International Journal of Tropical Insect Science (2022) 42:1619–1626
https://doi.org/10.1007/s42690-021-00683-5

ORIGINAL RESEARCH ARTICLE

Assessment of *Bacillus thuringiensis* and emamectin benzoate on the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) severity on maize under farmers' fields in Ghana

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Received: 23 October 2020 / Accepted: 30 October 2021 / Published online: 16 November 2021
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Abstract
The introduction of fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae) into Ghana is a threat to maize production. This study determined the severity of this pest on maize production subjected to *Bacillus thuringiensis* (Bt), emamectin benzoate (Eb) sprayed and unsprayed farms under farmers' practices in Ghana. At least one farm per treatment was selected in each Agro-Ecological Zone (AEZ) for data collection throughout the maize phenology during three production seasons. Percent damaged plants and ears were determined, the proportion of feeding damage on leaves and ears was scored, and yields measured on each farm. Ear damage was most severe in the Guinea Savannah Agroecological Zone with a correspondingly lower yield. The highest yield was recorded from the Tropical Rain Forest zone. The damage levels decreased when plants aged, but the scoring of damage level on attacked ears was greater than that on leaves. Maize plant damage was highest with corresponding lowest yields on unsprayed farms compared to sprayed farms which recorded similar results for both insecticides. *Bt* and Eb based insecticides (applied at 50g/15L H_2O/ha and 75mL H_2O/ha, respectively) are effective on FAW larvae and are therefore recommended for FAW management in Ghana.

Keywords Fall armyworm · Incidence · Severity · Seasons · Maize phenology · Management

Introduction

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a major pest of maize and many crops of economic importance in the Americas (Luginbill 1928; Bass 1978; Pitre 1979; Sparks 1979; Young 1979; Pitre and Hogg 1983; Wiseman et al. 1983; Pitre et al. 1983; Nagoshi and Meagher 2004; Hernández-Mendoza et al. 2008; Goergen et al. 2016). It has spread throughout Sub-Saharan African countries and recently to Asia (Nagoshi et al. 2017, 2018; IITA 2018; ICAR-NBAIR 2018; IPPC 2018, 2019; FAO 2019). The damaging stage of this insect is limited to the larval stage which feeds on crops and causes damage that results in yield losses and eventually impacts the livelihoods of farmers as well as the economy of countries (Casmuz et al. 2010). The larvae of FAW attack all the phenological stages of the maize plant by feeding on the leaves, inside whorl, and tender tissues of the tassel and ears. At the early stages of the maize plants, the young larvae firstly feed on the tender portions of leaves leaving intact the membranous epidermis on the other side (Capinera 2000, 2017), whereas mature larvae feed on the leaf by making holes or may destroy small plants and strip larger ones (Cruz 1995). Inside the whorl, larvae are protected from external factors and are free to cause severe leaf-damage. Depending on the developmental stage of the maize plant infested by the FAW, pest density, management strategies, capacity of natural factors to reduce the pest population, and agronomic practices, the yield losses may vary from mild to severe (Perdiguero et al. 1967; Carvalho 1970; Cruz and Turpin 1982, 1983; Williams and Davis 1990; Willink et al. 1991; Cruz et al. 1996; De Almeida Sarmento et al. 2002).

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To minimize damages caused by the FAW, different management methods have been developed. The resistant maize hybrids with antibiosis and non-preference as key mechanisms have successfully produced greater yields compared to susceptible hybrids at similar infestation levels (Wiseman et al. 1981, 1983; Sparks 1986; Wiseman and Davis 1990). Biological control of FAW has been considered an important management method since the identification of 53 species of parasitoids that infest the FAW globally (Ashley 1979; Sparks 1986). However, when the infestation level is above the economic threshold, insecticides are the most effective method applied at the egg masses or early larval instar stages for population reduction (Beuzilin et al. 2014). Management of the FAW has thus become heavily reliant on insecticides, but unfortunately, incorrect and indiscriminate application of insecticides has induced resistance in the pest as well as affecting non-target organisms including native natural enemies (Tinoco and Halperin 1998; Gómez-Valderrama et al. 2010).

