Fall armyworm in West Africa: Earwig predation potential and insecticide selectivity

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Description of the subject. The fall armyworm, *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae) is a major pest of staple cereal crops established in West Africa since 2016. Recently, earwigs have been observed consuming *S. frugiperda* immature stages in maize fields.

Objectives. In this study, we evaluated the potential of earwigs, *Diaperasticus erythrocephalus* (Olivier) (Dermaptera: Forficulidae) to consume fall armyworm eggs and larvae in a laboratory setting. In addition, we compared the selectivity of the ten most used bio- and insecticides on this predatory species as well as on its prey for identifying products compatible with an integrated pest management strategy.

Method. Predation was assessed by feeding earwigs *ad libitum* and susceptibility tests following the adapted IRAC 020 protocol.

Results. Our results suggest that earwigs play an important role in the regulation of the fall armyworm: one individual consumes a mean of 90.3 ± 16.5 eggs or 36.4 ± 8.7 larvae per day. We found emamectin benzoate and spinetoram to be effective for controlling the fall armyworm, while not affecting the survival of this predator. On the other hand, chlorpyrifos-ethyl, methomyl and spinosad are not only effective against this pest but also highly toxic to the predator.

Conclusions. We discuss the potential of these results in the development of an integrated pest management program against this invasive pest. In particular, we recommend training the farmers on natural enemy recognition and their conservation practices.

Keywords. Biological control, integrated pest management, maize, *Spodoptera frugiperda*, *Diaperasticus erythrocephalus*.

La chenille légionnaire d'automne en Afrique de l'Ouest : potentiel de prédation des perce-oreilles et sélectivité des insecticides

Description du sujet. La chenille légionnaire d'automne *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera : Noctuidae) est un ravageur majeur des cultures céréalières de base établi en Afrique de l'Ouest depuis 2016. Récemment, des perce-oreilles ont été observés consommant des stades immatures de *S. frugiperda* dans des champs de maïs.

Objectifs. Dans cette étude, nous avons évalué le potentiel du perce-oreille *Diaperasticus erythrocephalus* (Olivier) (Dermaptera : Forficulidae) à consommer les œufs et les larves de la chenille légionnaire d'automne au laboratoire. En outre, nous avons comparé la sélectivité de dix bio- et insecticides les plus utilisés sur cette espèce prédatrice ainsi que sur sa proie afin d'identifier les produits compatibles dans une stratégie de lutte intégrée.

Méthode. La prédation a été évaluée en nourrissant des perce-oreilles *ad libitum* et les tests de susceptibilité en suivant le protocole adapté IRAC 020.

Résultats. Nos résultats suggèrent que les perce-oreilles jouent un rôle important dans la régulation de la chenille légionnaire d'automne : un individu consomme en moyenne 90,3 ± 16,5 œufs ou 36,4 ± 8,7 larves par jour. Nous avons constaté que l'émamectine benzoate et le spinétorame sont efficaces pour lutter contre la chenille légionnaire d'automne sans affecter la survie de ce prédateur. En revanche, le chlorpyrifos-éthyl, le méthomyl et le spinosad sont non seulement efficaces contre le ravageur, mais aussi très toxiques pour le prédateur.

Conclusions. Nous discutons du potentiel de ces résultats dans le développement d'un programme de lutte intégrée contre ce ravageur envahissant. En particulier, nous recommandons de former les agriculteurs à la reconnaissance des ennemis naturels et aux pratiques de leur conservation.

Mots-clés. Lutte biologique, lutte intégrée, maïs, *Spodoptera frugiperda*, *Diaperasticus erythrocephalus*.

