La chenille légionnaire d'automne en Afrique de l'Ouest : Etats des lieux, recherche et propositions de stratégies de gestion

Besmer Régis AHISSOU

COMMUNAUTÉ FRANÇAISE DE BELGIQUE
UNIVERSITÉ DE LIÈGE – GEMBLOUX AGRO-BIO TECH
UNIVERSITÉ NAZI BONI

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Promoteurs :
Prof François J. VERHEGGEN (ULiège, Belgique)
Prof Irénée SOMDA (UNB, Burkina Faso) et
Prof Aimé H. BOKONON-GANTA (UAC, Bénin)

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"*It always seems impossible until it's done*."

To Gisèle, my beloved.

AHISSOU Besmer Régis (2022). La chenille légionnaire d'automne en Afrique de l'Ouest : Etats des lieux, recherche et propositions de stratégies de gestion. Thèse de doctorat, Gembloux Agro-Bio Tech, Université de Liège, Belgique.

Résumé

La chenille légionnaire d'automne *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera : Noctuidae), est un important insecte ravageur des Amériques qui a envahi l'Afrique depuis 2016. Elle menace principalement la production de maïs, qui est un aliment de base. Les premières réponses mises en œuvre se sont heurtées à de nombreuses inconnues dans les zones nouvellement envahies. Cette thèse a été initiée pour générer des connaissances nécessaires à l'optimisation des recommandations et stratégies de lutte mises en place urgemment dans le contexte Ouest africain.

Les enquêtes menées montrent que la chenille légionnaire d'automne est devenue le plus important ravageur du maïs, obligeant les producteurs à faire un usage abusif d'insecticides chimiques souvent inefficaces. En évaluant la sensibilité de différentes populations du ravageur suivant le protocole IRAC N° 020, nous avons pu établir une liste positive d'insecticides chimiques et bioinsecticides. Cependant, un programme de suivi et de gestion de la résistance doit être mis en place pour préserver l'efficacité de ces produits.

La dynamique de cette espèce montre qu'elle persiste toute l'année, avec une abondance particulière pendant les grandes périodes de production de maïs. En saison sèche et en saison pluvieuse, les pics d'abondance du ravageur étaient synchronisés aux stades 6 à 12 feuilles du maïs, généralement 1 à 2 mois après les semis (avant la floraison), après lesquels les applications d'insecticides chimiques devraient être évités ou réduits autant que possible. Par ailleurs, l'utilisation de variétés de maïs à cycle court et les semis précoces pourraient permettre d'éviter les fortes infestations en fin de cycle dans certaines régions.

L'inventaire des ennemis naturels dans les champs de maïs a mis en évidence la présence de 13 prédateurs, 05 parasitoïdes, un champignon entomopathogène et un nématode parasite (Mermithidae). Le taux de parasitisme était de 10,5 % et le complexe dominé par les nématodes parasites, suivi des Braconidae et Tachinidae. Le complexe des prédateurs était dominé par les Forficulidae (51%), Formicidae (15%) et Coccinellidae (13%), mais comprenait aussi des Carabidae, Mantidae, Pentatomidae, Reduviidae et Araneae. La lutte biologique de conservation est une alternative très prometteuse contre ce ravageur, si les insecticides chimiques à large spectre sont utilisés judicieusement, et les pratiques agroécologiques mises en œuvre.

Les résultats obtenus ouvrent de nouvelles perspectives pour le développement d'une lutte intégrée contre ce nouveau ravageur par la préservation et la promotion des ennemis naturels locaux. Des actions de formation et de sensibilisation des producteurs sont également nécessaires pour parvenir à la gestion durable de ce ravageur.

Mots clés : connaissances des producteurs, espèce invasive, dynamique, lutte intégrée, ennemis naturels, résistance aux insecticides

AHISSOU Besmer Régis (2022). The fall armyworm in West Africa: Status, research and proposed management strategies. PhD thesis, Gembloux Agro-Bio Tech, University of Liege, Belgium.

Abstract

The fall armyworm *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae), is a major insect pest of the Americas that has invaded Africa since 2016. It primarily threatens maize production, which is a staple food. Initial responses implemented have faced many unknowns in newly invaded areas. This thesis was initiated to generate the knowledge necessary to optimize the recommendations and control strategies urgently implemented in the West African context.

Surveys conducted show that the fall armyworm has become the most important pest of maize, forcing farmers to overuse chemical insecticides that are often ineffective. By evaluating the susceptibility of different populations of the pest following the IRAC N° 020 protocol, we were able to provide a positive list of chemical and bioinsecticides. However, a monitoring and resistance management program must be implemented to maintain the effectiveness of these products.

The dynamic of this species show that it persists throughout the year, with particular abundance during major maize production periods. In the dry and rainy seasons, peak abundance of the pest was synchronized with the 6 to 12 leaf stages of maize, generally 1 to 2 months after planting (before flowering), after which chemical insecticide applications should be avoided or reduced as much as possible. Alternatively, the use of short-cycle maize varieties and early planting could help avoid heavy late-cycle infestations in some areas.

The inventory of natural enemies in maize fields revealed the presence of 13 predators, 05 parasitoids, one entomopathogenic fungus and parasitic nematode (Mermithidae). The parasitism rate was 10.5% and the complex was dominated by nematodes, followed by Braconidae and Tachinidae. The predator complex was dominated by Forficulidae (51%), Formicidae (15%) and Coccinellidae (13%), but also included Carabidae, Mantidae, Pentatomidae, Reduviidae and Araneae. Conservation biological control is a very promising alternative against this pest, if broad-spectrum chemical insecticides are used judiciously, and agroecological practices are implemented.

The results obtained open new perspectives for the development of an integrated pest management against this new pest through the preservation and promotion of local natural enemies. Training and awareness-raising activities for farmers are also necessary to achieve sustainable management of this pest.

Key words: farmers' knowledge, invasive species, dynamic, integrated pest management, natural enemies, insecticide resistance

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Introduction générale

Les insectes ravageurs en Afrique de l'Ouest

L'agriculture est un secteur déterminant pour la création de richesse économique et l'emploi en Afrique de l'Ouest. L'économie alimentaire représente 66% de l'emploi total, dont la majorité est dans l'agriculture (78%) (Allen *et al.*, 2018). La production agricole est dominée par les cultures céréalières et maraîchères, qui contribuent majoritairement à la sécurité alimentaire et nutritionnelle des populations locales. Alors que les cultures céréalières ont toujours été la principale ressource alimentaire dans le monde (Adjalian *et al.*, 2014; Sow *et al.*, 2018), les cultures maraîchères jouent un rôle primordial pour compléter les programmes de nutrition, de lutte contre la pauvreté et contribuent de manière significative aux revenus des familles (James *et al.*, 2010). Ces cultures seraient plus rentables sans les contraintes biotiques et abiotiques qui les affectent. Parmi ces nombreuses contraintes figurent en bonne place les insectes nuisibles aux cultures céréalières et maraîchères. De manière générale, ils infligent des dommages directes et indirectes qui affectent la production par la destruction des différents organes, la succion de sève et la transmission de maladies (James *et al.*, 2010; Paini *et al.*, 2016; Prasanna *et al.*, 2018; Yarou *et al.*, 2017).

Parmi les principaux insectes ravageurs en Afrique de l'Ouest, la noctuelle de la tomate, *Helicoverpa armigera* (Hübner) (Lepidoptera : Noctuidae) cause des dommages considérables à un large éventail de cultures, notamment le coton, le maïs, le sorgho et la tomate (Diatte *et al.*, 2016; Sene *et al.*, 2020). La fausse-teigne des crucifères, *Plutella xylostella* (L.) (Lepidoptera : Plutellidae) et le foreur du chou, *Hellula undalis* Fabricius (Lepidoptera : Pyralidae) peuvent occasionner des pertes énormes estimées à plus de 90% en production des choux (James *et al.*, 2010; Labou *et al.*, 2016). Dans la région sahélienne de l'Afrique de l'Ouest où le petit mil est une culture vivrière de subsistance majeure, la mineuse du mil, *Heliocheilus albipunctella* (de Joannis) (Lepidoptera : Noctuidae) est un insecte ravageur clé pouvant entrainer des pertes de rendement 40 à 85 % (Sow *et al.*, 2018). Les foreurs de tige du maïs, du mil et du sorgho tels que *Busseola fusca* Fuller, *Sesamia calamistis* Hampson (tous deux Lepidoptera : Noctuidae), *Chilo partellus* Swinhoe et *Eldana saccharina* Walker (tous deux Lepidoptera : Pyralidae) causent également des pertes de rendement considérables sur leurs cultures hôtes respectives lorsqu'il n'existe pas de mesures de contrôle efficaces (Diatte *et al.*, 2016; James *et al.*, 2010; Nafiu *et al.*, 2014; Niassy *et al.*, 2020).

Par ailleurs, cette même région a connu plusieurs invasions d'insectes exotiques d'importance économique au cours des deux dernières décennies. Ils nécessitent une surveillance constante sans laquelle les pertes de production pourraient atteindre 50 à 80% (Niassy *et al.*, 2020), les échanges seraient limités en raison des restrictions de quarantaine (Dohino *et al.*, 2017) et les répercussions économiques seraient estimées à plusieurs milliards de dollars US (Day *et al.*, 2017; Niassy *et al.*, 2020; Paini *et al.*, 2016). La mouche orientale des fruits, *Bactrocera dorsalis* (Hendel) (Diptera :

Tephritidae) qui infeste une large gamme d'espèces de fruits avec des niveaux élevés de dommages sur certains types de fruits commerciaux tels que les mangues et les agrumes a été signalée en 2004 (Drew *et al.*, 2005) et la mineuse de la tomate, *Tuta absoluta* (Meyrick) (Lepidoptera : Gelechiidae) qui est l'un des ravageurs les plus redoutés de la tomate dans le monde a été signalée en 2012 (Pfeiffer *et al.*, 2013) en Afrique de l'Ouest. Plus récemment, la chenille légionnaire d'automne, *Spodoptera frugiperda* J.E. Smith, 1797) (Lepidoptera : Noctuidae), qui était connue depuis longtemps comme un important ravageur en Amérique a envahi l'Afrique depuis 2016 et certaines parties du Moyen-Orient, de l'Asie et de l'Australie plus tard (Goergen *et al.*, 2016; Prasanna *et al.*, 2021). Hautement polyphage et vorace, elle menace la sécurité alimentaire et nutritionnelle des populations en raison des importants dégâts causés principalement sur les céréales (principalement le maïs), dont l'importance n'est plus à démontrer.

Cette nouvelle espèce invasive a donc suscité de nombreuses recherches pour une meilleure compréhension et une gestion durable dans les zones nouvellement envahies. C'est dans ce contexte que la présente thèse de doctorat intitulée « **La chenille légionnaire d'automne en Afrique de l'Ouest : Etats des lieux, recherche et propositions de stratégies de gestion** » a été initiée. La suite de cette section introductive lui est donc entièrement consacrée.

Invasiveness, biology, ecology, and management of the fall armyworm, *Spodoptera frugiperda*

Cette section est une adaptation de l'article suivant :

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1. Introduction

The fall armyworm *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae), has long been known as a pest in the Americas and has invaded most of Africa and parts of the Middle-East, Asia, and Australia since 2016 (Goergen *et al.*, 2016; Prasanna *et al.*, 2021). Its new status as an invasive species causing serious damage in many regions worldwide has highlighted the need for better understanding and generated much research. Highly polyphagous, it feeds and develops on the leaves, stems and reproductive parts of over 350 plant species, primarily Poaceae, causing serious economic damage to key food crops (e.g., maize, sorghum, rice, soybean) and fibre crops (e.g., cotton) (Montezano *et al.*, 2018).

2. Taxonomy and morphology

The fall armyworm was originally described as *Phalaena frugiperda* by Smith & Abbot (1797; cited by Simmons & Wiseman, [1993]), then placed in the genus *Laphygma* to be finally classified as *Spodoptera frugiperda* in a note published by Todd (1964; cited by Simmons & Wiseman, [1993]). The genus *Spodoptera* has about 31 species on six continents; and about 15 of these species (including *S. frugiperda*) are important pests of many crops (Pogue, 2002).

Misidentifications of *S. frugiperda* with other species, such as the beet armyworm *Spodoptera exigua* (Hübner), can occur at all developmental stages (Goergen *et al.*, 2016). However, some morphological criteria of the larvae can be used to accurately identify *S. frugiperda* in the field. Among them: "the presence of four pinacula on the eighth terga forming a square, and a line forming an inverted Y shape on the head"

(Figure 1). Larvae range in size from about 1 mm (instar 1) to 45 mm (instar 6) and head capsule width extends from about 0.3 mm to 2.6 mm during this period. Key details of morphological characteristics of the adult moths were revised (Pogue, 2002): the male moths have triangular white spots at the tip and near the center of the forewing, while females' forewings are less distinctly marked and uniform. The moths have a wingspan of 32 to 40 mm (Prasanna *et al.*, 2018).

In addition, *S. frugiperda*, appears to be an assemblage of two closely related strains referred to as the maize and rice strains (Pashley *et al.*, 2004). They have long been considered morphologically indistinguishable but differ in their host plant distribution. Rice strain is usually associated with millet and grass species associated with pasture habitats while maize strain is rather associated with maize and sorghum (Pashley, 1988).

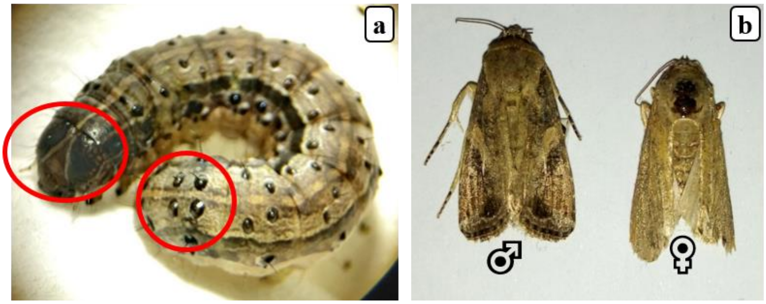

Figure 1. Typical morphological markings on the fall armyworm. (a) Larva (a square of 4 pinacula on the 8th terga and an inverted Y shape on the head), (b) adult male and female moth.

3. Worldwide status and geographic spread

The fall armyworm is native to the Americas, where it is widely distributed and frequently reaches outbreak densities and has long been regarded as a pest (Luginbill, 1928). However, in Honduran subsistence maize production natural enemies often suppress fall armyworm populations (Wyckhuys & O'Neil, 2006). The native, year-round distribution of fall armyworm extends from Argentina to southern US, and it is found in suitable habitats throughout Central America and the Caribbean feeding on many different host plants (Casmuz *et al.*, 2010; Montezano *et al.*, 2018). As fall armyworm does not diapause and cannot survive low temperatures, its year-round distribution is limited to tropical and subtropical regions. However, it is able to migrate long distances to seasonally suitable areas (Johnson, 1987), greatly extending the area over which it can cause crop damage. Thus, while in the US it only overwinters in southern parts of the Gulf States (Florida and Texas), it seasonally migrates north and has been recorded as far north as Canada.

Fall armyworm was first found established outside its native range in early 2016, in Benin, Nigeria, São Tomé and Príncipe, and Togo (Goergen *et al.*, 2016). Genetic analysis indicated the West African population originated in the area of Florida and the Antilles (Nagoshi *et al.*, 2018). Possible routes of entry into Africa are most likely the transport of adults and/or egg masses on direct commercial flights between the Americas and West Africa, followed by flight dispersal of adults into Africa (Cock *et al.*, 2017). Lepidoptera can survive in the wheel-bays of planes on long haul flights (Russell, 1987) and fall armyworm is known to lay eggs on non-plant surfaces (Luginbill, 1928; Pashley *et al.*, 2004).