A State of Emergency for agriculture was declared in Ghana in 2017 after the invasion and severe infestation of this pest on maize (Koffi et al. 2020a). The Government as part of the response assisted farmers with different type of insecticides, training, and awareness creation among actors. However, due to the invasive nature of the pest, and rapid spread, the effectiveness of pesticides was not tested. This study therefore aimed at evaluating the two most commonly used pesticide active ingredients (*Bacillus thuringiensis* and emamectin benzoate) by farmers to manage this pest. The damage levels on maize plants at different phenological stages and ears as well as yield were studied in the AEZs of Ghana.

Materials and methods

Study area and sampling schedule

Inspections as well as data collections were done on maize farms at different phenological stages from different localities of the major AEZs of Ghana (Fig. 1) during three consecutive cropping seasons from 2017 to 2018. During each cropping season, five maize farms were selected within each AEZ. The first data collection covered the period from 5th May to 22nd July 2017, the second from 29th August to 27th November 2017, and the third from 12th July to 20th October 2018. The first period (Per 1) was during the major cropping season in the South and the beginning of the cropping season in the North. The second period (Per 2) was in the minor cropping season in the South and covered the end of the cropping season in the North. The third period (Per 3) covered the last half of cropping season in the north and the first half of minor cropping season in the south.

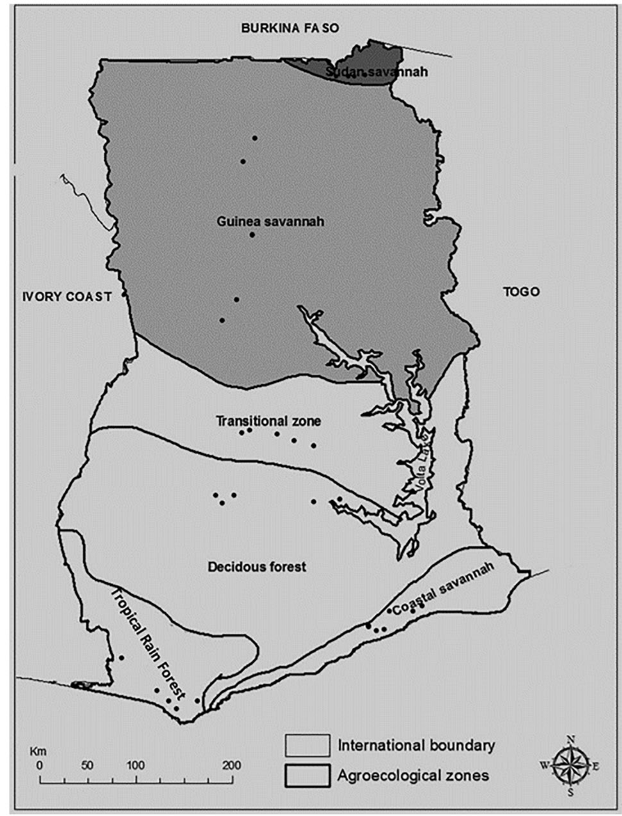

Fig. 1 Agro-ecological zones with geo localization of study sites in dots, CS-Coastal Savannah, GS-Guinea Savannah, SDF-Semi Deciduous Forest, SS-Sudan Savannah, TRF-Tropical Rain Forest, TZ-Transitional Zone

