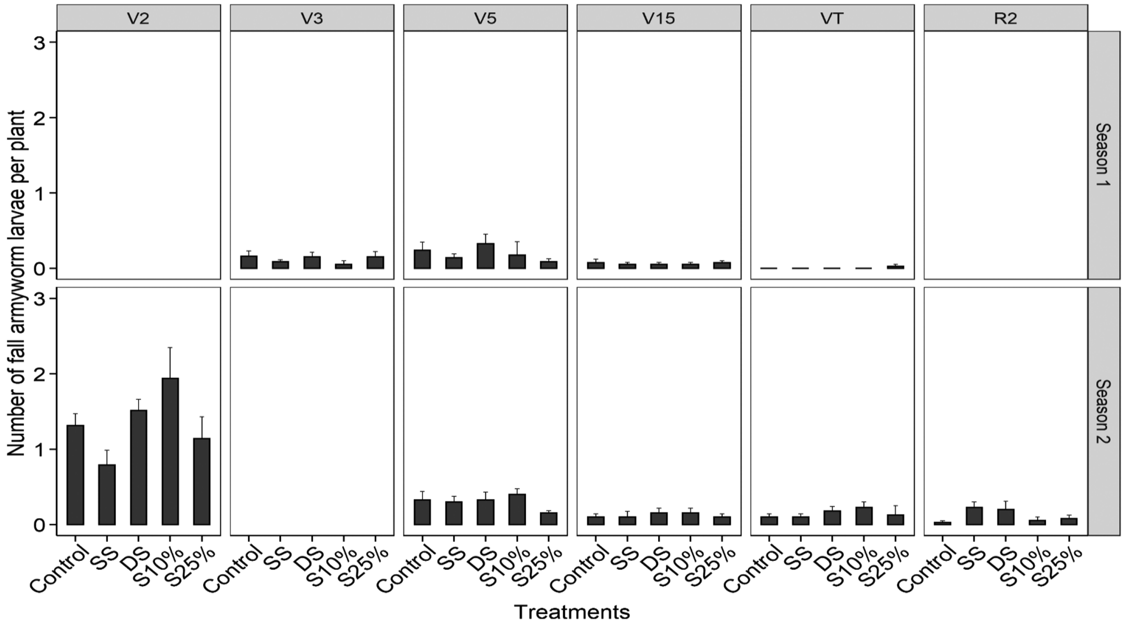

Fig. 4. Average abundance (Mean ± SE) of FAW larvae per plant in the 4 insecticide treatments and the control at various crop growth stages in season 1 and season 2. Vertical bars are SEMs (An empty chart means no sampling occurred during that stage; hence no data is available).

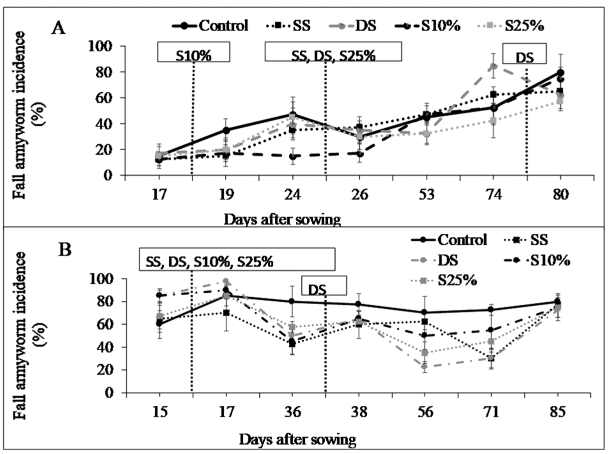

Fig. 5. Changes in FAW incidence (Mean ± SE) for the treatments and the control between sampling dates in days after sowing (DAS) during season 1 (A) and season 2 (B) showing the timing of insecticide applications: Single spray (SS), Double spray (DS) Spray at 10% incidence (S10%), Spray at 25% incidence (S25%).