By 2018, fall armyworm was found in most countries in sub-Saharan Africa. It is now thought to be present in all mainland sub-Saharan and Sahelian countries except Lesotho (Figure 2) (Prasanna *et al.*, 2021). Most of the areas where fall armyworm is found in Africa appear to support year-round populations. However, in South Africa and neighbouring countries, most areas may be too cold for populations to persist (du Plessis *et al.*, 2020; Early *et al.*, 2018). The damage reported in at least some parts of Zimbabwe (Baudron *et al.*, 2019; Chimweta *et al.*, 2020) might therefore be due to immigrant populations. Because of variation in the rate with which countries have detected and reported fall armyworm, it is not feasible to give an accurate chronology of its global spread.

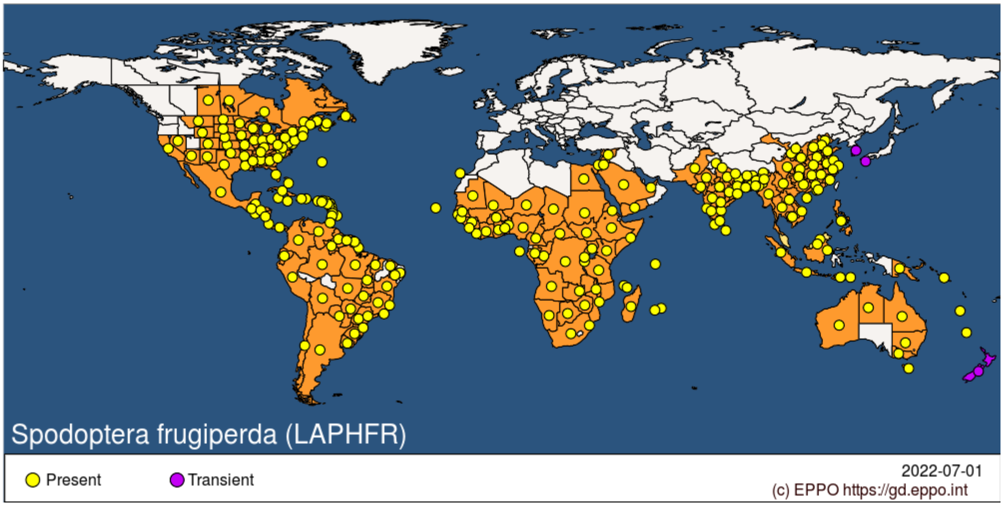

Figure 2. Global distribution of fall armyworm.

4. *Life cycle and developmental biology*

Fecundity and fertility of *S. frugiperda* is high (Luginbill, 1928), but the reproductive parameters are generally affected by temperature, host plant species and host plant phenology (Barfield & Ashley, 1987; Van Huis, 1981; Wang *et al.*, 2020). The optimum temperature for egg production is at 25 °C (Barfield and Ashley 1987). Under optimal temperatures for egg hatching (≈30°C), two days only are needed for all the eggs to hatch (du Plessis *et al.*, 2020). Larvae usually go through six instars. The entire duration of the larval stage can be as short as 10 days (32°C) and longer than 30 days (<20°C) (du Plessis *et al.*, 2020). For instance, two to three days are needed for each of the six instars at 26°C. Larval survival is the highest between 26 and 30°C.

Pupation typically occurs in the soil. Duration of the pupal stage is about eight to nine days at optimal temperatures (≈30°C), but can be as long as 30 days at 18°C. At lower temperatures, the mortality rate is drastically increased. After emergence, adult females experience a preoviposition period of ~5 days, but some individuals need up to 9 days before initiating oviposition (Luginbill, 1928). During their adult lifetime mating with more than one partner is common (Simmons & Marti, 1992).Females lay most of their eggs during the first five days following maturation but continue to produce some eggs during their entire lifespan, which is typically between two and three weeks. Each female produces an average of 1500 eggs at optimal temperatures (Prasanna *et al.*, 2018). Both larval and adult diets affect the longevity and the fecundity of fall armyworm moths (Luginbill, 1928).

The optimal range for egg-to-adult development is between 26 and 30°C, while a plateau is experienced at slightly higher temperatures (du Plessis *et al.*, 2020). As a result, the life cycle is completed in about 30 days under optimal conditions (28°C; 65% RH) and can last up to 90 days at lower temperatures. This pest does not diapause, is chill susceptible and therefore cannot survive extremely low temperatures.

The biology of fall armyworm is also affected by its host plant species and varieties. It has been reported that oviposition is highest during the early whorl and heading stages (Van Huis, 1981), but in contrast, more eggs are laid in the late vegetative stage compared to the reproductive stage of maize according to another study (Barfield & Ashley, 1987). Suitable host plants result in high survivorship, shorter larval development time and higher reproductive rates (Wang *et al.*, 2020).

5. Host range, damage to crops and economic impact

The fall armyworm is a highly polyphagous herbivore whose larvae are able to feed upon the aerial parts of a wide range of cultivated and wild plants (Figure 3). A recent bibliographic survey together with field observations suggested that the pest can feed on 353 host plants belonging to 76 botanical families, with the Poaceae being the most common, followed by Asteraceae and Fabaceae (Montezano *et al.*, 2018). However, due to the high number of eggs in the fall armyworm egg masses, young larvae, after an initial feeding step, start dispersing mainly by ballooning onto other nearby plants (Sokame *et al.*, 2020). This suggests that several host records may be due to this behaviour and do not necessarily indicate actual maternal oviposition preference (Prasanna *et al.*, 2021).

The main crops where fall armyworm causes economic injury include cereals, forage and grasses, especially maize, rice and sorghum, and other main arable crops, such as soybean and cotton (Barros *et al.*, 2010). The whorl and young leaves, ears and tassels are the most consumed plant structures by fall armyworm (Goergen *et al.*, 2016). Still, foliar damage of maize may not necessarily translate to high grain yield losses in contrast to ear damage (Hruska, 2019; Wightman, 2018).

Figure 3. Newly hatched fall armyworm larvae and damage to different parts of maize.

Economic losses due to fall armyworm in maize worldwide have been estimated up to 73%, with major impact in developing countries (Hruska & Gould, 1997). Recent studies in Africa highlight the economic importance of the fall armyworm. In Ethiopia, the pest causes an average annual loss of 36% in maize production, reducing yield by 0.67 million tonnes of maize (0.225 million tonnes per year) between 2017 and 2019 (Abro *et al.*, 2021). In the absence of control measures, the fall armyworm can cause estimated maize yield losses of 8 - 20 million tons in 12 African countries per year (Day *et al.*, 2017). The recent invasion of fall armyworm in developing countries also has an important impact on household income and food security. For example, households affected by fall armyworm in Zimbabwe had a lower per capita income and were 12% more likely to experience hunger compared to unaffected households (Tambo *et al.*, 2021).

6. Population dynamics and behavioural ecology

It is reported that temperature and rainfall significantly affect fall armyworm population densities (Murúa *et al.*, 2006). On maize, fall armyworm infestations display a plant age-dependent response, young instars being prominently found on early plant stages (V1-V3), often with more than one larva per plant, whereas older larvae occur on older plant stages, usually with only one larva per plant (Murúa *et al.*, 2006). However, in the tropics, overlapping generations occur, with all fall armyworm developmental stages found on all plant stages.

Due to a high fecundity, a short generation time and a good dispersal capacity, fall armyworm has a strong ability to invade and colonize new regions (Early *et al.*, 2018). More recently, it has been shown that the moth can move distances of 250 km overnight in China (Jia *et al.*, 2021). 2021). The dispersal capacity of this pest can explain why, after the first record in West Africa in 2016 (Goergen *et al.*, 2016) it quickly spreads to most of the continent as well as parts of Asia in just three years.

Inter-plant dispersal by mean of ballooning is done by neonates, whereas older larvae migrate by crawling between plants (Sokame *et al.*, 2020). The capacity of larvae to move to new, non-infested plants is important because larvae are cannibalistic and, usually, only one or two larvae per plant develop to maturity.

7. Monitoring, sampling and pest forecasting

While pheromone trap catches provide early warning of moth activity in a region (Meagher *et al.*, 2008), monitoring and scouting for pest-infested plants provide information on field infestation levels which informs decisions whether to apply control measures (Linduska & Harrison, 1986; Prasanna *et al.*, 2018).

Pheromone trapping. Since the 1960s, behavioural bioassays suggested that female fall armyworm moths release a blend of chemicals that attracts males. The main chemical component was first identified as (Z)-9-tetradecen-1-ol acetate (Z9-14:OAc) (Sekul & Sparks, 1967). Lures were made with this component but trapping results were not successful. Another compound, (Z)-9-dodecen-1-ol acetate (Z9-12:OAc), was later found to be the primary pheromone component and was then used extensively as the pheromone lure (Sekul & Sparks, 1976). However, moth numbers in traps were variable and a large amount of the component was required. Further analysis showed that females produce four additional compounds: including (Z)-7-dodecenyl acetate (Z7-12: Ac), (Z)-11-dodecenyl acetate (Z11-12:OAc), (Z)-11-hexadecenal (Z11-16:Ald), and (Z)-11-hexadecenyl acetate (Z11-16:OAc) (Tumlinson *et al.*, 1986). Field tests revealed that Z9-14:OAc and Z7-12:OAc were critical for male attraction (Tumlinson *et al.*, 1986) and this two-component blend became commercially available in the US in the mid-2000s. and is still used today. However, lures do not always attract large number of moths (Cruz-Esteban *et al.*, 2020). Furthermore, pheromone blends that attract fall armyworm also attract other noctuids, including species that can be confused with fall armyworm, creating issues for monitoring in newly invaded areas (Meagher *et al.*, 2019). Interestingly, it was also found that the compound Z11-16: Ac interrupts the attraction of non-target sympatric moth species (Cruz-Esteban *et al.*, 2020).

The combination of different traps with different pheromone components and substrates that influence release into the environment guided the development of trapping techniques (Malo *et al.*, 2004). Many types of traps were developed with different designs and colours (Meagher *et al.*, 2019). Trap height (Malo *et al.*, 2004), trap color (Malo *et al.*, 2018), and host plant volatiles (Unbehend *et al.*, 2013) affect the performance of pheromone-baited traps. Other factors such as weather, crop habitat, and proximity to trees also affect trap captures (Koffi *et al.*, 2021).

Monitoring and sampling. Pheromone trap catches indicate the presence of moths in an area but are not necessarily good indicators of egg-laying intensity and larval numbers (Prasanna *et al.*, 2018). The positive relationship between trap catches and fall armyworm infestation levels was reported (Linduska & Harrison, 1986).

Once moths are detected, scouting for eggs and damaged plants should commence. Scouting implies the periodic checking of fields to determine if the incidence of infested plants exceeds predetermined action threshold levels (Prasanna *et al.*, 2018). Scouting is especially important when the crop is attacked by a complex of pest species, since pheromones only attract one or closely-related species. This is particularly the case in the Americas on crops such as cotton and soybean. Scouting protocols have been described and should begin soon after seedling emergence (Prasanna *et al.*, 2018). Early detection is highly advantageous since insecticide and biocontrol applications are more effective on eggs and early larval stages (Linduska & Harrison, 1986; Prasanna *et al.*, 2021).

8. Action threshold levels

Large variations exist in the injury resulting from a given level of fall armyworm infestation and in plant response to injury. On-farm studies in Zimbabwe suggested that yield loss cannot be predicted from once-off assessments of infestation and leaf damage alone (Baudron *et al.*, 2019). Given the high degree of uncertainty surrounding relationships between infestation levels, plant damage and yield loss, more conservative thresholds should be used, especially in the case of smallholder farmers. Action thresholds based on expert opinion have been recommended for fall armyworm control (Prasanna *et al.*, 2018). These recommendations have been presented as different thresholds for different maize growth stages as follows: during the early whorl stage, if 20% (range of 10-30%) of the seedlings are infested, or during the late whorl stage, if 40% (range of 30-50%) of the plants are infested, an insecticide application is warranted. During the tassel and silk stage, if 20% (range of 10–30%) of plants are infested an insecticide application may be justified. However, action thresholds should be based on the value of projected yield losses versus the cost of the proposed intervention. Moreover, given early application of chemical pesticides usually requires repeated spraying, because natural enemies are impacted to a greater extent than the pest (Meagher *et al.*, 2016), this should be imputed into any calculations. Urgent research is required to elucidate reliable metrics for predicting yield loss.

Stratégies de gestion de la chenille légionnaire d'automne en Afrique de l'Ouest

Suite à la récente invasion de la chenille légionnaire d'automne, l'Afrique a dû investir massivement dans l'utilisation d'insecticides chimiques. Par ailleurs, la mise en place et le développement d'options de lutte se sont appuyés sur plus de 100 ans d'expérience sur la chenille légionnaire d'automne en Amérique. Dans cette section, nous décrivons et discutons le potentiel des options alternatives pour le contrôle de la chenille légionnaire d'automne dans le contexte ouest-africain. Nous analysons également les perspectives d'avenir et les leviers d'action pour assurer la transition de la protection conventionnelle à la protection agro-écologique des cultures.

Cette section est une adaptation de l'article suivant :

Ahissou B. R., Sawadogo W. M., Bokonon-Ganta, A. H., Somda I., & Verheggen F. J. (2021). Integrated pest management options for the fall armyworm *Spodoptera frugiperda* in West Africa: Challenges and opportunities. A review. *Biotechnology, Agronomy and Society and Environment, 25*(3), 192–207. https://doi.org/10.25518/1780-4507.19125

1. *Abstract*

The fall armyworm *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) is a voracious and generalist insect pest native to America. It was first detected in West Africa in 2016 and rapidly spread across the continent. The indiscriminate use of chemical insecticides poses risks to human health and threatens the few natural enemies present in these environments. Despite the existence of alternative control measures in America (*e.g.* genetically modified maize), efforts are needed to develop environmentally friendly approaches that are affordable for smallholder farmers and compatible with the African context.

In this literature review, we describe the potential of the available alternative controls methods which include cultural, physical, biological and semiochemical strategies. The potential of their association is discussed considering their cost-benefice balance and local economic and agricultural context. Several affordable mitigation options could be implemented rapidly, pending proper communication efforts, including (i) the promotion of indigenous natural enemies by promoting refuges and training smallholder farmers on their identification; (ii) cultural methods, mainly by planting directly after the main rainfalls, as well as performing intercropping and crop rotation; and (iii) the use of microbial biopesticides, and avoiding some of the already identified ineffective chemical insecticides.

2. Introduction

Agriculture plays an important role in the creation of economic wealth and employment in West Africa. The food economy accounts for 66% of total employment, most of these jobs are in agriculture (78%), specially in cereals production (FAO, 2018). Maize (*Zea mays* L.) is the most widely grown crop and consumed by people with varying food preferences and socio-economic background. Maize is a staple for over 200 million people who depend on that crop for food security (Day *et al.*, 2017). But in Western Africa, maize production is hampered by several insect pests including stem borers, termites, silkworms, grasshoppers and weevils. Stem borers were previously reported as the cause of low to moderate maize yield loss (Abang *et al.*, 2020; Nafiu *et al.*, 2014). These include *Busseola fusca* Fuller, *Sesamia calamistis* Hampson, *Chilo partellus* Swinhoe and *Eldana saccharina* Walker (Nafiu *et al.*, 2014). However, the recent invasion of the fall armyworm *Spodoptera frugiperda* (Smith), in 2016, has become the most important threat to maize production in Western Africa (Goergen *et al.*, 2016).

The fall armyworm originates from America, where it is considered one of the most damaging agricultural pests, feeding on over 100 different crops including maize, rice, sorghum, sugarcane, tomato, potato, cotton and others (Montezano *et al.*, 2018). It is commonly controlled by association of the latest generation of chemical insecticides with the culture of genetically modified maize (Day *et al.*, 2017; Hruska, 2019; Matova *et al.*, 2020). These technologies are reserved for commercial farmers who have access to subsidies and international markets seeking maize for animal feed, ethanol production and as a source of sweeteners. But maize production in West Africa is dominated by smallholder farms, whose context is very different from that of larger American farm companies. Moreover, the favorable climatic conditions in most African countries allow the pest to complete several generations per year, wherever host plants are available or not, including off-season and irrigated crops (Prasanna *et al.*, 2018). As a result, yield losses in maize crops range from 22-67% in Ghana, 25-50% in Zambia, and 32-47% in Ethiopia and Kenya (Day *et al.*, 2017; Kumela *et al.*, 2019).