1. INTRODUCTION

Over the last decade, the fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae) has become one of the most important damaging invasive pests worldwide. It is native to the tropical and subtropical regions of the Americas, then its global distribution has expanded widely across Africa and Asia (Goergen et al., 2016; Maino et al., 2021; Kenis et al., 2023). This pest poses a significant threat to the production of staple cereal crops, consequently nutritional food security, and livelihoods of millions of farmers (Goergen et al., 2016). In maize, FAW is mainly managed by the application of chemical insecticides (Houngbo et al., 2020; Tambo et al., 2020; Palli et al., 2023), despite repeated demonstrations of resistance (Ahissou et al., 2021a; Kenis et al., 2023).

A diversity of FAW natural enemies have been identified in Senegal (Tendeng et al., 2019), Benin, Côte d'Ivoire, Ghana (Kenis et al., 2019; Agboyi et al., 2020; Koffi et al., 2020; Dassou et al., 2021), Niger (Laminou et al., 2020) and Burkina Faso (Ahissou et al., 2021b). While, natural enemies vary by country, some species are repeatedly reported in many countries, including *Coccygidium* spp., *Chelonus* spp. (Hymenoptera: Braconidae), *Trichogramma* spp. (Hymenoptera: Trichogrammatidae), *Telenomus* sp. (Hymenoptera: Platygastridae), earwigs (Dermaptera: Forficulidae), and various ant species. In Burkina Faso, the predatory guild is dominated by two Forficulidae species, *Diaperasticus erythrocephalus* (Olivier) and *Forficula senegalensis* (Serville) (Ahissou et al., 2021b). However, their potential as FAW biological control agents has never been evaluated in Africa, despite field observations suggesting their importance.

Studies have shown that certain earwigs are one of the most important natural enemies for controlling pests in maize crops in Brazil (Figueiredo et al., 2006; Cruz, 2007). Management decisions that focus exclusively on reducing insect pests such as chemical insecticides may also eliminate predators, and thus lead to pest control failure (Guedes et al., 2016). Broad-spectrum insecticides like carbamates, organophosphates, and pyrethroids are highly toxic to earwigs (Zotti et al., 2010; Campos et al., 2011). An alternative to keep these predators in the field is to use selective insecticides only. The choice of more selective insecticides is therefore warranted to allow compatibility and complementarity of chemical and biological control methods, which is vital for the successful of integrated pest management programs against FAW.

This research was conducted during the Ph.D. thesis of Besmer Régis Ahissou (Ahissou, 2022a) and aimed to investigate the predation potential of an earwig species commonly observed in Burkina Faso maize fields, *D. erythrocephalus*. Besides, the selectivity of the most used chemical and biological insecticides on adult earwigs and their prey to identify products compatible with an integrated pest management strategy against FAW were evaluated. This study will provide authorities and farmers with detailed information to choose the most appropriate insecticides to incorporate into the biological control of FAW in recently invaded areas.

2. MATERIALS AND METHODS

2.1. Insect culture

Earwig and FAW colonies were collected from different maize fields located in province of Houet (11°20'N, 4°15'W), and shipped to the laboratory at the University Nazi Boni (UNB) in Bobo-Dioulasso, Burkina Faso. Approximately 60 earwigs were reared in transparent plastic boxes (20 × 10 × 10 cm) with openings covered with a thin white cloth for ventilation. They fed on a diet made of maize powder (10 g) and insect remains consisting of dead pupae and adults of the FAW (50 g) from the laboratory stock rearing. The diet was replaced every two days. Wet cotton in a Petri dish was maintained in each plastic box as a water source for the insects. They were acclimated under laboratory conditions for one month before testing.

FAW larvae were fed daily on fresh maize leaves until pupation. Pupae were daily collected and placed

in a cage (60 × 40 × 40 cm); providing with a white paper for female oviposition. FAW adults were fed on a sugar water solution (100 g·l⁻¹). After oviposition, the white paper was removed and cut to individualize each egg mass in separate boxes (Ahissou et al., 2021a). The F1 generation of FAW was used for all bioassays. Both insects were reared under standard laboratory conditions of 25 ± 2 °C, 60 ± 15% relative humidity, and a 12L: 12D photoperiod.