Survey and data collections

Among 90 maize farms randomly selected from all the six AEZs of Ghana, 33 farms were sprayed with emamectin benzoate (at 75mL/15L H_2O/ha), 27 farms with *Bacillus thuringiensis* (at 50g/15L H_2O/ha), and 30 farms as control or unsprayed. Farms were sprayed three times at vegetative four-six leaves, eight-ten leaves, and tasseling stages. All The farms were inspected once at each phenological stage which included vegetative V4-8, vegetative V8-12, tassel, and mature stages to record damage parameters on 100 plants. Sampling followed the diagonal quadrant method with 20 plants sampled from each of four corners of the farm plus the intersection of the two diagonals to obtain five sampling plots. The number of plants or ears damaged by fall armyworm as described by Capinera (2000, 2017) was recorded for each phenological stage and the percentage of damaged plants or ears calculated using Eq. (1). Scoring of damage severity on leaves and ears followed the scale of Davis and Lewis. At harvest, yields were estimated as total grain weight per hectare.

$$Dl = \frac{Ndp}{Np} \times 100 \quad (1)$$

where: Dl - Percentage of damaged plants or ears, Ndp - number of damaged plants or ears, and N_p = total number of inspected plants or ears. The proportion of control with a specific control method was calculated using Eq. (2):

$$Cl = \frac{ncf}{nf} \times 100 \quad (2)$$

where: Cl – control level of a specific control method, ncf – number of farms controlled with a specific method, nf – total number of inspected farms.

Data analysis

All computations were carried out with Excel and grouped into AEZs, plant phenological stages, and types of management methods adopted during the three periods of this study. The percentage values were arcsine ARSIN (SQRT(X)) transformed before analysis. All data were subjected to a Schapiro test in GenStat Twelfth Edition (GenStat Procedure Library Release PL20.1) for normality. Normally distributed data were further subjected to ANOVA that carried out the interaction effects among the factors and means separated with Tukey at a 5% error level. In the absence of normality, data were subjected to a non-parametric test (Kruskal-Wallis) at the 5% confidence level.

Results

Damage across cropping periods

Significant interactions were observed between the cropping periods and AEZs distributed within the two cropping seasons of the south and a cropping season of the north by analyzing the percent damaged plants ($F_{2, 10}$=3.58; P<0.001), the score of damaged leaves ($F_{2, 10}$=5.80; P<0.001), and percent damaged ears ($F_{2, 10}$=2.09; P=0.036). This interaction was not significant for the damage score on ears ($F_{2, 10}$=0.47; P=0.902), and yield ($F_{2, 4}$=0.13; P=0.969). Interactions were significant between the cropping periods and management practices regarding the percent damaged plants ($F_{2, 4}$=3.44; P=0.009), damage score on leaves ($F_{2, 4}$=7.04; P<0.001) but not for the percent damaged ears ($F_{2, 4}$=1.34; P=0.263), damage score on ears ($F_{2, 4}$=1.82; P=0.133) and yield ($F_{2, 4}$=0.13; P=0.969).

The percentages of damaged plants during the Per1 and Per2 were nearly three times higher than those of Per3. When the total surface of damaged leaves by the FAW larvae was scored, they were all under half of the total leaf surfaces. The scores during the Per1 and Per2 were similar but higher than the score of Per3. The levels of damage due to the FAW feeding on maize ears also showed similarities between Per1 and Per2 which were approximately three times higher than the percentage recorded during the Per3. Concerning the feeding scores of ears by the FAW larvae, a considerable decrease was observed during the Per3 compared to the previous periods. The yield estimation for the three seasons showed similar and low yields in Per1 and Per2 compared to the Per3.

Impact of FAW on maize production within and across AEZs

The AEZs and the management practices did not show significant interactions for the percent damaged plants ($F_{5, 9}$=0.18; P=0.996), damage score of leaves ($F_{5, 9}$=1.01; P=0.436), percent damaged ears ($F_{5, 9}$=0.80; P=0.618), damage score on ears ($F_{5, 9}$=0.83; P=0.590), and yield ($F_{5, 9}$=1.16; P=0.333).