In West-Africa, maize production is typically included in polyculture plots and the vast majority of cultivation areas are smaller than 2 ha (Day *et al.*, 2017; Prasanna *et al.*, 2018). Smallholder maize farmers also lack access to high and stable prices for their maize, subsidies or risk transfer mechanisms, preventing them to have access to expensive control technologies (Hruska, 2019). Chemical insecticides still constitute the bulk of the phytosanitary arsenal (Popp *et al.*, 2013). Often effective, agrochemicals have also shown many limitations in that region:

– they are too expensive for a significant portion of smallholder farmers;

– they lead to the selection of resistant populations of pests (as highlighted recently in Burkina Faso (Sawadogo *et al.*, [2020a]);

– they have adverse effects on non-target organisms (including natural enemies) (Desneux *et al.*, 2007) and human health (Damalas & Eleftherohorinos, 2011).

In their current composition, the fate of chemical pesticides appears limited in the long term, as do several molecules already subject to increasing environmental and toxicological restrictions (Deguine *et al.*, 2017). Consequently, there is a need for affordable alternatives to chemical insecticides to overcome the challenges of fall armyworm sustainable control (Bateman *et al.*, 2018).

In this literature review, we will attempt to describe and discuss the potential of alternative options for the control of fall armyworm in the West African context. The available alternatives will be listed and discussed, including cultural, biological, physical and semiochemical strategies of control. The potential of their association is discussed considering their cost-benefice balance and local economical and agricultural context. We will also analyze future prospects and action levers to ensure the transition from conventional to agro-ecological crop protection.

A systematic bibliographic research was conducted in Scopus (Elsevier), Google Scholar and BASE (Bielefeld Academic Search Engine) databases. All terms were queried as follows: "fall armyworm" OR FAW OR "*Spodoptera frugiperda*" OR "*Laphygma frugiperda*" OR "*Phalaena frugiperda*" OR "*Trigonophora frugiperda*" OR "*Laphygma macra*" OR "*Laphygma inepta*" OR "*Prodenia signifera*" OR "*Prodenia plagiata*" OR "*Prodenia autumnalis*" OR "*Noctua frugiperda*" and were associated with a combination of synonyms of one of the following keywords: integrated pest management, biological control, natural enemies, parasitoids, predators, entomopathogenic fungi, entomopathogenic viruses, entomopathogenic bacteria, entomopathogenic nematodes, pesticidal plants, cultural methods, push-pull, insecticides, smallholders, farmers' strategies, West Africa. Abstracts obtained for each research question were read to select only those directly related to the topic. This process led to the identification of 126 bibliographic references.

3. Chemical control

In West Africa, the Sahelian Pesticides Committee (CSP) authorizes pesticides for all member countries of the Permanent Inter-State Committee for Drought Control in the Sahel (CILSS), which includes Benin, Burkina Faso, Cape Verde, Chad, Gambia, Guinea, Guinea Bissau, Côte d'Ivoire, Mali, Mauritania, Niger, Senegal and Togo. The CSP makes decisions common to all CILSS countries on the circulation of pesticides and their use. According to the latest update of the global list of authorized pesticides published in November 2019, no molecule is specifically registered against the fall armyworm (CSP, 2019a), probably as a result of the relatively early introduction of the pest in this new area. However, the use of chemical insecticides has remained the primary means of control for fall armyworm since its introduction, although their efficacy has not been proven (Harrison *et al.*, 2019; Sisay *et al.*, 2019a). The molecules commonly used by farmers include emamectin benzoate, imidacloprid, lindane, chlorpyriphos-ethyl, acetamiprid, cypermethrin, lambda-cyhalothrin, deltamethrin, permethrin, maltodextrin, ethyl palmitate, carbaryl and fipronil (Chimweta *et al.*, 2020; Kansiime *et al.*, 2019; Rwomushana *et al.*, 2018). In Burkina Faso for instance, more than 12,000 liters of synthetic insecticides were sprayed on 14,000 ha of fall armyworm infested fields, during the 2018-2019 crop season (MAAH, 2018).

Although heavy infestations of fall armyworm in Africa may have justified chemical control, their frequent applications is unsustainable because they lead to the development of insecticide resistance, increase production costs, and cause biodiversity decline as well as health risks to the growers and consumers (Damalas & Eleftherohorinos, 2011; Day *et al.*, 2017). Unfortunately, problems of residue are not monitored. The fall armyworm is known to have developed strong resistance to various chemical insecticides such as pyrethroids, organochlorines, organophosphates and carbamates (Diez-Rodriguez & Omoto, 2001) that are widely used in Africa. As a result, farmers have increased frequencies and doses of insecticide applications. However, indiscriminate spraying wastes money and can have negative effects on environment and human health, particularly in cases where knowledge about the safe use of these toxic chemicals is limited (Meagher *et al.*, 2016). Natural enemies complex is reduced and its impact on fall armyworm populations is significantly diminished (Meagher *et al.*, 2016). Moreover, smallholder farmers in Sub-Saharan Africa, with limited resources, cannot afford expensive chemical insecticides against fall armyworm in the long term (Khan *et al.*, 2016). They are often unwilling or unable to purchase appropriate safety equipment, representing a high risk to human health (Day *et al.*, 2017; Rwomushana *et al.*, 2018). In this context, pesticides are frequently applied without adequate safety precautions, and there is increasing evidence of pesticide poisoning in Africa, although to date this is not the result of fall armyworm control (Day *et al.*, 2017). Besides, the African pesticide market is complex due to informal distribution channels for unlabeled pesticides and the limited capacity of regulatory agencies to phase out highly hazardous compounds by replacing them with effective, low-risk alternative pesticides (Popp *et al.*, 2013).

Many synthetic insecticides registered and recommended for controlling fall armyworm in Latin America (Day *et al.*, 2017) are available in West Africa. Their application should be based on monitoring and thresholds, and not used as a prophylactic or preventive measure (Day *et al.*, 2017). Pesticides should be applied when the crop is infested by a pest population sufficient to lead to yield loss greater than the cost of the intervention. Farmers should apply pesticides to coincide with the presence of first instars fall armyworm (which are easier to eliminate than older ones) using the dose and concentration recommended by the manufacturer. In addition, they should avoid treating successive generations of fall armyworm using products having the same mode of action, in order to reduce resistance risks (Day *et al.*, 2017; Rwomushana *et al.*, 2018). However, fall armyworm brought with it resistance to multiple insecticides that was evidenced in America many years ago (Young & McMillian, 1979). The resistance status of this new pest to most available insecticides should be evaluated on representative populations collected from the entire area.

However, predicting the presence of a pest and then estimating the severity and incidence of an infestation allows for timely mitigation of the problem with minimal and safe means to effectively and economically protect yields (Prasanna *et al.*, 2018). In the case of the fall armyworm, effective control program implementation requires monitoring, surveillance and detection. Lures that mimic natural pheromones are efficient in monitoring the moth populations when they are associated with sticky traps (Matova *et al.*, 2020).

4. *Cultural methods: cultivation periods, resistant varieties, and plant associations*

Recommended cultural methods include timely planting following the main rainfalls, intercropping, crop rotation and landscape management by clearing major and alternate hosts around maize fields (Assefa, 2018; Kasoma *et al.*, 2020). Unlikely to provide adequate control alone, they help in reducing the fall armyworm populations and damages.

Early planting after the first effective rains usually provides better growing conditions for maize (Harrison *et al.*, 2019). However, planting dates have a strong influence on the levels of damage inflicted by fall armyworm, as there is a synchronization between the life cycles of the insect and its host plant. A valuable option could be the creation of an asynchrony between the critical growth stages of crops and pests. Heavy infestations (occurring at the end of the crop season) can be avoided by an earlier sowing and the use of early maturing varieties (Chhetri & Acharya, 2019). The current advice to farmers is to wait for the first 30 to 50 mm rains that fall in two to three consecutive days before seeding. This normally provides adequate soil moisture for crop establishment and reduces the risk of crop failure (Harrison *et al.*, 2019). This method is effective and used by large proportions of smallholder farmers in Ghana (56%) and Zambia (70%) (Rwomushana *et al.*, 2018). However, early planting may be more effective where infestation occurs through the arrival of migrant moths (Abrahams *et al.*, 2017a). Although the potential of prevention and avoidance options is considerable and well-proved, they are not yet widely implemented in Western Africa (Prasanna *et al.*, 2018), probably because of a lack of communication efforts by local authorities.

Staggered planting in the same maize field should be avoided so as not to constantly provide food sources for the fall armyworm (Chhetri & Acharya, 2019; Rwomushana *et al.*, 2018). This would allow them to have their preferred food (*i.e.* young maize plants) over a longer time period and promote the development of local populations. In addition, late-planted maize is often infested with high levels of fall armyworm that have developed on previously planted maize (FAO, 2018; Hruska, 2019). For instance, Farmer Field School farmers in Kenya have reported higher yield losses to fall armyworm on late-planted maize plots compared to adjacent crops planted earlier (FAO, 2018).

Crop rotation is a traditional method of managing pest damage in agriculture by rotating host and non-host crops in alternate years. Unfortunately, this approach may not be directly effective against fall armyworm for two reasons. Firstly, the fall armyworm is a polyphagous pest that attacks 350 crop species belonging to diverse families, including grasses, vegetable crops, and shrubs (Montezano *et al.*, 2018) and secondly because of the migratory nature of the pest, whose population builds up quickly in poorly managed neighboring fields (Kansiime *et al.*, 2019). However, crop rotation improves soil fertility, provides adequate plant nutrition, supports healthy plant growth and increases pest resistance (Harrison *et al.*, 2019; Prasanna *et al.*, 2018). In addition, diversify the farm environment through crop rotation increases natural enemy abundance (Meagher *et al.*, 2016; Prasanna *et al.*, 2018).

The availability of tolerant maize varieties would be valuable, especially as regard to the economic context of Western Africa: cost-effective, easy to apply, environmentally friendly, and compatible with most other control methods (Dakouo *et al.*, 2005). Unfortunately, there is still no maize cultivar (non-Bt maize) adapted to Africa with scientifically validated resistance to fall armyworm (Prasanna *et al.*, 2018). Genetic selection work for maize resistance to fall armyworm was recently initiated following its identification on the continent in 2016 (Goergen *et al.*, 2016). In West Africa, the International Institute of Tropical Agriculture (IITA) rapidly initiated traditional breeding of maize for resistance to fall armyworm. Several maize lines adapted to Africa, germplasm with natural resistance to armyworms and other varieties are also being evaluated by International Maize and Wheat Improvement Center (CIMMYT) to identify new sources of resistance compatible with the African context (Prasanna *et al.*, 2018).

Intercropping is the establishment on the same surface of several plant species and varieties simultaneously or which cross during an important part of their growth cycle. The rows of the main crop are intercropped with additional crops in rows or strips. In general, intercropping provides a protecting microclimate that increases richness and abundance of beneficial insects (Matova *et al.*, 2020). In Ethopia for instance, Kebede *et al.* (2018) reported increased abundance of generalist predators as well as the predation rate of stem borer eggs and fall armyworm by associating common bean (*Phaseolus vulgaris* L.) with maize. In Uganda, damages caused by the fall armyworm were significantly reduced in intercropping maize with legumes, such as *P. vulgaris*, *Glycine max* (L.) Merr. and *Vigna unguiculata* L. Walp. (Hailu *et al.*, 2018).

Some plants may lead to anti-appetizing or repellent action towards insect pests of other plants. This is the basis of the push-pull approach, in which different plants growing next to each other protect themselves *via* substances secreted by roots, leaves, flowers or fruits (Hruska, 2019). The combination of repellent and attractive stimuli modifies the behavior of insect pests and/or their natural enemies (Cook *et al.*, 2007). The insect pests are repelled or deterred away from a cultivated plant (push) thanks to stimuli that mask host volatile signature or are repellent or deterrent. They are simultaneously attracted (pull), using highly apparent and attractive stimuli, to other areas such as traps or trap crops where they are concentrated, facilitating their elimination (Cook *et al.*, 2007). In the system, Cook *et al.* (2007) used *Melinis minutiflora* P. Beauv., *Desmodium uncinatum* (Jacq.) DC. and *D. intortum* (Mill.) Urb. as repellent plants to protect maize from the fall armyworm. Simultaneously, the grasses *Pennisetum purpureum* Schumach and *Sorghum vulgare* (Pers.) were used as trap plants. In addition, *M. minutiflora* and *Desmodium* spp. are known to attract the parasitoids, *Cotesia sesamiae* Cameron (Hymenoptera: Braconidae) through volatile compounds emitted from their flowers and provide a favorable environment for their proliferation (Khan *et al.*, 2016). The push-pull approach was shown to be effective against some stem borers, but also against other lepidopteran pests of maize and other cereals (Hassanali *et al.*, 2008). It has been adopted by thousands of farmers in East Africa: early works in this region have demonstrated that the approach may be effective against the fall armyworm as well (Midega *et al.*, 2018).

5. Physical control: local fall armyworm management practices

Hand-picking of egg masses and larvae has proven a popular method for fall armyworm control in Africa, and is widely used by farmers as a first line of defence (Rwomushana *et al.*, 2018; Yigezu & Wakgari, 2020). Although time-consuming, it can reduce the population level when performed during the early maize development.

Several locally available substances are commonly used by smallholders to attempt to control the fall armyworm, including application of salt, urine, oils, detergents and soaps (Hruska, 2019; Rwomushana *et al.*, 2018; Yigezu & Wakgari, 2020). Their efficacy is not properly documented in the scientific literature, and some of them should not be recommended. An inexpensive and effective management option promoted by FAO is the application of ash or sand directly to the whorls of attacked maize plants. Sand can directly kill fall armyworm larvae, *via* abrasiveness or absorption of wax from the cuticle, causing larval desiccation (FAO, 2017; Hruska, 2019). Sand often contains a rich ecosystem of micro-organisms such as *Bacillus thuringiensis* Berliner and *Beauveria bassiana* (Balsamo) Vuillemin which may also promote the fall armyworm control (Ramirez-Rodriguez & Sánchez-Peña, 2016). It is presented as an immediate solution for smallholder farmers who cannot afford chemical insecticides. However, the high demand for labor makes it not applicable for large plots, or is likely to increase children workload (Harrison *et al.*, 2019). Among the other physical methods of fall armyworm management are ploughing and weeding to expose pupae to their natural enemies (Abrahams *et al.*, 2017a). In addition, burning stubbles and crop residues in infested fields could destroy unhatched eggs, larvae, pupae and adults (Assefa, 2018).

Nocturnal insects are often attracted to light sources that emit large amounts of UV radiations, and light traps may be efficient in controlling these pests (Shimoda & Honda, 2013). Recently, a study conducted in Ethiopia reached valuable fall armyworm control results by using night-time light traps (Gebreziher, 2020). Future development and use of new light sources such as light-emitting diodes is anticipated for promoting these results of capture (Shimoda & Honda, 2013).

6. Biological control: promoting indigenous natural enemies

Biological control is the beneficial action of predators, parasites, pathogens, and competitors in controlling pests and their damage (Nafiu *et al.*, 2014). The fall armyworm is attacked by various natural enemies including over 150 parasitoid species (Sisay *et al.*, 2018), nematodes (Sun *et al.*, 2020; Tendeng *et al.*, 2019), diverse taxa of insect predators (Harrison *et al.*, 2019; Koffi *et al.*, 2020), diverse spider predators (Firake & Behere, 2020) and entomopathogens such as fungi, bacteria and viruses (Shylesha *et al.*, 2018). Natural enemies are responsible for significant fall armyworm mortality (up to 42%) in its native continent. Africa may be more appropriate for fall armyworm biological control than North America for two reasons. Small scale maize production systems are predominant and other crops are often closely cultivated (Day *et al.*, 2017) and chemical insecticides were rarely used in maize crops before the arrival of the fall armyworm in Africa in 2016 (Caniço *et al.*, 2020a; Hruska, 2019; Matova *et al.*, 2020). Both reasons probably make natural enemies more easy to protect and promote (Midingoyi *et al.*, 2016).