2.2. Insecticides

We evaluated the survival of earwigs after exposure to ten commercial insecticide formulations used in maize fields against FAW (NAR = Normal Application Rate): abamectin 18 g a.i.·l⁻¹ (Acarius® EC, Savana, France, NAR = 1 l·ha⁻¹), chlorpyriphos-ethyl 480 g a.i.·l⁻¹ (Pyrical™ 480 EC, Arysta Lifescience, France, NAR = 1 l·ha⁻¹), deltamethrin 25 g a.i.·l⁻¹ (Tamega® EC, Savana, France, NAR = 0.5 l·ha⁻¹), emamectin benzoate 19 g a.i.·l⁻¹ (Emacot® 019 EC, Savana, France, NAR = 0.5 l·ha⁻¹), lambda-cyhalothrin 25 g a.i.·l⁻¹ (Sunhalothrin® 2.5% EC, Wynca Sunshine, Mali, NAR = 0.5 l·ha⁻¹), methomyl 250 g a.i.·kg⁻¹ (Savahaler® WP, Savana, France, NAR = 1.5 kg·ha⁻¹). Some biopesticides were also included in the assay as spinetoram 120 g a.i.·l⁻¹ (Radiant™ 120 SC, Dow AgroSciences, NAR = 100 ml·ha⁻¹), pinosad 480 g a.i.·l⁻¹ (Laser™ 480 SC, Dow AgroSciences, NAR = 100 ml·ha⁻¹), *Bacillus thuringiensis* 16,000 IU·mg⁻¹ (Bio K® 16 WP, Savana, France, NAR = 1.5 kg·ha⁻¹), and *Azadirachta indica* extracts (HN, Bioprotect, Burkina Faso, NAR = 5 l·ha⁻¹). The ten active ingredients, their IRAC group and modes of action are listed in **table 1**.

2.3. Predation on eggs and larvae of fall armyworm

FAW eggs (≤ 24 h old) were placed with a brush in each Petri dish (9 cm diameter). Preliminary tests showed that egg viability was not affected by this manipulation. Predation rate was assessed individually by placing *D. erythrocephalus* male or female (previously starved for 24 h) in Petri dish containing prey and sealed with parafilm. Egg predation rate was determined using 130-150 eggs. To evaluate the predation capacity on the FAW larval instars, the same protocol was used by introducing 60 L1, 30 L2 and 10 L3 larvae in each dish containing fresh maize leaves where a male or female earwig was subsequently added. The controls consisted of dishes containing fresh maize leaves and either eggs or larvae only. Five replicates of (10) earwigs were used for each sex and prey stage. The boxes were maintained under the same aforementioned conditions. After 24 h of earwig exposure, each dish was carefully examined with a binocular microscope to determine prey consumption (eggs and larvae). The eggs were totally consumed and sometimes only a thin transparent film remained. Consumed larvae were easily identified because only the cephalic capsule usually remained.

Table 1. Insecticides used against earwigs and fall armyworm populations. Group numbers and mode of action are those of IRAC, the Insecticide Resistance Action Committee — *Insecticides utilisés contre les populations de perce-oreilles et de chenille légionnaire d'automne. Les numéros de groupe et le mode d'action sont ceux du Comité d'Action contre la Résistance aux Insecticides (IRAC)* (https://www.irac-online.org/modes-of-action/).