During three periods of study, the percentage of damaged plants was higher in the Guinea Savannah (GS) zone which is bordered by the Sudan Savannah (SS) zone where the lowest damaged plants was recorded. Within all the AEZs, the percentages of damaged plants were higher during the Per1 and Per2 of 2017 than the Per3 in the 2018 cropping season (Table 1). Fall armyworm larval damage severity on leaves was higher in GS than the other AEZs during Per1 and Per2. However, during Per3, the highest scores were registered in SS. Within all the AEZs, damage severities were higher during the Per1 and Per2 than Per3 (Table 1).

The percentages of damaged ears were higher in CS and GS than the other AEZs. In terms of seasonal trends, the percentages of damaged ears were higher during the first two periods than the Per3 in all the AEZs (Table 1). No significant difference was established for damage severity among the AEZs during the study period (Table 1). Within the AEZs, the damage scores were high during the Per1 and Per2 than the Per3 in all AEZs except SDF and SS (Table 1).

The yields recorded during the Per1 and Per2 showed no significant difference across the AEZs, while the yields were higher in Tropical Rain Forest (TRF) and Semi-Deciduous Forest (SDF) than other AEZs during the Per3. Within the AEZs, only the SDF presented significant differences among the three periods with the highest yield in Per3 (Table 1).

Damage variations among maize plant phenological stages

Between the management practices and plants stages, the interactions were not significant for the percentage of damaged plants ($F_{2, 4}$=0.10; P=0.982), and damage score of leaves ($F_{2, 4}$=1.60; P=0.175).

The damages of FAW larvae on maize plants and ears were most severe during the early vegetative growth

Table 1 Severities of fall armyworm on maize plants and ears within and across the AEZs of Ghana

Factors	Periods	CS	TRF	SDF	TZ	GS	SS	df	F	P
Damaged plants (%)	Per1	67.47Bbc	60.73Bab	73.93Bcd	58.07Bab	84.66Bd	54.47Ba	5, 89	13.49	<0.001
	Per2	66.87Bbc	59.40Bab	73.53Bcd	59.40Bab	84.66Bd	54.40Ba	5, 89	14.63	<0.001
	Per3	21.40Abc	19.87Aab	23.40Ac	19.80Aab	28.07Ad	18.00Aa	5, 89	15.02	<0.001
	df	2, 44	2, 44	2, 44	2, 44	2, 44	2, 44			
	F	213.72	160.91	360.51	160.69	284.35	133.40			
	P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
Damaged Leaf-scores	Per1	2.29Ba	1.53Ba	1.91Ba	1.52Ba	3.89Bb	1.76Ba	5, 89	14.32	<0.001
	Per2	2.36Bb	1.53Ba	1.88Bab	1.56Ba	3.69Bc	1.79Bab	5, 89	13.63	<0.001
	Per3	0.95Aab	0.76Aa	0.75Aa	0.77Aa	1.02Aab	1.18Ab	5, 89	4.51	0.001
	df	2, 44	2, 44	2, 44	2, 44	2, 44	2, 44			
	F	15.99	9.12	10.71	21.07	30.89	3.74			
	P	<0.001	<0.001	<0.001	<0.001	<0.001	0.032			
Damaged ears (%)	Per1	45.36Bd	29.40Bc	25.21Bbc	19.02Bab	41.97Bd	18.23Ba	5, 29	9.51	<0.001
	Per2	43.97Bd	30.00Bc	25.21Bbc	19.82Bab	40.18Bd	19.82Ba	5, 29		<0.001
	Per3	12.79Ac	9.80Ab	8.40Ab	6.40Aa	12.99Ac	6.41Aa	5, 29		<0.001
	df	2, 14	2, 14	2, 14	2, 14	2, 14	2, 14			
	F	14.80	39.29	27.02	36.94	105.75	31.02			
	P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
Damaged ear-scores	Per1	4.16Cab	4.12Bab	3.64Bab	4.32Bb	4.26Bb	3.03Aa	5, 29	1.03	0.422
	Per2	3.64Ba	3.78Ba	3.44Ba	4.06Ba	3.88Ba	3.36Aa	5, 29	0.53	0.754
	Per3	2.38Aa	2.46Aa	2.78Aa	2.50Aa	2.74Aa	2.38Aa	5, 29	0.76	0.589
	df	2, 14	2, 14	2, 14	2, 14	2, 14	2, 14			
	F	11.24	10.76	2.44	20.91	5.99	1.03			
	P	0.002	0.002	0.129	<0.001	0.016	0.385			
Yield (t/ha)	Per1	1.56Aabc	1.72Ac	1.48Aabc	1.620Abc	1.32Aa	1.34Aab	5, 29	1.36	0.274
	Per2	1.58Aab	1.68Ab	1.42Aab	1.58Aab	1.30Aa	1.32Aa	5, 29	0.99	0.447
	Per3	1.30Aa	1.84Ac	1.90Bc	1.74Abc	1.48Aab	1.52Aab	5, 29	3.63	0.014
	df	2, 14	2, 14	2, 14	2, 14	2, 14	2, 14			
	F	0.95	0.71	3.68	0.71	0.64	0.33			
	P	0.414	0.512	0.047	0.512	0.546	0.725			