Despite the limited number of available reports, several species of fall armyworm natural enemies are encountered in Africa (Table 1).

Table 1. Natural enemies of the fall armyworm reported after introduction into new areas of Africa and Asia since 2016. EP: egg parasitoid; LP: larval parasitoid; PP: pupal parasitoid; ELP: egg-larval parasitoid; LPP: larval-pupal parasitoid; Pr: predator; LPPa: larval-pupal parasite; LPa: larval parasite; *: parasitoid species undetermined and stage of fall armyworm attacked unspecified.

Species of natural enemies	Type	Countries	References
Arenae			
Lycosidae			
Lycosa sp.	Pr	India	1
Oxyopidae			
Oxyopes birmanicus Thorell	Pr	India	1
Salticidae			
Marpissa sp.	Pr	India	1
Rhene flavicomans Simon	Pr	India	1
Coleoptera			
Carabidae			
Undetermined sp.	Pr	RD Congo	2
Chrysomelidae			
Undetermined sp.	Pr	RD Congo	2
Cicindelidae			
Cicindela spp.	Pr	India	1
Undetermined sp.	Pr	RD Congo	2
Coccinellidae			
Coccinella transversalis Fabricius	Pr	India	3
Harmonia octomaculata Fabricius	Pr	India	3
Undetermined sp.	Pr	RD Congo	2
Undetermined sp.	Pr	Burkina Faso	4
Curculionidae			
Undetermined sp.	Pr	RD Congo	2
Staphylinidae			
Paederus fuscipes Curtis	Pr	India	5
Dermaptera			
Forficulidae			
Forficula sp.	Pr	India	3, 6
Undetermined sp.	Pr	India	1
Undetermined sp.	Pr	RD Congo	2
Undetermined sp.	Pr	Burkina Faso	4
Diptera			
Chloropidae			
Anatrichus erinaceus Loew	LP	Ghana	7
Tachinidae			
Drino quadrizonula Thomson	LP	Mozambique, Ghana, Benin	8, 9
Exorista sorbillans (Wiedemann)	LP	India	3
Exorista xanthaspis (Wiedemann)	LP	India	10
Palexorista zonata (Curran)	LP	Ethiopia, Kenya	11, 12

Species of natural enemies	Type	Countries	References
Undetermined sp.	LP	Ghana	7
Undetermined sp.	LPP	India	1
Undetermined sp.	*	Burkina Faso	4
Undetermined sp.	LP	Mozambique	8
Hemiptera			
Nabidae			
Undetermined sp.	Pr	Burkina Faso	4
Pentatomidae			
Andrallus spinidens (Fabricius)	Pr	India	1
Eocanthecona furcellata (Wolff)	Pr	India	1, 13
Podisus maculiventris (Say)	Pr	India	1
Reduviidae			
Cosmolestes sp.	Pr	India	1
Haematochares obscuripennis Stål	Pr	Ghana	7
Peprius nodulipes (Signoret)	Pr	Ghana	7
Undetermined sp.	Pr	RD Congo	2
Undetermined sp.	Pr	Burkina Faso	4
Hymenoptera			
Bethylidae			
Odontepyris sp.	LP	India	3
Braconidae			
Bracon sp.	ELP	Ghana	7
Chelonus bifoveolatus (Szépligeti)	ELP	Ghana, Benin	7, 9
Chelonus curvimaculatus Cameron	EP	Kenya	11, 12
Chelonus formosanus Sonan	ELP	India	1
Chelonus sp.	LP	Senegal	14
Coccygidium luteum (Brullé)	LP	Ethiopia, Kenya, Mozambique, Tanzania, Ghana, Benin	7, 8, 9, 11, 12
Coccygidium melleum (Roman)	LP	India	3
Cotesia icipe Fernandez-Triana & Fiobe	LP	Cameroon, Ethiopia, Kenya, Ghana, Benin	7, 9, 11, 12, 15
Cotesia ruficrus (Haliday)	LP	India	16
Glyptapanteles creatonoti (Viereck)	LP	India	6
Meteoridea testacea (Granger)	ELP	Ghana, Benin	7, 9
Microplitis manilae (Ashmead)	LP	India	1
Formicidae			
Pheidole megacephala (Fabricius)	Pr	Ghana	7
Undetermined sp.	Pr	RD Congo	2
Ichneumonidae			
Campoletis chlorideae Uchida	LP	India	3, 6
Campoletis sp.	LP	Senegal	14
Charops ater Szépligeti	LP	Kenya, Tanzania	11, 12
Charops sp.	LP	Benin, Ghana, Mozambique	8, 9
Eriborus sp.	LP	India	3
Ichneumon promissorius (Erichson)	PP	India	1

Species of natural enemies	Type	Countries	References
Metopius cf. *discolor* (Tosquinet)	LP	Mozambique, Ghana	8, 9
Metopius rufus Ashmead	LPP	India	1
Netelia sp.	LP	India	1
Pristomerus pallidus (Kriechbaumer)	LP	Benin	9
Procerochasmias nigromaculatus (Cameron)	PP	Cameroon	15
Undetermined sp.	PP	India	1
Undetermined sp.	LPP	India	6
Platygastridae			
Telenomus remus Nixon	EP	South Africa, Côte d'Ivoire, Niger, Benin, Kenya, Tanzania, Ghana, India, China, Cameroon	1, 9, 12, 15, 17, 18, 19
Telenomus sp.	EP	India	6
Undetermined sp.	*	Burkina Faso	4
Sphecidae			
Undetermined sp.	Pr	Burkina Faso	4
Trichogrammatidae			
Trichogramma chilonis Ishii	EP	Kenya	12
Trichogramma sp.	EP	Benin, India	6, 9
Trichogrammatoidea sp.	EP	Niger	18
Vespidae			
Polistes cf. *olivaceus* (De Geer)	Pr	India	1
Ropalidia brevita Das & Gupta	Pr	India	1
Undetermined sp.	Pr	RD Congo	2
Undetermined spp.	Pr	Burkina Faso	4
Nematoda			
Mermithidae			
Hexamermis cf. *albicans* (Siebold)	LPPa	India	1
Hexamermis sp.	LPPa	Senegal	14
Ovomermis sinensis Chen	LPa	China	20

1= Firake & Behere (2020); 2= Cokola (2019); 3= Sharanabasappa *et al.* (2019); 4= Kouanda (2020) ; 5= Rasheed *et al.* (2020); 6= Shylesha *et al.* (2018); 7= Koffi *et al.* (2020); 8= Caniço *et al.* 2020a); 9= Agboyi *et al.* (2020); 10= Navik *et al.* (2020); 11= Sisay *et al.* (2018); 12= Sisay *et al.* (2019b); 13= Keerthi *et al.* (2020); 14= Tendeng *et al.* (2019); 15= Abang *et al.* (2020); 16= Gupta *et al.* (2019); 17= Kenis *et al.* (2019); 18= Laminou *et al.* (2020); 19= Liao *et al.* (2019); 20= Sun *et al.* (2020).

Among the parasitoid species, the hymenopterans *Cotesia icipe* (Fernandez-Triana & Fiobe), *Coccygidium luteum* (Brullé), *Charops ater* (Szépligeti), *Chelonus curvimaculatus* (Cameron) and the diptera *Palexorista zonata* (Curran) have been found parasitizing the fall armyworm in Ethiopia, Kenya and Tanzania in 2017 (Sisay *et al.*, 2018). While *C. curvimaculatus* is an egg-larval parasitoid, the other species are larval parasitoids only. In Senegal, two solitary hymenoptera belonging to Braconidae (*Chelonus* sp.) and Ichneumonidae (*Campoletis* sp.), were found to parasite 12% of the fall armyworm population (Tendeng *et al.*, 2019). In Benin and Ghana, nine hymenopterans belonging to Braconidae [*C. luteum*, *C. icipe*, *Meteoridea* cf. *testacea* (Granger), *Chelonus bifoveolatus* Szépligeti], Ichneumonidae [*Pristomerus pallidus* (Kriechbaumer), *Charops* sp., *Metopius discolor* Tosquinet], Platygastridae (*Telenomus remus* Nixon), Trichogrammatidae (*Trichogramma* sp.) and the diptera *Drino quadrizonula* (Thomson) (Tachinidae) were found to parasite 5-38% of the fall armyworm in Ghana particulary (Agboyi *et al.*, 2020). In another study, *T. remus*, a parasitoid of several species of *Spodoptera* (Wojcik *et al.*, 1976) was observed to attack eggs of the fall armyworm in Benin, Côte d'Ivoire, Kenya, Niger and South Africa (Kenis *et al.*, 2019). *Telenomus remus* is the main egg parasitoid of fall armyworm in America, where it is already used in augmentative biological control programmes. In Ghana, Koffi *et al.* (2020) identified seven species of parasitoids including *C. icipe* and *C. luteum* that had previously been recorded in East Africa (Sisay *et al.*, 2018). The other species were *C. bifoveolatus*, *M. testacea*, *Bracon* sp. (Hymenoptera), *Anatrichus erinaceus* Loew and an undetermined Tachinidae fly. Among these parasitoids, *C. bifoveolatus* (29%) and *C. luteum* (24%) were the most abundant. The same conclusion was found in another study conducted in Benin and Ghana by Agboyi *et al.* (2020) who identified a total of 10 eggs and larvae parasitoid species.

In addition to insect parasitoids, a parasitic nematode, *Hexamermis* sp. (Mermithidae: Nematoda), was observed in Senegal parasitizing fall armyworm, a first report for Africa (Tendeng *et al.*, 2019). The mermithid genus *Hexamermis* has worldwide distribution and they have been recorded emerging from lepidopterans in various parts of the world (Poinar, 1975). Mermithidae have been reported to feed on the insect's hemolymph and then emerge to complete their development outside the host. Infective juveniles of mermithids climb onto plants during moist conditions, usually in the morning, and infect susceptible hosts, which feed on plant parts (Nickle, 1981). Moreover, juvenile nematodes would parasitize neonate that spend a short time on the ground (Tendeng *et al.*, 2019) by active entry through their cuticle. The entomopathogenic nematodes develop inside the host, which then lead to a slowed life with a marked decrease in their feeding. Mermithids almost always emerge from the insect in the last larval stage, called the postparasitic larva. It is equipped with a lance-like tooth, which is used to perforate the insect cuticle from the inside (Nickle, 1972). The violence of this emergence and the hole on the body of the insect caused by the emergence of this large mermithid usually lead to the death of the insect due to the loss of body fluids (Nickle, 1972).

Three different species of fall armyworm predators have been collected in Ghana: *Haematochares obscuripennis* Stål, *Peprius nodulipes* (Signoret) (both Hemiptera: Reduviidae) and *Pheidole megacephala* (F.) (Hymenoptera: Formicidae) (Koffi *et al.*, 2020). The latter being the most abundant (46% of the observations). They attack eggs and larvae of the fall armyworm. Other important generalist predators include Forficulidae (Dermaptera), Pentatomidae (Hemiptera), Coccinellidae (Coleoptera) and Mantidae (Mantodea), which all have been observed attacking the fall armyworm in Burkina Faso (personal observations). Their conservation requires providing refuges, food supplements and favorable propagation conditions. We suggest that the authorities provide training to smallholder farmers on the recognition, potential and practices for the preservation of these natural enemies. Considering their performance as biocontrol agent against fall armyworm in other parts of the world, further studies should be conducted to assess their potential in West Africa, before designing more comprehensive IPM strategies for the management of the fall armyworm.

Among the other methods of fall armyworm management is the application of sugar water to attract predators and parasitoids. A work carried out in Honduras by Canas and O'Neil (1998) showed a reduction of 18% of infested plants, and a reduction of 35% of damage caused by fall armyworm in maize fields where sugar water was applied. In some parts of Africa, fish soup is applied instead of sugar water, to reach the same effect (Harrison *et al.*, 2019). However, successful and effective implementation of these measures is highly dependent on the availability of natural enemies in the field vicinity, hence the importance of agro-ecological infrastructure. Increasing vegetable and floral biodiversity in the edges of maize fields is among the most valuable options. Mexican sunflower (*Tithonia diversifolia* [Hemsl.] A.Gray) and *Crotalaria* crops planted in maize field borders increased the biodiversity of beneficial insects such as different ant species (Prasanna *et al.*, 2018), some of them being predators of fall armyworm (Koffi *et al.*, 2020).

In East Africa, the abundance of stem borers predators (ants, earwigs and spiders) was increased in fields intercropping maize and *Desmodium*, *D. uncinatum,* with Napier grass (*P. purpureum*) as trap crop around the field (push-pull) (*e.g.* Kebede *et al.*, 2018). In an extension of push-pull approach, it was observed that intercropping maize with the non-host molasses grass *M. minutiflora* and *Desmodium* spp. significantly decreased levels of infestation by certain stem borer species in the main crop and also increased the parasitism of stem borer larvae by *C. sesamiae* (Khan *et al.*, 2016). Push-pull approach may not only impact some stem borer species, but also other lepidopteran pests of maize and other cereals (Hassanali *et al.*, 2008). Similary, a work carried out in Peru showed a better attraction of fall armyworm parasitoids and predators with refuge plants such as: *Foeniculum vulgare* Mill., *Gossypium barbadense* L., *Bidens Pilosa* L. *Helianthus annuus* L., *Malva parviflora* L., *Galinsoga parviflora* Cav. and *Sorghum halepense* (L.) Pers. (Quispe *et al.*, 2017).

Biological insecticides: pesticidal plants and microbial biopesticides

Several plant species are recognized by African smallholder farmers as having pesticidal properties. Either their leaves, flowers, fruits, seeds, bark or roots produce a wide variety of secondary metabolites that are repellent or toxic to insect pests. Yarou *et al.* (2017) listed 20 pesticidal plants specifically used in West Africa to control arthropod pests of vegetable crops. Compared to chemical insecticides, they are expected to be more environmentally friendly due to their short persistence, lower requested concentrations of a more diverse range of active substances and anti-feeding/repellent modes of action (Bhusal & Chapagain, 2020). According to the molecules registered in America, a recent analysis of national lists of pesticides and biopesticides from 19 African countries identified 29 biopesticides which could be allowed for use in fall armyworm management (Bateman *et al.*, 2018), pending their efficacy is proven against this new pest.

Following the introduction of the fall armyworm in Africa, a few studies have evaluated the efficacy of pesticidal plants for the control of this pest (Table 2). Seven plant extracts have shown potential in controling the fall armyworm (*i.e.* mortality greater than 75% after a 72-hour exposure): *Azadirachta indica* A. Juss., *Phytolacca dodecandra* (L'Her.), *Schinus molle* L., *Jatropha curcas* L., *Melia abyssinica* L., *Millettia ferruginea* (Hochst.) Baker and *Croton macrostachyus* Hochst. ex Delile (Sisay *et al.*, 2019a). Among these pesticidal plants, neem is probably the most widely used (James *et al.*, 2010; Yarou *et al.*, 2017). In other contact toxicity and feeding bioassays, the highest larval mortalities were obtained with *Nicotiana tabacum* L. and *Lippia javanica* (Burm.f.) Spreng (Phambala *et al.*, 2020). The same authors also suggested that *Cymbopogon citratus* (DC.) Stapf. and *A. indica* had some valuable deterrent effects (36 and 20%, respectively). In Burkina Faso, the use of aqueous extracts of *Cassia nigricans* Vahl also resulted in a 13% reduction of fall armyworm infestation in maize (Kambou & Millogo, 2019). These insecticides, as well as others also based on neem, capsaicin, orange oil and other aromatic plants, are commercially available in several African countries (Bateman *et al.*, 2018).