Active ingredient	IRAC group	Chemical subgroup	Mode of action	Label rate (a.i·l⁻¹)
Methomyl	1A	Carbamates	Acetylcholinesterase (AChE) inhibitors	937.5 mg
Chlorpyriphos-ethyl	1B	Organophosphates		1,600.0 mg
Deltamethrin	3A	Pyrethroids	Sodium channel modulators	
	37.5 mg			
Lambda-cyhalothrin	3A			83.3 mg
Spinetoram	5	Spinosyns	Nicotinic acetylcholine receptor (nAChR) allosteric modulators	60 mg
Spinosad	5			160 mg
Abamectin	6	Avermectins	Chloride channel activators	63.0 mg
Emamectin benzoate	6			31.6 mg
Bacillus thuringiensis	11A	*Bacillus thuringiensis*	Microbial disruptors of insect midgut membranes	$8 \cdot 10^7$ IU
Azadirachta indica	UN	Azadirachtin	Compounds of unknown or uncertain MoA	14.0 ml

2.4. Insecticide susceptibility of earwigs and fall armyworms

Bioassays were conducted according to the IRAC standard leaf bioassay protocol (http://www.irac-online.org/methods/) using adult earwig, *D. erythrocephalus* and FAW third instar F1. A minimum of five concentrations was used for each insecticide diluted with distilled water containing Triton (0.2 g·l⁻¹) for FAW. Regarding the survival of earwigs, only the recommended dose of different insecticides was tested. Non-treated maize leaves were collected, washed with tap water and dried. Then, they were immersed for 10 seconds in the insecticide solution and dried for 1 h. Control leaves were treated only with a solution of Triton in water. Leaves were placed in Petri dishes (9 cm in diameter) containing blotting paper. A total of 40 insects were exposed individually to each concentration, four replicates were performed for earwigs and five to six for FAW stages (Ahissou et al., 2021a). All bioassays were conducted under laboratory conditions of 25 ± 2 °C, 60 ± 15% relative humidity, and a photoperiod 12L: 12D. Earwig survival was assessed for 24, 48, and 72 h, and the diet (20 mg) was added daily to each Petri dish. FAW larval mortality was assessed after 72 h for all tested insecticides. Insects were considered dead if they failed to move when touched with a small brush.

2.5. Data analysis

Data recorded on the number of FAW eggs and larvae consumed by adult earwigs, as well as earwig survival to insecticides, were subjected to a generalized linear models (GLMs) procedure, binomial distribution respectively. Multiple comparisons for these data were performed with Tukey's post hoc test using the 'ghlt' function in the 'multcomp' package for R. The concentration-mortality of the FAW population were corrected for control mortality (Abbott, 1925), and were subjected to probit analysis (Finney, 1971), to calculate values of slope, lethal concentration (LC$_{50}$ and LC$_{80}$), and fiducial limits (95%). Insects responses were considered equal when the confidence limits overlapped (Robertson & Preisler, 1992). Control failure likelihood (CFL) was calculated using Guedes (2017) formula by multiplying the percentage of mortality achieved by 100, dividing the product by the minimum efficiency required and subtracting the result from 100. CFL is the probability of treatment failure and the achieved mortality is the percentage of individuals that die when the recommended dose is applied. The required efficacy was set at 80%, as the minimum efficacy threshold required to allow registration of insecticides (Guedes, 2017). If the achieved mortality was higher than the required efficacy of the commercial formulation, CFL values below or near 0% suggest a negligible risk of control failure. Except for the probit analysis performed in SPSS 25.0 statistical package for Windows, all other analysis were performed in R statistical software (R Core Team, 2021) using the RStudio-2021.09.2 interface.

$$CFL = 100 - \frac{\text{Achieved mortality (\%)} \times 100}{\text{Required efficacy (\%)}}$$