CS Coastal Savannah, *GS* Guinea Savannah, *SDF* Semi Deciduous Forest, *SS* Sudan Savannah, *TRF* Tropical Rain Forest, *TZ* Transitional Zone. Means of one factor in the column followed by the same upper letter show no significant difference and means in the same row follow by the same lower case letter show no significant difference. Otherwise, differences are observed at the 5% confidence interval

stages (V4-12). During the three cropping seasons of this study, the percentage of damaged plants decreased as plants advanced in age. However, the difference in FAW damage between the maize plants at V4-8 and V8-12 stages was not significant but differences were observed between these stages and the older (tassel and mature) stages. Larval feeding scores on maize leaves, though similar between the V4-8 and V8-12, decreased with the age of maize plants as observed during the Per1 and Per2. During the Per3, no difference was observed between the V4-8, V8-12, and tassel stages. But the damage scores on ears due to the FAW larvae were more severe than the damage score to leaves during the vegetative stages.

Impact of management practices on fall armyworm damage severity

Farms on which FAW was managed with insecticides containing the entomopathogenic bacteria *B. thuringiensis* and avermectin, emamectin benzoate as active ingredients, were compared to control farms where no insecticides were used. Under natural FAW infestation pressures, a higher percentage of damaged plants were observed on the control farms than both insecticide-treated farms during the three periods of this study. Farms treated with both insecticides recorded a closer percentage of damaged plants (Table 2). A similar trend was observed for FAW damage severity on leaves among the three treatments during three periods of study (Table 2).

Table 2 Comparison of FAW damage on maize plants treated with *Bacillus thuringiensis* and emamectin benzoate to control FAW during the three periods of study