In season 2, FAW damage severity was very high at the beginning, almost double that observed in season 1, and then decreased with DAS (Fig. 7B). The results based on key growth stages also showed that damage severity decreased; but at each stage, there were no significant differences between treatments. At V2 (16 DAS) severity ranged from 46 % in the control to 55% in the spray at 10% damage threshold treatment (F = 1.002; df = 4, 15; P = 0.437); at V5 (37 DAS), it ranged from 28% in the spray at 10% damage threshold treatment to 38% in the control (F = 1.86; df = 4, 15; P = 0.17); at V15 (56 DAS) from 25% in the double spray treatment to 34% in the spray at 10% damage threshold treatment (F = 1.26; df = 4, 15; P = 0.33), and at VT (71 DAS) from 38% in the spray at 10% damage threshold treatment to 25% in the double spray treatment (F = 1.940; df = 4, 15; P = 0.156). At the final stage – R2 corresponding to blistering (85 DAS), all treatments had dropped to the lowest level of the season and at virtually the same level of incidence of about 25% (Fig. 7).

Effect of Treatment on FAW Infestation Incidence and Severity and Mortality

Incidence of FAW (%) ranged from 37.5 ± 5.6 in the spray at 25% damage threshold treatment to 48.1 ± 8.1 on the control during season 1 (F = 0.82; df = 4, 15; P = 0.52) and from 53.3 ± 9.9 in the double spray treatment to 75.7 ± 3.0 in the control (F = 3.64; df = 4, 15; P = 0.008 in season 2; Table 2). The severity of damage ranged from 37.5 ± 4.7 in the spray at 10% damage threshold treatment to 42.7 ± 5.2 in the control in season 1 and from 33.9 ± 1.7 in the single spray treatment to 37.3 ± 1.3 in the spray at 10% damage threshold treatment in season 2 (F = 0.94; df = 4, 15; P = 0.45; Table 2).

During season 1, the average number of larvae per plant ranged from 0.07 ± 0.01 in the single spray treatment to 0.13 ± 0.3 in the double spray treatment (F = 0.587; df = 4, 15; P = 0.677) while during the season 2 it ranged from 0.20 ± 0.04 in the single spray treatment to 0.40 ± 0.06 in the spray at 10% incidence treatment (F = 3.31; df = 4, 15; P = 0.04 in season 2).

Mortality of FAW larvae 24 hr after spraying ranged from zero in the control to 32.4 ± 10.0% in the double spray treatment in season 1 (F = 6.0; df = 4, 15; P = 0.004) and from zero in the control to 93.8 ± 6.3% in the spray at 25% incidence treatment in season 2 (F = 6.27; df = 4, 15; P = 0.004; Table 2).

There was no significant difference among treatments in the number of plants with foliar damage at a given scale. During season 2, the spray at 10% damage threshold treatment had the highest percentage of plants with foliar damage at scale 5 (2.8 ± 0.8%) and at scale 4 (6.9 ± 0.8%; Table 3). The lowest was in the double spray treatment at scale 5 (1.6 ± 0.6%) and the single spray treatment at scale 4 (2.2 ± 1.4%). The control had the highest number of plants with scale 3 (13.8 ± 1.3%) and scale 2 (52.5 ± 2.2%). The percentage of plants without damage ranged from 26.6 ± 3.0% in the control to 42.5 ± 1.4% in the spray at 25% damage threshold treatment (Table 3). There were significant