3. RESULTS

3.1. Predation on eggs and larvae of fall armyworm

The consumption capacity of earwigs varied significantly with the developmental stage of the tested prey (FAW eggs or larvae), and the sex of the predator. Daily egg consumption by female earwigs (98.2 ± 17.6) was significantly higher than that of males (82.4 ± 10.3) (Df = 1; X^2 = 197.68; $p < 0.001$) (**Figure 1**). Moreover, adult females also consumed significantly more larvae (L1) (38.6 ± 8.2) than males (34.3 ± 8.7) (Df = 5; X^2 = 596.9; $p = 0.03$). In contrast, non-significant difference was observed in consumption between female and
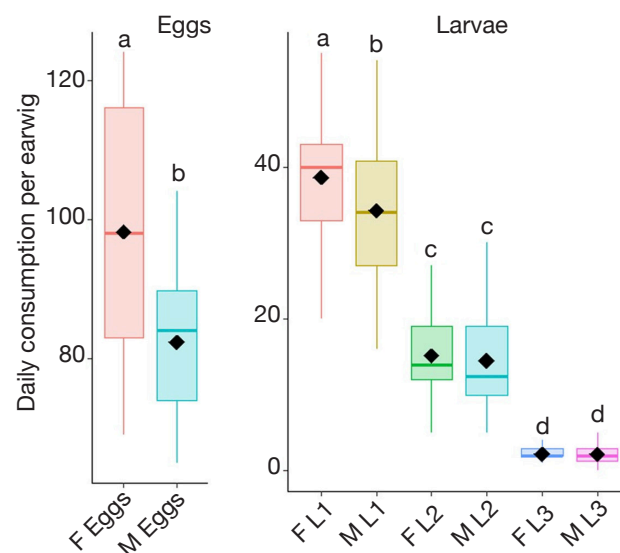
Figure 1. Predation of earwig females (F) and males (M) on fall armyworm eggs and larval stages (L1, L2 and L3) — *Capacité de prédation des femelles (F) et des mâles (M) de perce-oreilles sur les œufs et les stades larvaires (L1, L2 et L3) de la chenille légionnaire d'automne*.

Different letters indicate significant differences — *les lettres différentes indiquent des différences significatives* (GLM; Tukey test, $p < 0.05$); Figure shows the means (black diamonds), SE (boxes) and SD (whiskers) — *la figure montre les moyennes (losanges noirs), les erreurs standards (boîtes) et écarts-types (moustaches)*.

male earwigs when fed on FAW L2 ($p = 0.8$) and L3 ($p = 1.0$) larvae.

3.2. Survival rate of earwigs to insecticides and control failure likelihood (CFL)

No mortality was recorded on the control treatments. Survival of earwigs after 24, 48 and 72 h of exposure to insecticides varied significantly according to the type of insecticides (**Table 2**):
– chlorpyriphos-ethyl, methomyl, and spinosad insecticides were very toxic for earwigs that all died within the first 24 h of exposure (**Table 2**). With a zero CFL (-25), these products would eliminate earwigs from maize fields at the recommended dose;
– lambda-cyhalothrin and spinetoram insecticides were moderately toxic to earwigs at all tested exposure times with a survival rate between 41.9-65.6%. The CFL values of 57.0 and 27.4 respectively; suggesting that at the manufacturer's recommended rates, these products could provide moderate suppression of earwigs in maize fields;
– the insecticides abamectin, emamectin benzoate, deltamethrin, *A. indica* and *B. thuringiensis* did not affect earwig survival (100%) at all tested exposure times. With an CFL of 100, all earwigs could probably survive in maize fields after the applications of these products at the manufacturer's recommended rates.

3.3. Susceptibility of fall armyworm to insecticides

The natural mortality observed in the control treatments was below 5% and was used to correct the insecticide mortality. For all tested insecticides, the Probit model was considered appropriate (**Table 3**).

Spinosyns. Spinetoram and spinosad were highly toxic insecticides to FAW with LC_{80} values of $80.0\,\mu g \cdot l^{-1}$ and $420.0\,\mu g \cdot l^{-1}$, respectively (**Table 3**). These values are 99% lower than those recommended by the

Table 2. Survival rates of earwigs after the application of recommended doses of fall armyworm insecticides for 24, 48 and 72 h — *Taux de survie des perce-oreilles aux doses recommandées d'insecticides utilisés contre la chenille légionnaire d'automne après une exposition de 24, 48 et 72 h.*