Microbial biopesticides include bacteria, fungi, viruses and protozoa used for the biological control of pestiferous insects, plant pathogens and weeds (Chandler *et al.*, 2011; Deravel *et al.*, 2014). Fungi (*Metarhizium rileyi* [Farl.], *M. anisopilae* [Metschnikoff] Sorokin, *B. bassiana*), bacteria (*B. thuringiensis*) and protozoans have been suggested as the best option for the biological control of the fall armyworm (Chhetri & Acharya, 2019). Entomopathogenic fungi are already widespread in maize fields and naturally contribute to the suppression of many crop pests (Vega, 2018). After the introduction of the fall armyworm, larvae infected with entomopathogenic fungi were found in African maize fields according to early reports (Chinwada, 2018; Cokola, 2019). *Beauveria bassiana* is one of the most commonly used as biological control agent worldwide (James *et al.*, 2010), and has been identified in maize fields in West Africa (Cherry *et al.*, 1999; 2004). Recently, *B. bassiana* was demonstrated efficient against eggs and second instar larvae of fall armyworm (Akutse *et al.*, 2019). Some commercially available products, based on *M. anisopliae* or *B. bassiana* are available on the west African market (Bateman *et al.*, 2018; CSP, 2019a).

Several entomopathogenic bacteria also infect insects by ingestion and sometimes *via* parasitoids and predators. Those belonging to the families of Bacillaceae, Enterobacteriaceae and Pseudomonadaceae were the most widespread among the microbiome of 30 lepidopteran species (Paniagua Voirol *et al.*, 2018). Among them, *B. thuringiensis* are gram-positive bacteria producing toxic crystalline proteins called delta-endotoxins or Cry protoxins, which cause rapid deathafter ingestion (Popp *et al.*, 2013). In several West African countries, a number of microbial biopesticides based on these bacteria are registered and commercialy available: *B. thuringiensis* var. *Kurstaki* and *B. thuringiensis* subsp. *Aizawai* (Bateman *et al.*, 2018; CSP, 2019a).

Table 2. Toxicity of pesticidal plants assessed on fall armyworm in Africa since 2016.

Pesticidal plants	Rate (%)	Efficacy	Countries	Ref
Aloe vera (L.) Burm.f.	23	Lab & field	Malawi	1
Azadirachta indica A. Juss.	60-98	Lab & field	Ethiopia, Malawi, Benin	1, 2, 3
Capsicum annum L.	Unknown	Field	Burkina Faso	4
Cassia nigricans Vahl	Unknown	Field	Burkina Faso	4
Chenopodium ambrosoides L.	21	Lab	Ethiopia	2
Cleome viscosa L.	Unknown	Field	Burkina Faso	4
Croton macrostachyus Hocsht.	75	Lab	Ethiopia	2
Cymbopogon citratus (DC.) Stapf	50	Lab & field	Malawi	1
Eucalyptus globulus Labill.	8	Lab	Ethiopia	2
Jatropha curcas L.	91	Lab	Ethiopia	2
Lantana camara L.	10-40	Lab & field	Ethiopia, Malawi	1, 2
Lippia javanica (Burm.f.) Spreng	66	Lab & field	Malawi	1
Melia abyssinica L.	90	Lab	Ethiopia	2
Militia ferruginea (Hochst)	78	Lab	Ethiopia	2
Nicotina tabacum L.	50-66	Lab & field	Ethiopia, Malawi	1, 2
Ocimum basilicum L.	26	Lab & field	Malawi	1
Parkia biglobosa (Jacq.) R. Br.	Unknown	Field	Burkina Faso	4
Phytolacca dodecandra (L'Herit)	96	Lab	Ethiopia	2
Schinnus molle L.	96	Lab	Ethiopia	2
Tephrosia vogelii Hook.f.	<10	Lab & field	Malawi	1
Trichilia emetica Vahl	20	Lab & field	Malawi	1
Vernonia amygdalina Delile	38	Lab & field	Malawi	1

1= Phambala *et al.* (2020); 2= Sisay *et al.* (2019a); 3= Adeye *et al.* (2018); 4= Kambou & Millogo (2019).

However, the efficacy of these microbial biopesticides against the fall armyworm and their natural enemies remains to be properly evaluated (Kasoma *et al.*, 2020). In Central America, some smallholder farmers have developed their own artisanal production of entomopathogens, that they apply in maize fields. Others collect the dead larvae from their fields, crush them and apply a solution of the extract into maize plants infested with fall armyworm (Hruska, 2019). Both approaches led to significant results.

Recently, some entomopathogens were recovered from dead fall armyworm larvae and pupae in Madagascar, India and Indonesia. These biocontrol agents belonging to entomopathogenic fungi (*M. anisopliae*, *Nomuraea* (=*Metarhizium*) *rileyi*, *B. bassiana*), entomopathogenic virus (*Spodoptera frugiperda* Nuclear Polyhydrosis Virus (SpfrNPV), *Spodoptera frugiperda* multiple nucleopolyhedro virus (SfMNPV) and entomopathogenic bacteria (*Bacillus* sp.) (Chinwada, 2018; Firake & Behere, 2020; Sharanabasappa *et al.*, 2019; Shylesha *et al.*, 2018).

Additional recommendations and perspectives

Presently, alternative practices to chemical insecticides play a marginal role in the control of insect pests in production systems in West Africa. The pesticide market is still dominated by chemical pesticides despite the development of biopesticides and genetically modified plants (Thakore, 2006). With the exception of neem, plant biopesticides are not yet commercialized on a large scale due to the lack of control over their stability by ordinary manufacturers. Lack of material, financial resources and appropriate equipment also limit the production and availability of these plant biopesticides (Yarou *et al.*, 2017). However, the biopesticide market is growing faster than that of chemical pesticides (Popp *et al.*, 2013). Many biological control agents are not considered acceptable by farmers because they are evaluated for their immediate impact on insect pests. Compared to chemical pesticides, disadvantages of biopesticides include a slower rate of insect elimination, shorter persistence in the environment and sensitivity to adverse environmental conditions (Chandler *et al.*, 2011; Popp *et al.*, 2013; Rioba & Stevenson, 2020). However, agro-ecological management of insect pests not only has positive economic benefits, but it is crucial for biodiversity conservation (Epstein *et al.*, 2021). For this reason, evaluation of the efficacy of biological control agents must consider long-term impacts rather than only short-term performance, as is generally the case with conventional practices. However, the future of biopesticides in West Africa may depend on market forces rather than on their ability to compete with chemical pesticides as environmentally friendly alternatives, as in Kenya (Coulibaly *et al.*, 2007).

Reports are accumulating from over the planet to show the status of resistance of the fall armyworm to most of the active substances, and associated modes of action (Diez-Rodriguez & Omoto, 2001; Gutiérrez-Moreno *et al.*, 2019). Since West Africa is lacking data on the resistance status of the fall armyworm to the available insecticide substances, we suggest the establishment of laboratories accredited to measure susceptibility and resistance to the major classes of pesticides in all areas where the fall armyworm is present. A similar suggestion has recently been made for another invasive pest, *Tuta absoluta* Meyrick (Sawadogo *et al.*, 2020a). A unique methodology should be followed and applied to populations collected from the main maize areas of West African. The identification of less effective substances would allow to build a communication strategy at each country level.

Farmers need training to improve their knowledge, self-confidence, skill levels, and willingness to make no-spray decisions when it is safe to skip an insecticide application (Prasanna *et al.*, 2018). In addition, farmers involved in the agro-ecological transition stated that it can only be done with collectivity support, adapted accompaniment and training or coaching (Claveirole, 2016). Continuous training of farmers is imperative in order to equip them and give them more autonomy. Evaluation of farmer awareness of the range of entomofauna associated with sorghum and groundnut in Burkina Faso show that farmers have a fairly detailed knowledge of most of the major arthropod pests. Conversely, while they are able to identify some predatory arthropods, they do not know their usefulness in controlling crop pests (Dicko *et al.*, 1998). One of the best ways to meet this need is using of Farmers Field Schools, combined with various means of awareness and communication (Prudent *et al.*, 2006). For example, the dissemination of push-pull in East Africa has been done through several means of communication, including videos, radio scripts, brochures and training materials for producers in several languages. Push-pull system is one of the most successful examples of conservation biological control (Prasanna *et al.*, 2018). Farmer Field Schools improve farmers' knowledge and adoption of beneficial practices, and reduce overuse of pesticides. However, the success of these training initiatives also implies permanent interactions between scientists, farmers and those who define and implement public policies. Many farmers innovate and create in order to improve their products and reduce their production costs (Claveirole, 2016). Their knowledge must also be considered during exchanges of practices and know-how, observations and experiments. In the transition towards agro-ecological crop protection, appropriation of knowledge is based not only on the knowledge flows generated by the combination of disciplines, but also on discussions, practice and sharing of experiences (field meetings, group workshops) within a target or mixed audience maintaining the progress loop that drives agro-ecological evolution (Deguine *et al.*, 2017).

Alternatives should also be developed considering the specific context of West African countries. Agro-ecological practices and techniques have exceptional potential for the management of insect pests in crops while simultaneously helping the transition from conventional agriculture to agro-ecology. As an alternative, agro-ecological crop protection helps to overcome many problems resulting in chemical control such as: development of insecticide resistance, increases production costs, and negative environmental and human health impacts (Akutse *et al.*, 2019; Damalas & Eleftherohorinos, 2011). Resistance to biological control agents has not been observed in the fall armyworm; the cost of biological control, particularly classical and conservation biological control, is much lower and benefits smallholder production systems in Africa (Prasanna *et al.*, 2018). Natural resources and habitat management are important for agro-ecological crop protection using biological control agents, resistant or tolerant cultivars, plant biopesticides, while reducing pesticide use by more than 90% in integrated farms (Reddy, 2017; Rioba & Stevenson, 2020). Generally, agro-ecological crop protection offers sustainable with negligible ecological impacts, is cost-effective and harmless to beneficial organisms and other non-target species compared to chemical pesticides (Reddy, 2017). It also boosts employment opportunities through the development of small local industries (Rioba & Stevenson, 2020) for the production of quality bioproducts based on fungi, bacteria, viruses, and nematodes. For instance, local production of Trichograms for the control of fall armyworm and other lepidopteran species harmful to crops has been successful in a number of countries such as Brazil and Egypt (Hruska, 2019).

Conclusions

In West Africa, maize protection against the fall armyworm becomes essential. Cultural practices (early planting, intercropping, crop rotation, trap crops) should be promoted with more consideration, due to their easy implementation. Curative control of fall armyworm should give priority to biopesticides such as microbial pesticides. In order to exploit this potential, it is important to evaluate the diversity and effectiveness of natural enemies on the continent. The chemical pesticides that have to be applied when the damage exceeds economic threshold should have lower toxicity to natural enemies and human health. Furthermore, some local practices and innovations used by smallholder farmers should be evaluated in order to scientifically establish their effectiveness and robustness in space and time. Participative approach, Farmers Field Schools, adapted accompaniment and training of smallholder farmers would increase the competitiveness and adoption of alternative methods to chemical pesticides.

2

Objectifs et structure de la thèse

Dans la section introductive, nous avons justifié pourquoi la chenille légionnaire d'automne est considérée comme l'un des ravageurs agricoles les plus nuisibles. A sa grande polyphagie, sa fécondité et sa mobilité élevées, s'ajoute le développement rapide de la résistance aux insecticides dans les populations exposées.

Les méthodes de lutte mises en place se sont heurtées à de nombreux défis : la méconnaissance du ravageur (identification, bio-écologie, dynamique des populations, niveaux de dommages, ennemis naturels, …) et le manque de stratégies validées dans le contexte africain (inexistence d'insecticides homologués, méconnaissance des seuils d'intervention, résistance aux insecticides, …). Elles se sont focalisées essentiellement sur l'utilisation des insecticides chimiques sans une évaluation préalable de leur efficacité compte tenu de l'urgence de la situation, malgré les risques pour la santé humaine et environnementale. Cependant, de nombreux échecs de contrôle ont été signalés par les producteurs.

Il nous a donc semblé essentiel de mener des recherches afin de contribuer au développement de stratégies de gestion. L'objectif général de cette thèse réalisée au Burkina Faso est de **générer des connaissances sur ce nouveau ravageur en vue d'optimiser les stratégies de lutte adaptées au contexte ouest africain.**

Les objectifs spécifiques et hypothèses ci-dessous ont été fixés, chacun d'entre eux constituant un chapitre de cette thèse.

(1) Les nombreuses connaissances de gestion de la chenille légionnaire d'automne en Amériques et les premiers travaux menés en Afrique constituent une base importante pour l'orientation des recherches. Dans l'**introduction générale**, nous avons parcouru la littérature scientifique pour décrire la chenille légionnaire d'automne et discuter le potentiel des options de contrôle de ce nouveau ravageur dans le contexte ouest-africain.

(2) Avant de proposer des méthodes de gestion efficaces contre la chenille légionnaire d'automne, il était nécessaire de comprendre le contexte agricole local. Par conséquent, l'objectif développé dans le **chapitre 3** est d'**évaluer l'état des connaissances et les différentes méthodes de lutte mises en place par les producteurs pour gérer la chenille légionnaire d'automne**. Pour y parvenir, nous avons testé l'hypothèse que les agriculteurs ont mis en œuvre diverses méthodes permettant de lutter efficacement contre la chenille légionnaire d'automne, qui est devenue l'insecte ravageur le plus important du maïs.

(3) La dynamique de la chenille légionnaire d'automne (et des populations d'insectes ravageurs en général) est influencée par plusieurs facteurs environnementaux, climatiques et par la disponibilité des plantes hôtes. Il est donc important de prévoir les périodes de pullulation du ravageur pour adapter le calendrier agricole et les moments d'intervention. L'objectif du **chapitre 4** est de **caractériser la phénologie du ravageur et d'identifier les autres plantes cultivées qui permettraient au ravageur de survivre**. Deux hypothèses ont été testées : (i) les conditions climatiques sont favorables à la persistance de la chenille légionnaire d'automne tout au long de l'année et (ii) certaines plantes sont inadaptées car elles permettent un développement plus lent et entraînent une mortalité plus élevée de l'insecte.

(4) Sur la base des résultats du chapitre 3 et des données de la littérature, la lutte chimique demeure la principale méthode de lutte contre la chenille légionnaire d’automne. Les nombreux échecs signalés par les producteurs suggèrent une inefficacité des produits utilisés et une résistance des populations aux insecticides. L’objectif du **chapitre 5** est d’**évaluer la susceptibilité du ravageur aux insecticides chimiques et biologiques disponibles localement, pour établir une liste positive pouvant contrôler efficacement la chenille légionnaire d’automne**. À cette fin, nous avons testé l’hypothèse que certains insecticides utilisés par les agriculteurs ne présentent pas des niveaux de toxicité suffisants aux doses recommandées par les fabricants contre la chenille légionnaire d’automne.

(5) La connaissance des ennemis naturels de la chenille légionnaire d’automne est essentielle au développement de la lutte biologique pour le contrôle à long terme de ce ravageur. Ces informations permettront de mettre en place des stratégies et pratiques de préservation et d’optimisation de leur potentiel. L’objectif du **chapitre 6** est de **rechercher des ennemis naturels associés à la chenille légionnaire d’automne et des stratégies pour leur maintien dans les champs de maïs au Burkina Faso**. Nous avons testé les hypothèses selon lesquelles (i) les ennemis naturels locaux élargissent leur gamme d’hôtes en attaquant la chenille légionnaire d’automne et (ii) certains insecticides efficaces contre le ravageur sont sélectifs pour les ennemis naturels et donc compatibles dans un programme de lutte intégrée.

Enfin, **le chapitre 7** est consacré à la **discussion générale** des résultats obtenus, aux **perspectives** de recherche pour la gestion de la chenille légionnaire d’automne en Afrique de l’Ouest et à la **conclusion générale**.