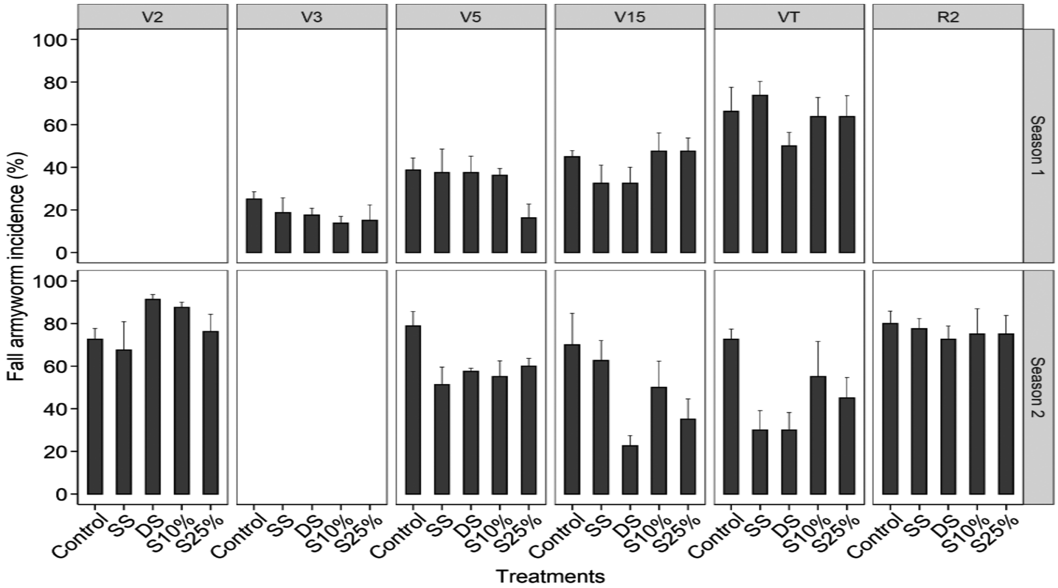

Fig. 6. Average incidence (Mean ± SE) of FAW in the 4 insecticide treatments and the control at various crop growth stages in season 1 and 5 in season 2. Vertical bars are SEMs (An empty chart means no sampling occurred during that stage; hence no data is available). Bars with different letters for each DAS are significantly different (Tukey's test at $P < 0.05$).

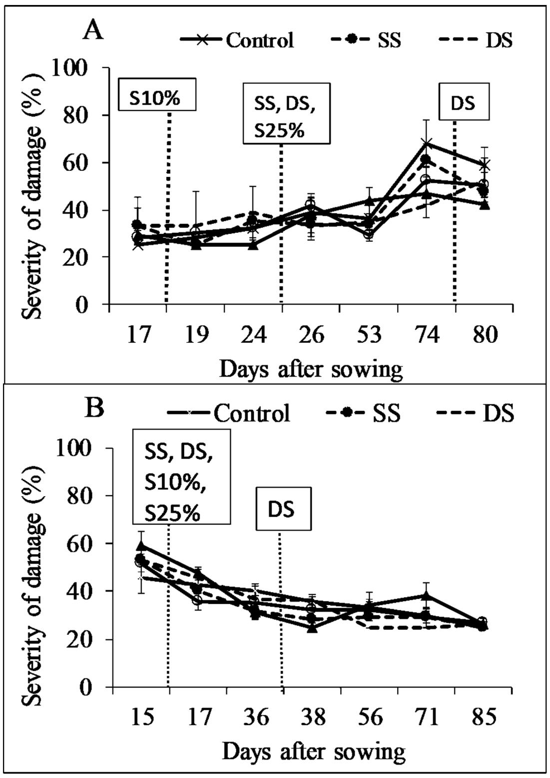

Fig. 7. Change in FAW damage severity (Mean ± SE) for the treatments and the control between sampling dates in days after sowing (DAS) during season 1 (A) and season 2 (B) showing the timing of insecticide applications: Single spray (SS), Double spray (DS) Spray at 10% incidence (S10%), Spray at 25% incidence (S25%).

differences among treatments in the number of plants with foliar damage at scale 1 ($F = 3.272$; df = 4, 15; $P = 0.04$), scale 2 ($F = 5.676$; df = 4, 15; $P = 0.006$), and scale 4 ($F = 3.59$; df = 4, 15; $P = 0.03$; Table 3).

Change in Plant Injury with Time

During season 1, damage severity (i.e., level of plant injury) had an increasing trend with sampling weeks on all treatments, reaching the highest values towards the end of sampling (Fig. 9). For each treatment, there were significant differences between weeks in injury to the plant in the control ($F = 8.14$; df = 6, 21; $P = 0.001$), except for the double spray ($F = 1.31$; df = 6, 21; $P = 0.295$). At each week, there were no significant differences among treatments ($P > 0.05$; Fig. 9).