Insecticide	Survival rate (%)			CFL
	24 h	48 h	72 h	
Abamectin	100.0[a]	100.0[a]	100.0[a]	100.0
Azadirachta indica	100.0[a]	100.0[a]	100.0[a]	100.0
Bacillus thuringiensis	100.0[a]	100.0[a]	100.0[a]	100.0
Deltamethrin	100.0[a]	100.0[a]	100.0[a]	100.0
Emamectin benzoate	100.0[a]	100.0[a]	100.0[a]	100.0
Lambda-cyhalothrin	78.1[b]	66.8[c]	65.6[c]	57.0
Spinetoram	53.7[d]	44.4[e]	41.9[e]	27.4
Chlorpyriphos-ethyl	0.0[f]	0.0[f]	0.0[f]	-25
Methomyl	0.0[f]	0.0[f]	0.0[f]	-25
Spinosad	0.0[f]	0.0[f]	0.0[f]	-25

Different letters indicate significant differences (GLM; Tukey test, $p < 0.05$) — *les lettres différentes indiquent des différences significatives (GLM ; test de Tukey,* p *< 0,05).*

Table 3. Susceptibility level of fall armyworm to ten insecticides — *Niveau de sensibilité de la chenille légionnaire d'automne à dix insecticides.*

Insecticide	n	LC_{50} (95% FL)[a]	LC_{80} (95% FL)[b]	Fit of probit line			CFL
				Slope ± SE	X^2 (ddl)	P	
Abamectin	240	71.6 (43.1-107.5)	115.1 (87.7-219.9)	0.02 ± 0.003	13.7 (4)	0.01	47.5
Emamectin benzoate	240	0.51 (0.33-0.8)	0.82 (0.61-1.5)	2,671 ± 353.2	10 (4)	0.03	-25.0
Deltamethrin	200	554.2 (476.5-648.0)	655.0 (581.1-841.3)	0.01 ± 0.001	8.0 (3)	0.04	100.0
Lambda-cyhalothrin	240	583.6 (477.8-693.6)	764.9 (661.4-971.6)	0.01 ± 0.000	9.7 (4)	0.04	100.0
Chlorpyriphos-ethyl	240	314.3 (248.0-437.2)	417.4 (338.0-667.6)	0.01 ± 0.001	12.9 (4)	0.01	-25.0
Methomyl	200	42.9 (14.5-75.2)	74.3 (51.7-164.0)	0.03 ± 0.004	8.3 (3)	0.04	-25.0
Spinosad	240	300 (210-380)	420 (350-560)	6.90 ± 0.70	11.4 (4)	0.02	-25.0
Spinetoram	200	51 (18-79)	80 (56-129)	28.5 ± 2.90	9.3 (3)	0.03	-25.0
Bacillus thuringiensis	240	2.9×10^8	13.0×10^8	0.00 ± 0.000	101.2 (4)	0.00	100.0
Azadirachta indica	240	126.3 (91.8-162.7)	177.1 (145.0-249.2)	0.02 ± 0.002	12.0 (4)	0.02	100.0

n: number of larvae tested — *nombre de larves testées*; [a], [b]: expressed in — *exprimées en:* mg a.i.·l⁻¹ (abamectin, deltamethrin, lambda-cyhalothrin, chlorpyriphos-ethyl, methomyl), μg a.i.·l⁻¹ (emamectin benzoate, spinosad, spinetoram), IU·l⁻¹ (*B. thuringiensis*), ml·l⁻¹ (*Azadirachta indica*); SE: standard error — *erreur standard*.

manufacturer. The high slope values (6.9 to 28.5) mean that a small increase in insecticide concentration is sufficient to significantly increase larval mortality; suggesting that the FAW population is very sensitive to both molecules. At the dose recommended, very limited failure treatment should be observed.

Organophosphates and carbamates. The LC_{80} values for chlorpyrifos-ethyl (417.4 mg·l⁻¹) and methomyl (74.3 mg·l⁻¹) were lower than the recommended doses by 74% and 92%, respectively. Their confidence limits do not overlap, methomyl has a higher toxicity than chlorpyrifos-ethyl. With a CFL of -25 for both molecules, they would be 100% effective against the FAW at the recommended rates.