3

Connaissances des producteurs et méthodes de lutte

Introduction au chapitre 3

La réaction immédiate des gouvernements suite à l'invasion de la chenille légionnaire d'automne en Afrique a été d'investir massivement dans les insecticides chimiques. Leur utilisation demeure la principale stratégie des agriculteurs pour lutter contre ce ravageur, bien que les résultats soient mitigés, avec des conséquences sur la santé et l'environnement. Les méthodes alternatives -qui réduisent l'application des insecticides chimiques- sont en conséquence recommandées et recherchées en Afrique. Les agriculteurs africains sont connus pour développer des stratégies et des pratiques de gestion des nuisibles et des problèmes qu'ils rencontrent en fonction de leurs connaissances et de leurs perceptions. Il est donc important d'en tenir compte, pour aborder les limites et proposer des méthodes de gestion appropriées et adaptées à leurs besoins, tout en les impliquant dans le processus de développement des technologies.

L'objectif de ce chapitre est d'évaluer l'état des connaissances et les différentes méthodes de lutte mises en place par les producteurs pour lutter contre la chenille légionnaire d'automne. Pour y parvenir, nous avons mené une enquête auprès des producteurs de maïs au Burkina Faso. Les données collectées concernent la connaissance du ravageur et ses ennemis naturels, le niveau d'infestation des champs de maïs selon les estimations des agriculteurs et les pratiques de gestion mises en place. Pour ceux qui utilisent des insecticides chimiques, des informations supplémentaires ont été demandées : type d'insecticide, matière active, nombre d'applications par cycle de culture, mesures prises en cas d'inefficacité, sécurité de gestion des pesticides, effets secondaires potentiels sur la santé. Ces résultats seront utiles pour identifier les besoins des producteurs et les actions nécessaires pour une gestion durable de la chenille légionnaire d'automne.

L'invasion de la chenille légionnaire d'automne (*Spodoptera frugiperda* Smith) au Burkina Faso a entraîné des modifications majeures des pratiques de lutte contre les insectes ravageurs du maïs

Cette section est une adaptation de l'article suivant :

Ahissou B. R., Sawadogo W. M., Bonzi S., Kambiré F. C., Somda I., Bokonon-Ganta A. H., & Verheggen F. J. Farmers' knowledge, perceptions, and management practices of the fall armyworm (*Spodoptera frugiperda* Smith) in Burkina Faso. Accepted *in Biotechnology, Agronomy and Society and Environment,*

1. *Abstract*

The fall armyworm *Spodoptera frugiperda* Smith has recently invaded sub-Saharan African countries where it causes significant losses to maize since 2016. In this study, we examined farmers' knowledge of the fall armyworm, changes in pest management practices, and the safety of insecticide use by farmers since the recent invasion of the pest in Burkina Faso. Data were collected through a survey of 197 maize farmers. A semi-structured questionnaire loaded on the KoboToolbox platform was used by trained interviewers in the local language during the interviews.

The majority of the farmers (96%) had experienced the fall armyworm invasion, mainly on maize, but also on sorghum and rice. Almost none of them (7%) used chemical insecticides to control maize pests before the arrival of the pest. Since then, 84% have used chemical insecticides, but various measures have also been implemented: cultural practices (48%) such as early planting, crop associations and fertilization; physical control (29%, i.e, handpicking, application of sand and ash) and applications of aqueous extracts of *Azadirachta indica* and *Khaya senegalensis* (12%). Most farmers do not use protective equipment when handling insecticides. Although they can name several natural enemies of the fall armyworm based on the photos presented to them, they are generally unable to describe their beneficial role.

We recommend evaluating the effectiveness of alternatives to chemical insecticides, publishing information on locally available insecticides that effectively control fall armyworm, and training farmers on proper pesticide application methods and natural enemy recognition.

2. *Introduction*

The fall armyworm *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) was first reported in 2016 in Benin, Nigeria, Sao Tome and Principe, and Togo (Goergen *et al.*, 2016) and has subsequently spread in several other countries including Burkina

Faso in 2017 (Tizie & N'Guessan, 2017). The pest is native to America and has been reported to feed on more than 350 host plants belonging to 76 plant families, mainly Poaceae, Fabaceae and Asteraceae (Montezano *et al.*, 2018). Although Africa has its native important *Spodoptera* species (*i.e*. *Spodoptera exempta* Walker, *Spodoptera exigua* Hübner, *Spodoptera littoralis* Boisduval) and stemborers (*i.e*. *Busseola fusca* Fuller, *Chilo partellus* Swinhoe, *Sesamia calamistis* Hampson, *Eldana saccharina* Walker) (Kfir *et al.*, 2002; Nafiu *et al.*, 2014), the fall armyworm has become the most damaging pest, especially affecting maize production (Goergen *et al.*, 2016; Rwomushana *et al.*, 2018; Wild, 2017). Given that the fall armyworm is new to Africa, there is relatively limited information on the pest in this continent.

Economic damage is caused by the larvae that destroy young maize plants by attacking fresh leaves and bore into the maize cob to feed on the kernels (Prasanna *et al.*, 2018). Therefore, in addition to foliar damages, the insect destroys the reproductive parts of the crop (Wild, 2017). In the absence of control methods, *S. frugiperda* was recently shown to reduce by 21% to 53% maize production in 12 of African countries (Abrahams *et al.*, 2017b; Prasanna *et al.*, 2018). The value of these losses was estimated between USD 2.48 and 6.19 billion. As maize is a staple food in most African countries, the food and nutritional security of millions of producers is threatened.

To mitigate the impact of this invasive pest, most national governments have made synthetic insecticides accessible to their farmers, although their efficacy has not been proven (Sisay *et al.*, 2019a; Tambo *et al.*, 2020). For instance, more than USD 7 million (Uganda), 4 million (Ghana), 3 million (Zambia) (Abrahams *et al.*, 2017b), 397,000 (Burkina Faso) (MAAH, 2018) were reportedly allocated by governments for the supply of insecticides, education and protective clothing. In Burkina Faso, more than 12,000 liters of synthetic insecticides were sprayed on 14,000 ha of fall armyworm infested fields, during the 2018–2019 crop season (MAAH, 2018). Besides the application of chemical insecticides, the control strategies and immediate directions were based on the experiences and research on the fall armyworm in the America. Consequently, it is essential to conduct fall armyworm research in Africa to generate the necessary information to develop context-specific management strategies. Understanding the types of practices that farmers have adopted in response to the fall armyworm attack and their impacts will offer some insights into actions required to ensure successful management of the pest in the continent. Some recent studies have investigated farmers' perceptions and management practices of fall armyworm in Kenya, Uganda and Tanzania (Midega *et al.*, 2018), Zambia (Kansiime *et al.*, 2019), Zimbabwe (Chimweta *et al.*, 2020), Benin (Houngbo *et al.*, 2020), Ghana (Asare-Nuamah, 2020). Although chemical control is the main management method for fall armyworm, farmers have adopted other control practices, such as plant extracts, handpicking of larvae, and applying soil or ash to maize whorls.

To our knowledge, there is no information on the extent of damage caused by the fall armyworm, the knowledge of farmers and the strategies implemented to control this pest in Burkina Faso. This study aims to contribute to the scientific literature by assessing how maize farmers in Burkina Faso respond to the fall armyworm invasion. We determine the level of fall armyworm infestation in maize based on farmers' estimates and assess farmers' perceptions and practices for managing fall armyworm.

We also examined farmers' pesticide use habits (type, toxicity, and management safety of pesticides used).

3. *Materials and methods*

3.1 Study area

This study was conducted between August and November 2020 among 197 maize producers in 3 communes located in two agro-ecological zones of Burkina Faso: Bobo-Dioulasso (Sudanian zone), Ouahigouya and Ziniaré (Sudano-Sahelian zone) (Figure 4).

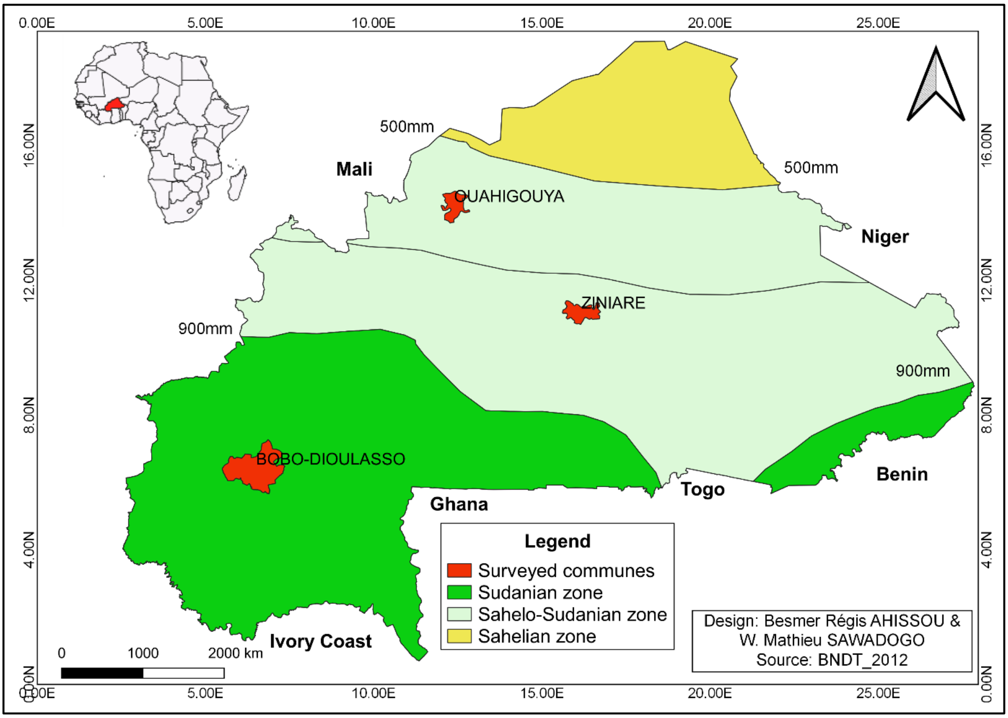

Figure 4. Map showing the location of the surveyed communes in Burkina Faso.

3.2 Questionnaire development and delivery

A semi-structured questionnaire was provided to trained interviewers (the complete list of questions can be found in the appendix as supplementary material). The questionnaire was loaded into the KoboToolbox platform, which was used to collect data using tablet computers. Interviews were conducted in the local language of the community during face-to-face interactions between the farmer and two interviewers. The final sample consisted of 197 maize producers.

The basic information collected included farmer's name, gender, age, educational level, organization and collaboration with research services, training in plant protection, maize production practices (production systems, intercropping, weeding method). The farmer's knowledge about the fall armyworm and perception to how they consider the pest problem, crop damage, and the effectiveness of the available control measures were assessed. We used photos of different stages of the fall armyworm, damage or symptoms, as well as natural enemies, to evaluate farmer's knowledge.

Farmers were asked to rate the severity of the fall armyworm infestation based on the proportion of maize area affected. Fall armyworm identification and damage quantification by farmers may be very different and less accurate than that of an expert. However, they make decisions based on what they think is the problem (Schreinemachers *et al.*, 2015).

Because the fall armyworm is new to Africa, understanding the types of practices that farmers have adopted in response to the pest attack and their impacts will provide insight into the actions required for effective integrated pest management. In this study, we questioned on the actions that farmers undertake to control the fall armyworm. Additional information was requested for those who used insecticides: trademark (the packaging was checked during the interview), active product, number of applications per crop cycle, measures undertaken in case of ineffectiveness, management safety of pesticides, potential health side effects. To determine whether the insecticides used by farmers were registered or not, the latest lists provided by the Sahelian Pesticides Committee (CSP) were used (CSP, 2018; 2019b).

4. Results

4.1 Farmers demographic and socio-economic characteristics

Table 3 summarizes the profiles of the farmers, their knowledge and perceptions of the fall armyworm and the control methods implemented. The maize producers surveyed are mostly men (87.8%), aged of 44.1 (±10.7) years. About 61.4% of farmers had no formal education and 30% did not attempt secondary school. Agriculture was their main activity and more than 49.3% of respondents have been farming for more than 15 years. In addition to maize, they produce rice, sorghum, pearl millet, peanut, cowpea and more than 66% of the respondents also practice market gardening. Maize production in the study area is predominantly small-scaled and the average field size was 1.5 ha, which represents a significant proportion of the total household cultivated land. The majority (77.8%) of producers had not received training in crop pest management.

4.2 Fall armyworm identification, host plants and natural enemies

Although the fall armyworm is a new pest for Africa, the majority (96.0%) of respondents could correctly identify the larval stage based on pictures. Most farmers are not familiar with the eggs and adult moths of the fall armyworm. They very accurately described the typical leaf damage, mainly in the whorl. Almost half (50.3%) of them recorded the first attacks of fall armyworm in 2016 (some even earlier). According to the respondents, the plants affected by the fall armyworm were mainly maize (99.4%), but some of them also cited sorghum (20.9%), tomato (7.1%) rice and cowpea (6.7%). Infestation levels in maize fields varied widely among producers and were less than 10% (for 19.5% of the farmers), 10 - 40% (30.3%) and 40 - 70% (41.6%).

During the survey, maize producers were shown photos of various predators of fall armyworm, without giving them their identity or their beneficial role. Farmers' knowledge of the natural enemies of the fall armyworm was found to be limited to a few predatory birds (26.2%). Concerning other predators such as earwigs, ants, spiders, coccinellids, praying mantis, they were mainly observed by the producers in maize fields. They are barely never identified as beneficials and in some cases, they are considered as pests that also need to be eliminated.

Table 3. Farmers' characteristics, knowledge and perceptions of fall armyworm and control methods in different communes. **Azadirachta indica* and *Khaya senegalensis*

Variables	**Bobo** N= 73	**Ziniaré** N= 64	**Ouahi** N= 60	**Mean** N= 197
Gender (%)				
Male	87.7	89.1	86.7	87.8
Female	12.3	10.9	13.3	12.2
Age (years)	44.5±9.9	44.1±10.3	43.5±11.9	44.1±10.7
Education (%)				
No formal education	35.6	33.3	43.3	37.4
Literacy	31.5	25.4	15.0	24.0
Primary school	24.7	33.3	33.3	30.4
Secondary school	8.2	4.8	8.3	7.1
Tertiary education	0.0	3.2	0.0	1.1
Years of farming experience (%)				
< 5	6.9	9.4	6.7	7.7
5 - 10	12.3	18.8	33.3	21.5
10 -15	26.0	18.8	20.0	21.6
> 15	54.8	53.1	40.0	49.3
Maize field size (ha)	1.7±2.1	1.2±0.9	1.4±1.2	1.5±1.5
Training in pest management (%)	26.4	21.9	18.3	22.2
Known fall armyworm larva (%)	94.5	98.4	95.0	96.0
First attacks of the fall armyworm (%)				
2015	5.6	6.2	5.1	5.6
2016	48.6	50.0	33.9	44.2
2017	41.7	37.5	54.2	44.5
2018	4.2	3.1	6.9	4.7
Major crops attacked (%)				
Maize	100	100	98.3	99.4
Sorghum	17.8	31.2	13.6	20.9
Rice	15.1	1.7	3.4	6.7
Tomato	8.2	7.9	5.1	7.1
Cowpea	4.1	10.9	5.1	6.7
Infestation levels in maize fields (%)				
< 10%	29.2	15.6	13.6	19.5
10 – 40%	22.2	28.1	40.7	30.3
40 - 70%	36.1	53.1	35.6	41.6
> 70%	12.5	3.1	10.1	8.6

Variables	**Bobo** N= 73	**Ziniaré** N= 64	**Ouahi** N= 60	**Mean** N= 197
Know fall armyworm natural enemies				
No knowledge	57.5	54.7	40.0	50.7
Birds	12.3	28.1	38.3	26.2
Insecticide before the invasion (No)	94.5	93.8	90.0	92.8
Pest control methods (%)				
Synthetic insecticides	90.3	82.8	79.7	84.3
Cultural practices				
➢ Fertilization	16.7	21.9	50.0	29.5
➢ Early planting	5.6	12.5	13.3	10.5
➢ Intercropping and rotation	1.4	17.2	5.0	7.9
Physical control (%)				
➢ Handpicking	15.3	18.8	23.3	19.1
➢ Ash and sand	4.2	3.2	8.3	5.2
➢ Soaps or liquid detergents	5.6	6.2	1.7	4.5
Botanical insecticides* (%)	11.1	17.2	6.7	11.7
Reponses to chemical insecticide inefficacy (%)				
Increase treatment frequency	75.4	58.5	43.5	59.1
Increase pesticide dose	32.3	49.1	54.3	45.2
Change insecticides	10.8	24.5	8.7	14.7
Mixe insecticides	7.7	13.2	13.0	11.3
Nothing	9.2	5.7	10.9	8.6
Number of insecticide applications (%)				
Once	16.9	30.2	14.9	20.7
Two times	27.7	15.1	42.6	28.5
Three times	36.9	41.5	27.7	35.4
Four times and more	18.5	13.2	14.9	15.5
Insecticide selection (%)				
Pesticide vendor’s advice	46.2	39.6	21.3	35.7
Personal experience	15.4	35.8	51.1	34.1
Agriculture officer’s advice	24.6	13.2	12.8	16.9
Another producer’s advice	33.8	32.1	14.9	26.9
Combination of methods (%)				
Insecticides + Cultural practices	19.2	28.1	50.0	32.4
Insecticides + Physical control	17.8	21.9	18.3	19.3
Insecticides + Botanical insecticides	12.3	15.6	6.7	11.5
Security of pesticide management (%)				
Protective gear	1.4	3.4	5.8	3.5
Nose mask	66.2	71.2	78.8	72.1
Gumboots	36.6	37.3	44.2	39.4
Gloves	28.2	35.6	38.5	34.1
Reported side effects of insecticide (%)				
Eyes or skin irritation	62.3	41.4	60.8	54.8
Headaches	52.2	29.3	33.3	38.3
Tiredness	11.6	13.8	5.9	10.4

4.3 Fall armyworm management practices

More than 92.8% of farmers were not using any synthetic insecticides to control insect pests in maize production before the arrival of the fall armyworm in Burkina Faso. Since fall armyworm invasion, farmers use various methods of pest control. During our survey, the most common measure was the application of synthetic insecticides (84.3%), followed by cultural practices (47.9%), physical control (28.8%) and botanical insecticides (11.7%).