Contrary to season 1, damage severity (injury to the plant) in season 2 had a decreasing trend with sampling weeks on all treatments (Fig. 9). The injury was significantly high at the initial damage compared with subsequent observations. For each treatment, there were significant differences between weeks, in percentage of injury to the plant in the control ($F = 4.82$; df = 6, 21; $P = 0.003$), the single spray treatment ($F = 9.07$; $P = 0.001$), the double spray treatment ($F = 13.4$; df = 6, 21; $P = 0.001$), the spray at 10% damage threshold treatment ($F = 9.97$; df = 6, 21; $P = 0.001$) and the spray at 25% damage threshold treatment ($F = 3.52$; df = 6, 21; $P = 0.014$). At each week, there were no significant differences between treatments ($P > 0.05$; Fig. 9), except between observations at week 4 ($F = 6.26$, $P = 0.004$; Fig. 9).

Effects of Treatment on Agronomic Parameters

There was no difference between the treatments and the control in plant height, stem diameter, cob length, cob width, and grain yield (Tables 4 and 5).

Discussion

This is the first study in Africa evaluating decision tools for the management of FAW. FAW moths colonize maize soon after plant emergence. Daily moth captures indicated there are several peaks of moth flight each season. In season 2, both percentage damage thresholds occurred at 14 DAS which coincided with vegetative stage 2 (V2), suggesting that the 3-d interval for observation is long as incidence at 10% threshold and 25% threshold was separated by a less than 3-d

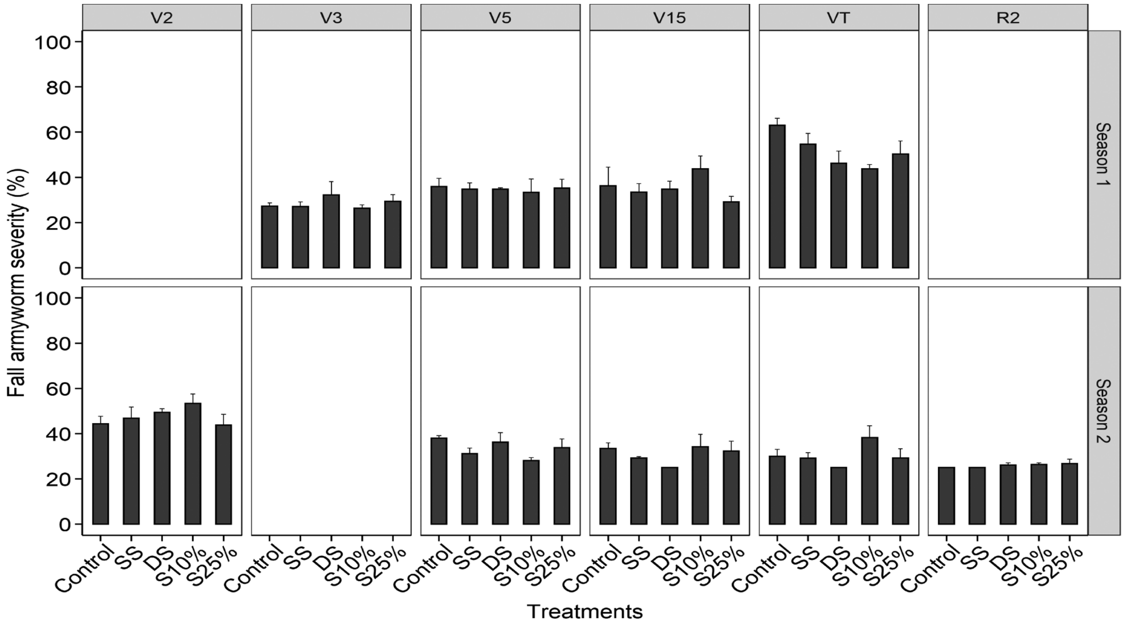

Fig. 8. Average severity (Mean ± SE) of FAW damage in the 4 insecticide treatments and the control at various crop growth stages in season 1 and 5 stages in season 2 (An empty chart means no sampling occurred during that stage, hence no data available). Vertical bars are SEMs.