Avermectins. The LC_{80} values of emamectin benzoate and abamectin were 0.82 μg·l⁻¹ and 115.1 mg·l⁻¹, respectively. Since their confidence limits do not overlap, abamectin has a lower toxicity than emamectin benzoate. This value for emamectin benzoate is 99% lower than that recommended by the manufacturer. At the doses recommended by the manufacturers, the CFL is 47.5 for abamectin and -25 for emamectin benzoate.

Pyrethroids. Deltamethrin and lambda-cyhalothrin were less toxic to FAW with similar LC_{80} values (confidence limits overlap) of 655.0 mg·l⁻¹ and 764.9 mg·l⁻¹, respectively. These values were 9 to 17 higher than the manufacturer's recommended rates, at which the CFL is very high (100).

The LC_{80} values of *A. indica* (177.1 ml·l⁻¹) and *B. thuringiensis* (13.0 × 10⁸ IU·l⁻¹) were 12 to 16 times higher than the manufacturer's recommended rates, respectively. Their slope is low (< 0.001); suggesting that a large increase in concentration is required to obtain a small increase in mortality. The probabilities that *A. indica* and *B. thuringiensis* would not be effective to eradicate the FAW from fields are high (100%).

4. DISCUSSION

Our study was conducted in the context of associations of several natural enemies with the FAW in West Africa after its invasion (Agboyi et al., 2020; Koffi et al., 2020; Ahissou et al., 2021b). This study assessed the predation potential of earwigs on FAW eggs and larvae in the laboratory. Also, the insecticide's effectiveness against the FAW as well as less toxic to the earwigs that were abundant in untreated maize fields in Burkina Faso were studied (Ahissou et al., 2021b). Most of them are generalist predators that are considered to be major components of biological control agents for insect pests (Cruz, 2007; Prasanna

et al., 2018). Their conservation and promotion in the field is an important strategy to promote biological control of arthropod pests.

Earwig, *D. erythrocephalus* consumed an average of 90 eggs or 36 larvae of the FAW per day in the present study. Similar results were recorded in Brazil and Argentina for *Euborellia annulipes* (Lucas) on FAW eggs (da Silva et al., 2009a, 2009b), and *Doru luteipes* (Scudder) on larvae (Reis et al., 1988; Romero Sueldo et al., 2010). They are recommended for augmentative releases for biological control of FAW in Brazil (Cruz, 2007). These results show that earwigs could play a crucial role in the regulation of the FAW in maize fields in Africa, particularly by consuming their egg masses and early larval stages that are gregarious. We recommend additional studies to test the effectiveness of certain agricultural practices and plants in attracting earwigs in the field for biological control. For example, spraying a sugar solution on maize led to the increase of some species of earwigs in Brazil (Bortolotto et al., 2014). In East Africa, the abundance of some predators is increased in maize fields cultivated in push-pull with intercrops *Melinis minutiflora* P.Beauv. (Poaceae), *Desmodium uncinatum* (Jacq.) DC., *Desmodium intortum* (Mill.) Urb. (both Fabaceae) and trap crops *Pennisetum purpureum* Schumach., and *Sorghum vulgare* Pers. (both Poaceae) (Cook et al., 2007; Kebede et al., 2018).