injuries	Period	*Bt*	*Eb*	Unsprayed	df	F	P
Damaged plants (%) (±SD)	Per1	62.70 ± 2.51	59.91 ± 2.27	77.33 ± 2.39	2, 89	14.22	<0.001
	Per2	63.70 ± 2.60	61.58 ± 2.35	74.23 ± 2.46	2, 89	7.04	0.001
	Per3	21.04 ± 0.84	20.27 ± 0.76	24.03 ± 0.80	2, 89	5.72	0.005
	df	2, 14	2, 14	2, 14			
	F	17.23	16.32	19.53			
	P	<0.001	<0.001	<0.001			
Shewed leaf-score	Per1	1.69 ± 0.18	1.49 ± 0.16	3.29 ± 0.17	2, 89	35.57	<0.001
	Per2	1.69 ± 0.17	1.57 ± 0.15	3.16 ± 0.16	2, 89	31.70	<0.001
	Per3	0.71 ± 0.04	0.72 ± 0.04	1.29 ± 0.04	2, 89	60.57	<0.001
	df	2, 14	2, 14	2, 14			
	F	7.29	6.58	8.09			
	P	<0.001	<0.001	<0.001			
Damaged ears (%) (±SD)	Per1	24.89 ± 4.00	25.00 ± 3.62	39.70 ± 3.80	2, 29	4.63	0.019
	Per2	26.00 ± 3.92	27.09 ± 3.55	36.10 ± 3.72	2, 29	1.92	0.167
	Per3	8.67 ± 1.09	8.72 ± 0.99	11.00 ± 1.04	2, 29	1.64	0.212
	df	2, 14	2, 14	2, 14			
	F	6.54	5.98	9.08			
	P	<0.001	<0.001	<0.001			
Damage ear-score (±SD)	Per1	3.49 ± 0.26	3.74 ± 0.23	4.65 ± 0.24	2, 29	6.17	0.006
	Per2	3.24 ± 0.23	3.56 ± 0.21	4.24 ± 0.22	2, 29	5.20	0.012
	Per3	2.50 ± 0.15	2.48 ± 0.14	2.64 ± 0.14	2, 29	0.37	0.697
	df	2, 14	2, 14	2, 14			
	F	3.25	6.56	8.13			
	P	0.016	<0.001	<0.001			
Yield (±SD)	Per1	1.72 ± 0.06	1.66 ± 0.05	1.14 ± 0.05	2, 29	34.97	<0.001
	Per2	1.64 ± 0.09	1.65 ± 0.08	1.14 ± 0.08	2, 29	12.77	<0.001
	Per3	1.80 ± 0.08	1.78 ± 0.07	1.31 ± 0.08	2, 29	12.77	<0.001
	df	2, 14	2, 14	2, 14			
	F	0.89	0.76	0.92			
	P	0.058	0.063	0.059			

Bt Bacillus thuringiensis*, Eb* emamectin benzoate

The percentage of damaged ears was lower in the insecticide-treated farms than the control farms during the Per1, but the Per2 and Per3 showed no significant differences for the percent damaged plant from the different treatments (Table 2). When the damage scores on ears were compared among the treatments, it showed a significantly higher damage proportion on ears in control farms than sprayed farms during the Per1 and Per2. While no significant difference was observed among the three treatments during Per3 (Table 2). The farms sprayed with the entomopathogen and avermectin insecticide registered closer yields per hectare, which were higher than the control farms (Table 2).

Discussion

This study was conducted to assess the severity of FAW on maize production subjected to *Bacillus thuringiensis* and emamectin benzoate sprays which were compared to unsprayed control farms during three cropping seasons across the AEZs of Ghana. The invasion of FAW in Ghana was reported in 2016 (Cock et al. 2017; Koffi et al. 2020a) and by 2017, the pest had established in all the AEZs of the country (Koffi et al. 2020a, c). In the absence of appropriate control measures and under favourable natural conditions, the new pest rapidly multiplied and increased in population leading to outbreaks with severe impact on maize production in 2017 as observed during the Per1 and Per2 of this study. Considering the agricultural emergency, urgent control measures were taken with considerable involvement of the Government of Ghana and its partners to assist farmers. Efforts towards finding sustainable solutions included of the identification of seven species of larval parasitoids and three species of larval predators of FAW which were collected at Ghana in 2017 (Koffi et al. 2020b), and later egg and larval parasitoids in 2018 (Agboyi et al. 2020). Other efforts to manage the new pest, combined with the presence of natural enemies reduced this pest population, and therefore its impact on maize in 2018 as evident during the Per3 of this study (Koffi et al. 2020c). Koffi et al. (2020a) in their study on maize infestation of FAW within AEZs of Togo and Ghana in West Africa three years after this pest invasion, reported higher infestation in 2016 and 2017 than in 2018 in both countries. The high damage impacts on maize plants and ears during the Per1 and Per2 affected the yields which were lower than the yield of Per3.