Table 2. Average FAW incidence, severity, and larva infestation (mean ± SE) (24 hr after insecticide application) on maize plant over two cropping seasons

Treatment	FAW incidence (%)		FAW severity (%)		Larvae/plant		Corrected mortality (%)	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Control	48.1 ± 8.1	75.7 ± 3.0a	42.7 ± 5.2	36.1 ± 1.1	0.12 ± 0.03	0.32 ± 0.02ab	0.0 ± 0.0b	0.0 ± 0.0b
Single spray	42.5 ± 7.5	56.7 ± 7.0b	38.7 ± 4.4	33.9 ± 1.7	0.07 ± 0.01	0.20 ± 0.04b	7.0 ± 4.2b	62.9 ± 21.8ab
Double spray	44.4 ± 8.3	53.3 ± 9.9b	38.4 ± 4.9	35.3 ± 1.0	0.13 ± 0.3	0.31 ± 0.01ab	32.4 ± 10.0a	80.1 ± 15.7a
Spray at 10% incidence	39.1 ± 9.5	63.8 ± 6.5ab	37.5 ± 4.7	37.3 ± 1.3	0.07 ± 0.11	0.40 ± 0.06a	4.2 ± 4.2b	49.2 ± 16.8ab
Spray at 25% incidence	37.5 ± 5.6	55.8 ± 5.7b	37.7 ± 5.5	34.7 ± 1.4	0.08 ± 0.02	0.24 ± 0.06ab	6.6 ± 3.6b	93.8 ± 6.3a
$F_{(4, 15)}$	0.82	3.64	0.66	0.94	0.587	3.312	6.001	6.270
P-value	0.52	0.008	0.63	0.45	0.677	0.039	0.0039	0.0036

Mean with different letters in a column are significantly different from Tukey's test at $P < 0.05$.

interval. According to Evans and Stansly (1990), the economic injury level is lowest (14 %) at 14 d after germination (V2), and highest (50 %) at tasseling (60–67 d after emergence). In the current study, only FAW incidence during season 2 was close to the economic injury level reported at tasseling. However, the success recorded by (Cruz et al. 2012) suggests that incidence should be coupled not only with the number of larvae per plant but also with the severity of damage and stage of plants as these are the determinants of yield loss.

Spraying maize plants with insecticide once or twice after 3-moth capture did not consistently reduce FAW incidence and abundance during the two seasons in the treatments compared with the control, especially during season 1. In season 2, we observed a significant reduction of FAW incidence, especially in the double spray treatment, which is consistent with Costa et al. (2005) who suggested that two insecticide applications are needed to achieve effective control of FAW in maize fields. However, since differences between the first and second insecticide applications were not consistent between the two seasons, our results suggest that the second pesticide application can be skipped. Similar findings were reported by Jaramillo-Barrios et al. (2020) where one season recorded differences in FAW abundance between single and multiply sprays based on different threshold levels, but the other season did not. This indicates that using moth-capture in pheromone traps as a threshold for pesticide intervention against FAW does not provide consistent results.

The reduction in FAW damage obtained for the treatment at a 25% damage threshold in season 2 validates those of Bessin (2004) and Cruz et al. (2012). The failure to obtain the same results at 25% in season 1 cannot be attributed to a delay in spraying because even spraying at 10% which occurred one week earlier was not effective in significant yield improvement. Furthermore, a threshold of 50% of the plants with severe leaf damage was recommended as a threshold by other authors (Steffey et al. 1999, Hruska 2019), even went as far as 75% of the plants exhibiting whorl feeding damage and larvae are less than 1–1/4 in (31 mm) long. In the present study, the thresholds used were far below those recommendations. Therefore, an appropriate threshold in the African context should be established considering already proven threshold dimensions.

The observed inconsistency between treatment efficacy between the 2 seasons highlights the role of environmental factors that do not promote exponential growth of FAW in season 1 versus the

Table 3. Percentage of plants (mean% ± SE) in each of the damage severity scales during the two cropping seasons