Many farmers used a combination of methods, and a majority of farmers combined insecticides with cultural or physical practices. In case of treatment failure, producers increased the frequencies of chemical insecticide application (59.1%), dose of chemical insecticide (45.2%), or used another chemical insecticide (14.7%) or mixed insecticides in a single spray (11.3%). We also found that male farmers (85.5%) are more likely than female farmers (70.8%) to adopt synthetic insecticides to control fall armyworm.

Cultural practices were dominated by fertilization (29.5%), early planting (10.5%), intercropping, crop rotation (7.9%). Intercropping was practiced with groundnut, cowpea, and sorghum.

For physical control and local remedies, they were dominated by handpicking of egg masses and larvae (19.1%), application of ash and sand (5.2%) (Figure 5) and application of soaps or liquid detergents (4.5%). These physical practices were more prevalent among women than men. Moreover, some farmers use plant extracts of neem (*Azadirachta indica* A. Juss) and african mahogany (*Khaya senegalensis* A. Juss) alone or in combination with chemical insecticides to manage fall armyworm (11.5%).

Figure 5. Application of ash in the maize cob.

4.4 Types of chemical insecticides and security of pesticide management by maize producers

At the time the survey was conducted, there were no registered chemical insecticides recommended for fall armyworm management in Burkina Faso and other member countries of the Sahelian Pesticides Committee (Benin, Cape Verde, Chad, Gambia, Guinea, Guinea Bissau, Ivory Coast, Mali, Mauritania, Niger, Senegal and Togo). This is probably due to the early introduction of the pest into this new area. Consequently, farmers tried every chemicals available on the market to control the pest. Among the 21 insecticides used by the interviewed farmers, three insecticides (Duel, Kapaas and Lambda Power) were not registered by the Sahelian Pesticides Committee. All insecticides are formulated from 14 active ingredients and are available as single (15), binary (5) or ternary (1) formulations (Table 4). Most insecticides were registered for use on cotton (57.1%) and vegetable crops (42.9%).

We found that the most popular active ingredient used were: emamectin benzoate (62.4%), lambda-cyhalothrin (19.4%), abamectin (18.2%) and deltamethrin (10.9%). Most farmers applied insecticides once (20.7%), twice (28.5%) or three times (35.4%) without any specific timing. The choice of insecticides by farmers is based on the advice of the pesticide seller (35.7%), their personal experience (34.1%) or on the advice of another producer (26.9%). According to the World Health Organization (WHO) classification of pesticides, the majority of insecticides are classified as class II (moderately hazardous) and class III (slightly hazardous) of pesticides (Table 4).

Given that insecticide application was the most common control option used by the surveyed farmers, we examined whether certain safety precautions were taken when handling pesticides. Any pesticide application activity requires specific protective measures. However, this study showed that the majority of maize producers (96.5%) did not protect themselves adequately, even though they were aware of the harmful effects of chemical pesticides. The use of protective gear was very uncommon (3.5%) and maize growers generally protect themselves with certain items including: nose mask (72.1%), gumboots (39.4%) and gloves (34.1%).

This scenario is undesirable as it predisposes farmers to health risks. For instance, some of farmers who sprayed pesticides reported side effects, particularly eyes or skin irritation (54.8%) and headaches (38.3%). In this context, several practices were adopted by farmers to mitigate the risk of pesticide intoxication, among which are: drinking milk, vinegar or lemon after pesticide application and using lemon and potash to wash hands after pesticide handling.

Table 4. Insecticides used by maize farmers for fall armyworm control in Burkina Faso and their WHO classification. a : Percentages are based on farmers that used insecticides for fall armyworm control; b : WHO Recommended Classification; II = moderately hazardous; III = slightly hazardous; U= unlikely to present acute hazard in normal use. RC = Recommended crops: C = cotton, T = tomato, Ca = cabbage, Sw = sweet pepper, Ga = gardening crop.

Trade name	Active ingredient	%[a]	C[b]	RC
Abalone 18 EC	Abamectin 18g/l	4.2	II	T
Acarius	Abamectin 18g/l	7.3	II	T
Bio K 16	*Bacillus thuringiensis* 16000 UI/mg	5.5	U	Ga
Bomec 18 EC	Abamectin 18g/l	1.2	II	T
Caiman B19	Emamectin benzoate 19.2g/l	6.7	II	C, T
Conquest C 176 EC	Acetamiprid 32g/l + Cypermethrin 144g/l	4.8	II	C
Cypercal 50 EC	Cypermethrin 50g/l	6.1	III	C, T
Décis 25 EC	Deltamethrin 25g/l	1.2	II	T
Duel CP 186 EC	Cypermethrin 36g/l + Profenofos 150g/l	4.2	II	C
Emacot 019 EC	Emamectin benzoate 19g/l	24.8	II	C
Emacot 050 WG	Emamectin benzoate 50g/kg	30.9	II	C
Emapyr	Emamectin benzoate + Pyriproxyphen	5.5	III	C
Kapaas	Emamectin benzoate +Abamectin +Acetamiprid	5.5	II	C
K-Optimal	Lambda-cyhalothrin 15g/l + Acetamiprid 20g/l	1.2	II	C
Lambda Power	Lambda-cyhalothrin 25g/l	3.6	II	C, Ga
Laser 480 SC	Spinosad	1.8	III	C,T,Ca
Radiant 120 SC	Spinetoram	1.2	III	T
Savahaler	Methomyl 250g/kg	6.1	II	Ca
Sunhalotrin 2,5% EC	Lambda-cyhalothrin 25g/l	14.5	III	T
Tamega	Deltamethrin 25g/l	9.7	II	T, Sw
Thunder 145 O-TEQ	Imidacloprid 100g/l + Betacyfluthrin 45g/l	0.6	II	C

5. *Discussion*

Similarly to previous studies conducted in Zambia (Kansiime *et al.*, 2019) and Benin (Houngbo *et al.*, 2020), we found that the majority of the farmers could identify the fall armyworm larvae despite its new pest status. This observation can be explained by the frequency and severity of the attacks caused by this pest in maize fields. Therefore, the lack of training among other farmers has not prevented them from recognizing the pest. The levels of fall armyworm infestation recorded in this study are also consistent with that reported in several other studies on the continent (Chimweta *et al.*, 2020; Houngbo *et al.*, 2020; Rwomushana *et al.*, 2018). According to farmers' observations, the pest was present in Burkina Faso at least 1 or 2 years before it was officially reported. It is probable that the insect was present, but that its damage became significant and noticeable later. Farmers' perceptions are consistent with findings that reported the pest in early 2016 in West and Central Africa (Goergen *et al.*, 2016).

Farmers in Burkina Faso had to quickly adapt to fall armyworm invasion. They have reported an unexpected diversity of unconventional methods and combinations of methods (application of ash, sand, detergents). They reflect confusion among farmers, and are probably the result of a lack of knowledge and the ineffectiveness of the traditional methods (Chimweta *et al.*, 2020; Matova *et al.*, 2020). Similarly to what has been observed in other African countries (such as Zambia, Ghana (Kansiime *et al.*, 2019; Rwomushana *et al.*, 2018), Benin (Houngbo *et al.*, 2020), Kenya and Ethiopia (Kumela *et al.*, 2019)), we found that the most common fall armyworm management option was the use of synthetic pesticides. They are easily accessible for farmers (Houngbo *et al.*, 2020) and they are known by them to be effective against most pests (Tambo *et al.*, 2020). Farmers also showed a lack of knowledge on the beneficial role of natural enemies. In addition, African governments, including Burkina Faso (MAAH, 2018), Zambia (Kansiime *et al.*, 2019), Kenya and Ethiopia (Kumela *et al.*, 2019) distributed free insecticides to the affected areas. Despite their extensive use, reports pointed out the limited effectiveness of insecticides in controlling *S. frugiperda* (Kumela *et al.*, 2019). This would be due to: (i) application of ineffective active substances (Ahissou *et al.*, 2021a; Matova *et al.*, 2020), (ii) use of wrong types of pesticides (such as fungicides) (Tambo *et al.*, 2020), (iii) poor timing of application, as the larvae are relatively inactive during the day (Kumela *et al.*, 2019) and 3) pest resistance to insecticides used (Matova *et al.*, 2020). For example, three of the four insecticides most commonly used against the fall armyworm by farmers (lambda-cyhalothrin, abamectin and deltamethrin) were found to be ineffective against seven populations collected in different regions of Burkina Faso (Ahissou *et al.*, 2021a). Several product applications were usually required, as also shown in a study in Brazil: an average of five sprays were required to control fall armyworm infesting maize (Ribeiro *et al.*, 2014). However, indiscriminate spraying can have negative effects on environment and human health, particularly in cases where knowledge about the safe use of these toxic chemicals is limited (Damalas & Eleftherohorinos, 2011; Desneux *et al.*, 2007). Natural enemies complex is reduced and its impact on fall armyworm populations is significantly reduced (Meagher *et al.*, 2016). We recommend proper communication on locally available insecticides that effectively control fall armyworm (Ahissou *et al.*, 2021a).

Like most other African farmers, they did not apply insecticides to maize for pest control before the first detection of the fall armyworm (Caniço *et al.*, 2020a; Matova *et al.*, 2020). They have implemented alternative methods that deter or kill the pests, including the use of ash (Babendreier *et al.*, 2020; Kansiime *et al.*, 2019). Work conducted in Ghana reported that sand and ash reduced the number of larvae (Babendreier *et al.*, 2020). We hypothesize on an abrasiveness role on the insect cuticle.

Different plant extracts are mentioned by the interviewed farmers. Neem-based products are being used against the fall armyworm (Houngbo *et al.*, 2020; Kansiime *et al.*, 2019; Tambo *et al.*, 2020). Their action is typically slower than conventional insecticides, they have a shorter persistence in the environment (Babendreier *et al.*, 2020; Rioba & Stevenson, 2020), they are less easy to find on the market and are usually sold at relatively high price (Abrahams *et al.*, 2017b). In West Africa, based on the recommended rates, chemical insecticides cost about USD 7-18 (4,000-10,000 FCFA) per hectare, while neem-based products (HN, TopBio) can cost USD 25-35 (14,000-20,000 FCFA). In some cases, the rates of insecticide use per hectare may be higher than recommended, which increases the total price. It is very unlikely that resource-less farmers can afford anything other than cheap chemicals because of this price differential. However, increased use of biopesticides could be achieved through a national policy to subsidize and recommend their use as in Ghana, where two-thirds of biopesticide users received their product for free (Rwomushana *et al.*, 2018). Additional research is required to evaluate the effectiveness of different alternatives to chemical insecticides made by farmers against the fall armyworm and its natural enemies.

In the present survey, farmers' knowledge of the natural enemies was limited to predatory birds. Despite its recent introduction into Africa, the fall armyworm is attacked by predators and parasitoids. In Ghana, three species of predators namely *Peprius nodulipes* (Signoret), *Haematochares obscuripennis* Stål (both Hemiptera: Reduviidae) and *Pheidole megacephala* (F.) (Hymenoptera: Formicidae) were identified (Koffi *et al.*, 2020). However, fall armyworm predators were observed in Burkina Faso, including Forficulidae (*Diaperasticus erythrocephalus* Olivier and *Forficula senegalensis* Serville), Coccinellidae (*Cheilomenes sulphurea* Olivier) and Formicidae (*Pheidole megacephala* Fabricius) (Ahissou *et al.*, 2021b). Among the parasitoid species found in African countries, the diptera *Anatrichus erinaceus* Loew, *Drino quadrizonula* (Thomson) *Palexorista zonata* (Curran) and the hymenopterans *Charops ater* (Szépligeti), *Chelonus bifoveolatus* Szépligeti, *Chelonus curvimaculatus* (Cameron), *Coccygidium luteum* (Brullé), *Cotesia icipe* Fernandez-Triana & Fiobe, *Meteoridea* cf. *testacea* (Granger), *Metopius* cf. *discolor* Tosquinet, *Telenomus remus* Nixon and *Trichogramma* sp. have been observed parasitizing the fall armyworm in African countries (Agboyi *et al.*, 2020; Koffi *et al.*, 2020; Sisay *et al.*, 2018). A simple method of attracting certain parasitoids and predators consists in applying sugar water and fish soup to the maize leaves. Increasing plant and floral biodiversity with border plants *Melinis minutiflora* P. Beauv., *Tithonia diversifolia* (Hemsl.) and *Desmodium* spp. (Khan *et al.*, 2016; Prasanna *et al.*, 2018) and refuge plants *Bidens pilosa* L., *Foeniculum vulgare* Mill., *Galinsoga parviflora* Cav., *Gossypium barbadense* L., *Helianthus annus* L., *Malva parviflora* L. and *Sorghum halepense* L (Pers.) (Quispe *et al.,* 2017) is also one of the options to attract and preserve natural enemies. Considering their performance, it is important to train farmers on the recognition, preservation of natural enemies and the implementation of cultural practices that promote their action.

A low level of education correlated with a lack of training favors the misuse of pesticides, since there is a repetition of bad practices. For instance, the application of pesticides recommended only on non-food products (i.e. cotton) could have an impact on maize consumers. With regard to protective equipment, the situation was similar in Ghana, Rwanda, Uganda, Zambia, and Zimbabwe, where low use of protective clothing among smallholders was reported (Tambo *et al.*, 2020). The farmers' reported adverse health effects show the importance of protective equipment when handling and applying pesticides. The consumption of milk before and after the application of pesticides and the use of products considered to absorb pesticide residues on the skin were reported in Nigeria (Ugwu *et al.*, 2015). In addition, the use of unregistered pesticides found in this study could also increase the poisoning of producers and consumers. In Africa, where borders are porous, illegal trading of pesticides is a real public health problem (Diallo *et al.*, 2020). In this context, it is important to train farmers in proper pesticide application methods to avoid health risks. Farmers' awareness and continuous training remain a real alternative to this scourge.