The highest damage on maize plants and ears was recorded at the GS which is traditionally considered as a high maize production zone (MoFA 2016). It was also reported among the three zones forming a boundary where high infestations of FAW were reported in 2016 and 2017 (Koffi et al. 2020a). However, the high damages recorded did not result in low yield as expected, indicating that other factors may affect maize yield across the AEZs. These factors can be associated with the type of soils, rainfall patterns, and agronomic practices. But the Savannah zones are characterized by sandy soil that can be found in SS, GS, and CS. If maize yield is only depending on the type of soil, the yields from these three zones should be similar with or without similar damages of FAW on plants and ears. The damages from GS were however higher than the two other zones, thus eliminating the assumption of the effect of type of soils on the yield during this study. Southern Ghana, which includes CS, TRF, SDF, and TZ has bimodal rainfall while the North covered by GS and SS has unimodal rainfall. If the similarities of yields observed during this study should be affected by the rainfall pattern, the yield from GS may be lower than the SS due to high damages in GS. This assumption should also be eliminated for the results of this study. The most probable factor that may have lowered the yields in other AEZs to the level observed in GS should be the agronomic practices that vary among farmers. These practices include ploughing, weeding, ridging, and fertilizer applications that were not taken into consideration by this study.

The tissues of young maize plants are much succulent and preferred for feeding by FAW larvae. This also attracts females to lay eggs and since food is available, newly hatched larvae survive and disperse to the adjacent plants (Ali et al. 1989, 1990) to increase the number of damaged plants and the feeding proportion on leaves of the early-stage plants. As plants age, the leaf tissues become hard and unsuitable for larvae which are exposed to high mortality and progressively reduce the percentage of damaged plants and the damage severity on leaves. During the vegetative period, however, plants continue to produce new leaves that are suitable and available for the FAW larvae. This accounts for a similar percentage of plants damaged and damage severity on the V4-8 and V8-12 stages. During the tassel stage, larvae move to the axis of the leaves and are more exposed to mortality factors such as parasitoids and predators that reduce the number of damaged plants. At this stage, feeding is limited to the tassel and ears. At the maturity stage, which covers the ear formation and ear filling up to harvest, the tender tissues suitable for FAW larval feeding are limited to the ears which are usually too tough for young larvae, considerably reducing ear damage. However, when 234 the larva force ear-boring, it gets into the newly formed cob and causes severe damage. Once larvae find their way into the ear, they stay protected and cause significant feeding damage to the kernel with a consequence for grain yield.

When damage is above the economic threshold level, control measures need to be applied to the FAW larvae. In Ghana, insecticides remain the main tools for managing this new pest on maize farms though the effectiveness of some commonly used insecticides is questionable (Abrahams et al. 2017). The significance of this pest has been further enhanced by the inconsistent reliance on foliar insecticide sprays (Adamczyk et al. 2001). Some farmers do not spray their maize farms against FAW and the effectiveness of insecticide applications was not scientifically proven in Ghana. To test the field effectiveness of some insecticides, products based on two active ingredients *Bacillus thuringiensis* and emamectin benzoate, which are most widely used in Ghana against the FAW larvae were selected. The choice of these two insecticides is to compare the avermectin insecticides, emamectin benzoate to an alternative entomopathogen-based biopesticide (*Bacillus thuringiensis*). The bioefficacy of the two insecticides was similar, resulting in higher yields compared to the unsprayed farms. However, owing to the adverse effects of synthetic insecticides such as being harmful to humans and non-targeted organisms, as well as the environment, (Yu 1983), *Bacillus thuringiensis* based insecticides are recommended for FAW management in Ghana. Alternatively, since both insecticides have completely different modes of action, the two can be alternated as a mean of insecticide resistance management.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s42690-021-00683-5.

Declarations

Competing interest Authors declare no competing interests.

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