Severity scale (%)	Control	SS	DS	S10%	S25%	$F_{(4,15)}$	P
Season 1							
Scale 1 (0%)	56.4 ± 4.3	60.7 ± 4.9	58.2 ± 6.9	66.1 ± 5.1	65.4 ± 3.8	0.70	0.60
Scale 2 (1–25%)	22.5 ± 2.1	22.1 ± 3.2	25.0 ± 5.2	20.4 ± 4.4	21.1 ± 3.7	0.21	0.93
Scale 3 (26–50%)	10.0 ± 3.1	9.6 ± 2.1	10.4 ± 2.8	8.6 ± 1.0	8.2 ± 1.2	0.18	0.95
Scale 4 (51–75%)	6.1 ± 1.6	4.6 ± 1.4	4.3 ± 1.0	3.2 ± 0.7	3.2 ± 1.2	0.96	0.46
Scale 5 (>75%)	5.0 ± 2.2	2.9 ± 1.3	2.1 ± 1.2	1.8 ± 1.4	2.1 ± 1.2	0.73	0.59
Overall mean	42.7 ± 5.2	38.7 ± 4.4	38.4 ± 4.9	37.5 ± 4.7	37.7 ± 5.5	0.66	0.63
Season 2							
Scale 1 (0%)	26.6 ± 3.0	41.3 ± 6.4	39.7 ± 1.9	33.1 ± 3.6	42.5 ± 1.4	3.27	0.04
Scale 2 (1–25%)	52.5 ± 2.2a	42.8 ± 3.2b	40.0 ± 0.7b	45.3 ± 1.3ab	40.0 ± 2.6b	5.68	0.01
Scale 3 (26–50%)	13.8 ± 1.3	11.6 ± 2.0	12.2 ± 1.6	11.9 ± 1.2	12.5 ± 1.6	0.30	0.88
Scale 4 (51–75%)	4.4 ± 0.6ab	2.2 ± 1.4b	6.6 ± 1.1ab	6.9 ± 0.8a	3.8 ± 1.1ab	3.59	0.03
Scale 5 (>75%)	2.8 ± 0.6	2.2 ± 1.5	1.6 ± 0.6	2.8 ± 0.8	1.3 ± 0.9	0.59	0.67
Overall mean	36.1 ± 1.1	33.9 ± 1.7	35.3 ± 1.0	37.3 ± 1.3	34.7 ± 1.4	0.94	0.45

Mean with different letters in a row are significantly different from Tukey's test at $P < 0.05$. Single spray (SS), Double spray (DS) Spray at 10% incidence (S10%), Spray at 25% incidence (S25%).

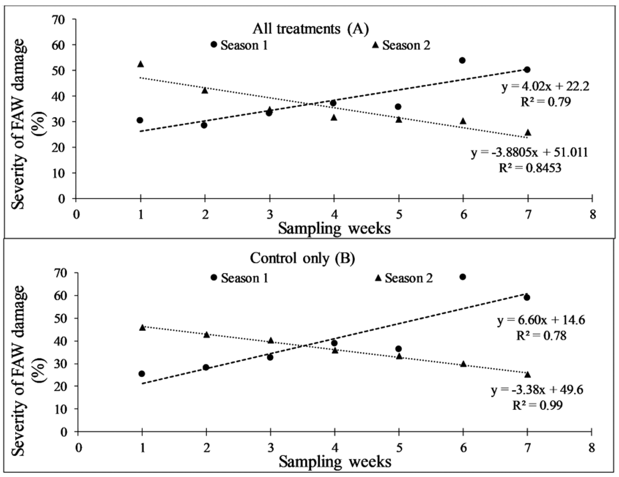

Fig. 9. Linear regressions of plant injury (damage severity) during each season with weekly observations for all treatments combined (A) and the control only (B).