Insecticides with three modes of action: chloride channel activators (emamectin benzoate), acetylcholinesterase (AChE) inhibitors (chlorpyrifos-ethyl, methomyl), and nicotinic acetylcholine receptor (nAChR) allosteric modulators (spinetoram, spinosad) were found effective on FAW; confirming previous works (Campos et al., 2011; Ríos-Díez & Saldamando-Benjumea, 2011; Gutiérrez-Moreno et al., 2019; Dassou et al., 2021) including those performed in Burkina Faso (Ahissou et al., 2021a; Ahissou et al., 2022b). Based on our results, control failure for FAW would be very low, as the doses required are lower than those authorized by the manufacturers, representing a safe environmental profile. In contrast, insecticides lambda-cyhalothrin, deltamethrin, and abamectin were ineffective against FAW populations collected in Burkina Faso, with a high risk of failure in the field. The ineffectiveness of some pyrethroid insecticides was documented worldwide, *e.g.* in Puerto Rico and Brazil (Carvalho et al., 2013; Gutiérrez-Moreno et al., 2019). The widespread treatment failures mentioned by producers in West Africa could be related to the use of ineffective molecules such as abamectin, deltamethrin, and lambda-cyhalothrin (Ahissou et al., 2021a), which are widely used against this pest in West Africa (Kansiime et al., 2019; Ahissou et al., 2022c), or to pest resistance to these molecules.

Genetic studies on the *Spodoptera* genus have shown that emamectin benzoate inheritance was autosomal, incompletely dominant, and polygenic in *S. frugiperda* (Muraro et al., 2021) and *S. exigua* Hübner (Che et al., 2015). Consequently, intensive and continuous application of this active ingredient has contributed to the rapid evolution of high resistance in field populations of *S. frugiperda* in Brazil (Muraro et al., 2022) and *S. exigua* in China (Che et al., 2015). However, a low (or absence) cross-resistance between emamectin benzoate and methomyl, spinetoram and chlorpyrifos has been demonstrated in FAW (Muraro et al., 2021). Given that high levels of FAW resistance to effective molecules identified in the present study have already been reported in the Americas (Gutiérrez-Moreno et al., 2019; Muraro et al., 2022), it would be judicious to develop alternative means of control and resistance management systems (*e.g.*, rotation of molecules with different modes of action) to delay this development (Sparks et al., 2021).

Obtained results categorized three groups of insecticides based on the toxicity values on earwigs and FAW:

– Emamectin benzoate and spinetoram are effective on FAW and have no (or very little) effect on the earwigs. Both insecticides were found to be selective and may be used in FAW control program in combination with earwigs or without affecting those available in the field. As in the present study, insecticides that target the chloride channel activators (emamectin benzoate, abamectin) and nAChR allosteric modulators (spinetoram) had a safety profile on earwigs, *Forficula auricularia* L. (Shaw & Wallis, 2010) and *E. annulipes* (Potin et al., 2022), respectively;

– Chlorpyrifos-ethyl, methomyl and spinosad are effective on FAW and their use in maize fields may eliminate the pest and the earwigs present. These results confirm previous studies that reported organophosphates and carbamates are generally broad-spectrum compounds with low selectivity for earwigs (Zotti et al., 2010; Campos et al., 2011) as in the case of spinosad, which was harmful to *F. auricularia* earwigs (Shaw & Wallis, 2010; Fountain & Harris, 2015). Since earwigs are nocturnal predators more likely to be exposed to insecticide residues on plants when feeding at night (rather than by direct contact), we recommend field studies to confirm these results, especially for highly toxic molecules;

– Deltamethrin, lambda-cyhalothrin, abamectin, *A. indica* and *B. thuringiensis* are not effective against either FAW or the predator. Generally, pyrethroid insecticides are considered highly toxic to natural enemies (Talebi et al., 2011), but they were not toxic to earwigs and did not cause mortality, as bioinsecticides in our study.

5. CONCLUSIONS

Earwigs could be promising biological control agents against FAW if they are present early before egg laying and/or hatching; alternatively, we can preserve their regulatory potential by using selective insecticides (like emamectin benzoate and spinetoram). These insecticides are effective against FAW larvae while posing minimal harm to earwigs and other beneficial insects, allowing them as natural predators and keeping the pest populations under the economic threshold. This approach makes chemical control compatible with preserving natural biological control, promoting a more sustainable and effective pest management strategy.

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