absence of these parameters in season 2, thus enabling normal growth of the population. Indeed, the incidence and abundance of larvae and their mortality after insecticide applications were higher during season 2 while severity was lower in season 2, probably influenced by rainfall patterns. Although this is a 1-yr-study duplicated during 2 cropping seasons, historical rainfall data of the study area collected at the IITA-Cameroon weather station shows that the 2017 total rainfall (1,830 mm) and the distribution were not too different from the 10-yr (or more) average of 1,767 mm. The four years after the study year (2018, 2019, 2020, and 2021) recorded 1,947 mm of average rainfall still similar to 2017. Although total rainfall was higher in season 1 (1,025 mm) than in season 2 (805 mm), it was not concentrated but was almost uniformly distributed (120 and 340 mm) throughout the season, in contrast to season 2 where rainfall was not uniformly distributed (Fig. 1). The highest rainfall occurred between 18 DAS and 49 DAS (September and October) in season 2 when the plants were most vulnerable (vegetative stages I and II) which could have led to the observed drop in FAW infestations at this point and consequently reduced damage, leading to the higher yield and plant parameters observed in the season 2. Rainfall seems to be the only climatic or weather parameter with clear seasonal variations compared to temperature and relative humidity. The presence of damage or larvae on plants indicates the incidence but the impact on the crop is determined by the severity of the damage. In both seasons, neither single nor double spray treatments affected FAW damage severity. This implies that moth capture with pheromone taken alone may not guide pesticide intervention decisions in the present agro-ecological context, contrary to the results obtained by (Cruz et al. 2012). It may also indicate that the indicated threshold is not suitable as a decision tool in tropical/sub-tropical contexts where factors such as temperature, humidity, rainfall, and season may greatly impact moth flight. There is a need to evaluate and set adapted thresholds that will trigger interventions in farmers' fields under local field conditions. In both cases external factors such as climate, natural enemies, agricultural practices present at the time of intervention may render the treatments ineffective, thus the necessity to investigate the role played by these factors to contextualize the recommendations (Buntin et al. 2001; Buntin et al. 2004a,b; Buntin 2008; Baudron et al. 2019).

The observed difference in incidence and infestation level between treatments and the control during season 2 did not translate into a significant increase in yield or differences in any of the plant parameters. Similar findings were reported by (Cruz and Turpin 1983) with no effect of FAW on maize yield if treated. This could mean the plant, was able to recover which rendered insecticide application unnecessary. More investigations on the maize plant's response to injuries and other external factors that could influence recovery from damage, the time, and the level of damage are recommended. Several studies (Buntin et al. 2001; Buntin et al. 2004a,b; Buntin 2008) led to the conclusion that other factors may contribute to FAW control, with or without the use of insecticides. The maize plant's response to FAW infestations is highly dependent on these factors including the level and timing of infestation and natural enemy levels – that can help regulate the populations – and the health and vigor of the maize plant (nutritional and moisture status). During the study, appropriate fertilization methods

Table 4. Average (±SE) maize agronomic parameters for each treatment and by season

Treatment	Plant height (cm)		Diam. stem (cm)		Cob length (cm)		Yield (t/ha)	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
Control	229.5 ± 5.8	213.2 ± 9.2	1.8 ± 0.0	2.2 ± 0.1	14.2 ± 0.4	16.2 ± 0.4	3.7 ± 0.2	5.0 ± 0.3
Single spray	224.1 ± 4.1	227.4 ± 6.3	1.8 ± 0.0	2.2 ± 0.1	13.1 ± 0.4	17.1 ± 0.6	3.5 ± 0.2	5.6 ± 0.6
Double spray	232.4 ± 6.1	238.6 ± 4.5	1.9 ± 0.0	2.2 ± 0.1	13.3 ± 0.8	18.6 ± 1.2	3.7 ± 0.5	6.7 ± 1.1
Spray at 10% incidence	235.3 ± 3.2	228.8 ± 5.8	2.0 ± 0.1	2.2 ± 0.1	14.1 ± 0.8	15.8 ± 0.8	3.7 ± 0.4	4.6 ± 0.4
Spray at 25% incidence	223.7 ± 7.2	227.3 ± 3.0	1.7 ± 0.1	2.4 ± 0.1	13.4 ± 0.8	16.8 ± 0.4	3.5 ± 0.4	5.2 ± 0.4
$F_{(4,15)}$	0.87	2.19	1.83	0.83	0.59	2.09	0.09	1.69
P value	0.51	0.12	0.18	0.53	0.68	0.13	0.98	0.20

Table 5. Interaction between the two seasons and the treatments

Statistics	FAW abundance	Larval mortality	Damage severity	Incidence	Plant Height	Stem Diameter	Cobs (per plan)	Cob Width	Cob Length	Yield
F	3.380	4.1	0.789	0.947	1.303	1.969	0.873	0.421	2.224	1.296
df	4, 30	4, 30	4, 30	4, 30	4, 30	4, 30	4, 30	4, 30	4, 30	4, 30
Residual	10.72	14280	476.3	2042.6	4036.3	0.770	0.365	14.73	59.61	30.53
Pr(>*F*)	0.021	0.009	0.542	0.451	0.291	0.125	0.491	0.792	0.090	0.294

were followed – such as organic manure before sowing, NPK (20:10:10), and urea at recommended rates for the study site (Abang et al. 2020). Seeds were treated with Calthio C, an insecticide and fungicide combination with 25% Chlorpyrifos-ethyl and 25% Thiram. These crop management practices may play a role in FAW control and yield improvement which calls for more research to determine their role in FAW management. Contrary to the results presented in the current study, two incidence levels (10 and 25%) were tested and reductions in damage and yield losses were obtained (Cruz et al. 2012). Failure to obtain a significant difference in yield at least between the control and 25% incidence or the double spray treatments in season 2 highlights the need to understand the effects of external factors. Under the present experimental conditions, it is evident that pesticide intervention was not necessary. Based on the results of field trials on FAW impact on maize yield in the USA, it was demonstrated that application of an insecticide is usually not economical for FAW control except when more than 75% of plants have whorl feeding damage and the plants are under stress (Hruska 2019). This calls for a critical understanding of the context under which recommended intervention thresholds are stated, and replication or transfer of recommendations should be guided by agroecological guidelines and regional conditions.

Barlow and Kuhar (2009) suggested that pheromone traps are more efficient and sensitive to regional changes and that catches are not necessarily good indicators of density but could simply indicate the presence of moths in an area. He added that insecticide applications should take place when a pheromone trap catches 70 to 140 FAW adults per night, whereas very few (2.3–8.35 per week) were caught during the current study. Cruz et al. (2012) also reported less capture but recorded results that were contrary to the current study, thus suggesting that there could be variations even within the same region. Moth counts in traps cannot be the sole trigger for FAW intervention while ignoring other biological factors such as the presence and number of FAW egg masses and larvae on the maize plants. Additionally, incidence only indicates that a plant was attacked by the pest but does not measure the pest injury. Hence, the severity of damage or injury should be a useful parameter in assigning intervention thresholds. During the present study, none of the treatments affected FAW damage severity. Damage severity was more important towards the end of the cropping cycle in season 1 as opposed to season 2. The decreasing severity in season 2 versus increasing severity in season 1 could also be a consequence of the fact that FAW came too early in season 2 resulting in lower pressure later in the season, while in season 1 it came later and increased gradually. Decreasing trends similar to those observed in season 2 have recently been reported in other studies (Murúa et al. 2006, Abang et al. 2020), and the plant is more susceptible during that period (Jaramillo-Barrios et al. 2019). Depending on the level, an early injury may come when the plants are still fragile and do not have enough vigor to recover, and late injury may occur at phenological stages that are critical for the kernel stage. According to (Hruska and Gladstone 1988), maize plants can compensate for FAW damage at any developmental stage. However, considering the importance of the degree of injury, it will be interesting to test a similar hypothesis in the context of the approach of the present study. Since the injury increased in season 1 and decreased in season 2, we expected maize yield loss in season 1, but it did not happen, suggesting that FAW damage alone cannot translate into yield loss without the contribution of external factors regulating pest population and feeding behavior and affecting plant growth (FAO and CABI 2019).

This study has shown that the two decision tools are not consistent in triggering intervention that could result in reducing FAW damage on maize, and even when the reduction is effective the damage and severity may not translate into significant yield loss. Proposed thresholds by various authors should not be used as they are suggested for all agro-ecologies, but should consider various factors (rainfall, natural enemies, soil fertility, maize recovery ability, etc.), in setting thresholds for specific areas. Studies should be envisaged where a higher threshold can be set in areas where parameters like weather and natural enemies could naturally curb FAW population growth, but lower thresholds can be set where FAW populations grow without any effects of natural factors such as rain belts or high intensity of natural enemies' activities. Similarly, investigations, where incidence is coupled with severity and number of larvae per plant, may have a direct impact on plant growth and subsequent yield, and contribute to establishing appropriate decision tools to spray against FAW at a threshold above which observed damage may translate into significant yield loss.

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