6. Conclusion

This study reported farmers' knowledge of the fall armyworm, particularly the larval stage which is the most damaging and most present in maize fields. In contrast to past insect pest management practices in maize fields, farmers have been using primarily chemical insecticides against the fall armyworm since its invasion. Misuse of chemical pesticides could have negative impacts on farmers, consumers and the environment. Several other alternatives implemented by farmers to control the fall armyworm need to be scientifically evaluated for scaling up. Therefore, continuous training of farmers on the proper use of chemical pesticides and the recognition and preservation of natural enemies are crucial.

Conclusion du chapitre 3

Cette étude présente les connaissances des agriculteurs sur la chenille légionnaire d'automne, en particulier sur le stade larvaire qui cause des dégâts et qui est le plus présent dans les champs de maïs. Contrairement aux anciennes pratiques de gestion des insectes ravageurs dans les champs de maïs, les agriculteurs utilisent principalement des insecticides chimiques contre la chenille légionnaire d'automne, qui est devenue le ravageur le plus nuisible depuis son invasion. Par ailleurs, de nombreux échecs de traitement sont rapportés et conduisent à une augmentation des doses et fréquences d'application des insecticides. Malheureusement, l'utilisation abusive et fréquente d'insecticides chimiques n'est pas sans effets négatifs sur les agriculteurs, les consommateurs et l'environnement. Comme il n'existe pas encore d'insecticides homologués spécifiquement contre la chenille légionnaire d'automne, il faudrait travailler à l'établissement d'une liste de produits efficaces. Plusieurs autres alternatives mises en œuvre par les agriculteurs pour lutter contre la chenille légionnaire d'automne doivent faire l'objet d'une évaluation scientifique et d'une optimisation. Il est donc essentiel de poursuivre les efforts financiers pour soutenir la recherche, le développement de méthodes de lutte durables et la formation des agriculteurs.

4

Phénologie et plantes hôtes de la chenille légionnaire d'automne

Introduction au chapitre 4

Les premières réponses à l’invasion de la chenille légionnaire d’automne se sont appuyées principalement sur des connaissances et méthodes de lutte provenant du continent d’origine du ravageur. Cependant, elles n’ont pas permis d’éliminer ce ravageur qui continue de causer de nombreux dégâts aux cultures céréalières, dont le maïs principalement. La recherche et le développement de méthodes de lutte durables dans le contexte spécifique de cette région nouvellement envahie est donc nécessaire.

Les fluctuations des populations d’insectes ravageurs sont influencées par plusieurs facteurs environnementaux et climatiques dont la température, les précipitations et l’humidité relative. Ces facteurs influencent la fécondité, la survie et la vitesse de développement des insectes ravageurs. Il est donc essentiel de générer des informations sur la dynamique des populations de la chenille légionnaire d’automne pour mettre en place une stratégie de gestion intégrée efficace.

L’objectif de ce chapitre est de caractériser la phénologie du ravageur et d’identifier les plantes cultivées les plus favorables à sa survie. Pour cela, nous avons collecté les données à l’aide de pièges à phéromones et d’observations visuelles durant une année. Pour finir, nous présentons certains traits du cycle de vie du ravageur sur dix cultures afin d’identifier les hôtes les plus appropriés qui permettraient au ravageur de survivre en absence du maïs.

Annual dynamics of fall armyworm populations in West Africa and biology in different host plants

Cette section est une adaptation de l'article suivant :

Ahissou B. R., Sawadogo W. M., Sankara F., Brostaux Y., Bokonon-Ganta A. H., Somda I., & Verheggen F. J. (2022). Annual dynamics of fall armyworm populations in West Africa and biology in different host plants. *Scientific African 16*, e01227. https://doi.org/10.1016/j.sciaf.2022.e01227

1. Abstract

Since its recent introduction in West Africa, the fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) has severely damaged maize and other crops. Control efforts face many challenges as the knowledge on this invasive pest is still limited. In this study, we assessed the annual population dynamics by monitoring this species using pheromone traps and visual observations, so as to contribute to the development of an integrated management strategy. In addition, we also evaluated some life history traits of *S. frugiperda* on different local host plants to identify the most suitable hosts in Burkina Faso.

Adult captures were recorded throughout the year, as a result of a favorable mean annual temperature (29°C). Two population peaks occured: one peak (15.5±3.1 adults per trap and per month) was recorded in December and January (dry season) while the second peak (17.5±2.5) occured in July and August (rainy season). These peaks were synchronized with the major maize production periods of the region, usually 1 to 2 months after planting, when the plants had 6 to 12 leaves. In addition, the proportion of infested maize fields and infested plants per field was higher in the dry season (94.0% and 44.9%) than in the rainy season (80.0% and 26.2%). Based on the larva to adult survival rate (65-80%), mean fecundity (700-1000 eggs per female) and short life span of 36-38 days, pearl millet, maize and groundnut were found the most suitable hosts for the insect development.

To better manage this insect pest, we suggest monitoring efforts in all crops associated with maize, the use of short-cycle varieties and early planting. In addition, curative treatments are more effective when applied on young maize plants, as the early instars are the most susceptible.

2. Introduction

The fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) was detected in 2016 in Nigeria (Goergen *et al.*, 2016) and subsequently in several other countries including Burkina Faso (Tizie & N'Guessan, 2017). Although it hascani a preference for maize, the fall armyworm also causes significant losses on many commercial crops such as groundnut, soybean, rice, sorghum, sugarcane and cabbage (Goergen *et al.*, 2016; Rwomushana *et al.*, 2018). Estimated yield losses in maize crops ranged from 22-67% in Ghana and Zambia (Rwomushana *et al.*, 2018) and from 12-58% in Zimbabwe (Baudron *et al.*, 2019). As a result, the food and nutritional security of millions of producers is threatened.

The fall armyworm is a highly mobile and polyphagous pest (Goergen *et al.*, 2016; Montezano *et al.*, 2018). Many generations of this pest occur in a year because it does not undergo diapause. Moreover, its cycle is relatively short (25 - 30 days) at an average daily temperature of 25 ◦C (Early *et al.*, 2018; Prasanna *et al.*, 2018). Damages are caused by larvae that attack maize plants at their growing points and bore into the maize cob to feed on the kernels (Luginbill, 1928; Prasanna *et al.*, 2018). Over the year, the dynamics and abundance of insect populations are influenced by the availability of host plants and environmental conditions (relative humidity, temperature, rainfall) (Cammell & Knight, 1992; Early *et al.*, 2018). The cycle is interrupted in regions characterized by a severe winter between crops, reducing population abundance (Favetti *et al.*, 2017). Overwintering fall armyworm populations in South Florida are responsible for annual infestations that spread to central and eastern United States and southern Canada (Luginbill, 1928).

The management strategies applied in Africa (including synthetic pesticides and sometimes alternatives) are mainly based on the data available from the America (Babendreier *et al.*, 2020; Hruska, 2019). However, Africa is likely to experience the greatest increase in fall armyworm threats according to predictive models based on the pest distribution patterns, land use and topography (Liu *et al.*, 2020). Therefore, several works are carried out to identify effective chemical and biological insecticides (Sisay *et al.*, 2019a), but also alternatives such as cultural methods and biological control (Agboyi *et al.*, 2020; Babendreier *et al.*, 2020). In Burkina Faso, where average annual temperatures and crop diversity are favorable to the development of the fall armyworm, this pest was expected to persist throughout the year. In the maize production regions (Hauts-Bassins region), maize is produced twice a year, during the rainy and the dry seasons (Sawadogo *et al.*, 2020b; Wellens *et al.*, 2013).

Developing an effective integrated management strategy against the fall armyworm requires basic information such as its population dynamics. A study conducted in Ghana reported that environmental factors such as rainfall, temperature and relative humidity influence the abundance of the pest (Nboyine *et al.*, 2020). In West Africa, and in Burkina Faso in particular, knowledge on the fall armyworm seasonal dynamics is very limited. Among the consequences, chemical treatments are performed preventively at any period of the year (Sisay *et al.*, 2019a). In this study, we assessed the annual population dynamics by monitoring this species using pheromone traps and visual observations, so as to contribute to the development of an integrated management strategy. In addition, we also evaluated some life history traits of *S. frugiperda* on different local host plants to identify the most suitable hosts in Burkina Faso.

3. *Materials and methods*

3.1 Seasonal dynamics of fall armyworm

Moth trapping was performed in three maize production sites in the province of Houet from January to December 2020. The province of Houet is located in the Hauts-Bassins region, which belongs to the Sudanian zone, and experience an average annual rainfall of 900 to 1200 mm (Ibrahim *et al.*, 2014; Wellens *et al.*, 2013). The region is characterized by a dry season from November to May and a rainy season from June to October.

Fall armyworm abundance was recorded using white delta traps and commercial pheromone lures for fall armyworm provided by Pherobank BV (The Netherlands). Delta traps consist of a triangular shaped body made of opaque white plastic, and a removable insert covered with a thin coating of high-quality, non-drying glue placed inside on the floor of the triangle. Male moths and other insects entering through the vents on both sides are captured by the glue on which the lure is placed. Four traps were installed at each of the three sites located in Bama, Léguéma and Nasso (Figure 6).

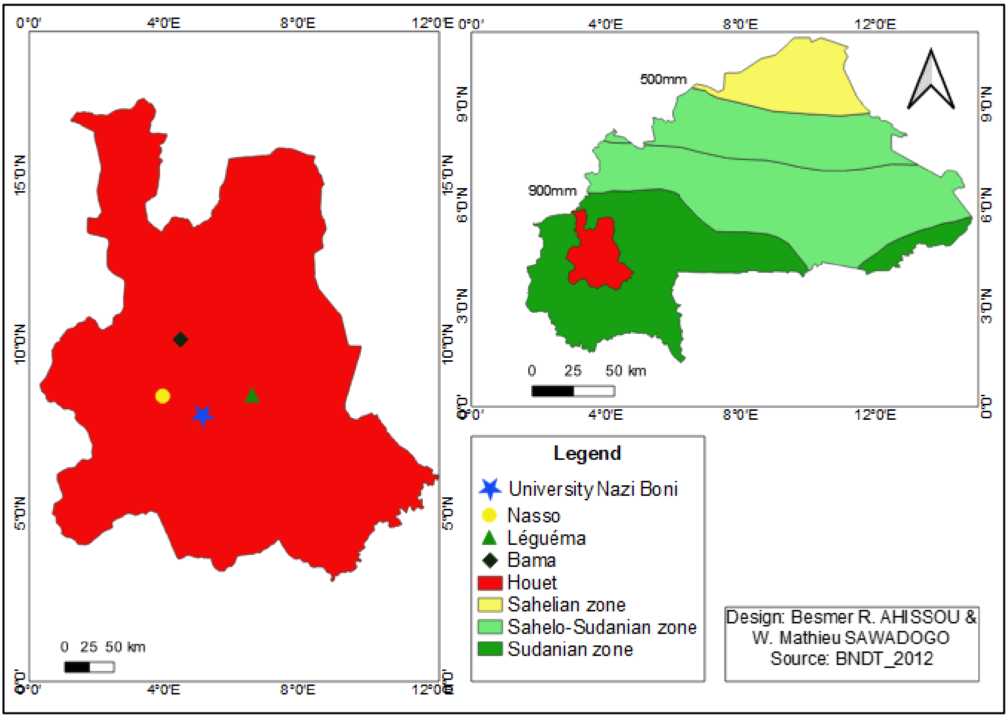

Figure 6. Insect capture sites, located in the province of Houet (red zone) where fall armyworm traps were deployed over the year (left figure). Climatic zones in Burkina Faso.

Each trap was suspended at a height of 1.5 m from the ground; and the traps were approximately 200 m apart at each site. In Bama, the traps were installed in an irrigated perimeter where maize, rice, sweet potato, cassava, cowpea, and groundnut are produced throughout the year. Production in Léguéma was dominated by vegetables (tomato, cabbage, common bean), cowpea and maize. In Nasso, maize, groundnut and rice were produced throughout the year. The sites were about 40 km apart. The traps were emptied every two weeks to count the males captured and the insert renewed. The pheromone dispenser was renewed every month.

To assess the infestation rate, randomly selected maize fields (n=107) were also surveyed for the presence of fall armyworm eggs and larvae during the dry (54 fields) and rainy (53 fields) seasons. Every two weeks, we visited four maize fields (different field on every visit). In each field, 25 plants were selected by using a "W" pattern, and sparing border plants (Prasanna *et al.*, 2018). A distance of 5 meters separated each observation point, where 5 maize plants were inspected. Data on mean monthly temperature and precipitation for the study period were obtained from the Infoclimat weather archive (Infoclimat, 2021).

3.2 Biology of fall armyworm on different hosts

An assay was conducted to evaluate the developmental capacity of the fall armyworm on ten common crops: maize; *Zea mays* L. (v. FBC 6), pearl millet; *Penissetum glaucum* L. R. Br. (v. Missari), sorghum; *Sorghum bicolor* L. (v. Kapelga), groundnut; *Arachis hypogea* L. (v. Fleur 11), cowpea; *Vigna unguiculata* L. Walp. (v. Komkallé), rice; *Orizea sativa* L. (v. Nerica 4), onion; *Allium cepa* L. (v. Noflaye), okra; *Abelmoschus esculentus* L. Moench (v. Indiana), cotton; *Gossypium hirsutum* L. (v. FK64) and tomato; *Solanum lycopersicum* L. (v. Mongal F1). These plants were grown in 15 liters pots filled with soil, and placed in a greenhouse belonging to the Training and Research Centre of the University Nazi Boni (UNB) in Bobo Dioulasso, Burkina Faso. Leaves of 1 - 2 months old plants were used for the test.

Fourth and fifth instars, as well as egg masses, were collected from the field and maintained under laboratory-controlled conditions (25±2 °C, 60±15 % relative humidity and 12:12 photoperiod) and fed on fresh maize leaves for seven generations (Ahissou *et al.*, 2021a). Eggs laid in a single layer on white paper were used to facilitate separation with a fine brush. Forty individual eggs were placed on four fresh leaves of each crop plant (for a total of 160 eggs per crops). The newly hatched larvae were fed individually in 300 ml plastic boxes with fresh leaves of one of the selected crops. Insect development and survival were checked twice a day (8 am and 4 pm). Pupae were collected daily and placed in a cage (60×40×40cm). The bottom of the cage was covered with white paper for female oviposition. Emerged adults were fed a sugar water solution (100 g/l) throughout their lives. The white paper was removed after oviposition, and cut to individualize each egg mass into separate boxes. Trials were performed under controlled laboratory conditions (26±2 °C, 70±15 % relative humidity, and photoperiod 12L:12D).

3.3 Data analysis

Data of larval, pupal and adult period duration were analyzed for normality by the Shapiro-Wilk test and and homoscedasticity by Levene test and were expressed as mean ± standard deviation. They were analyzed using the Kruskal-Wallis test and followed by the pairwise comparisons with the 'pairwise.wilcox.test' function.

Due to the complete separation of catch data from different sites and the variable presence probability on each site, they were analyzed using zero-inflated regression models to determine the influence of climate variables (annual temperature and precipitation) on fall armyworm catch with the 'glmmTMB' function in the 'glmmTMB' package for R.

The survival data (larvae to lupae and larvae to adults) and fecundity (number of eggs laid per female) were fitted in a generalised linear models (GLMs) analysis, binomial and Poisson family respectively. Multiple comparisons for survival and fecundity data were performed with Tukey's post-hoc test using the 'ghlt' function in the 'multcomp' package for R.

Finally, the 'prcomp' function was used to perform Principal Component Analysis (PCA) and Biplot is generated by using the 'fviz_pca_biplot' function in the 'factoextra' package for R. In the Biplot, the lines represent the measured variables and the points represent the evaluated crops. All analyses were performed in R statistical software (R Core Team, 2021) using the RStudio-2021.09.2 interface.

4. *Results*

4.1 Annual temperature and rainfall

During 2020, the annual temperature ranged from 19.9 to 38.5°C. The region is characterized by a dry season (November - May) and a rainy season for the rest of the year, for a mean annual rainfall of 898mm (Figure 7).

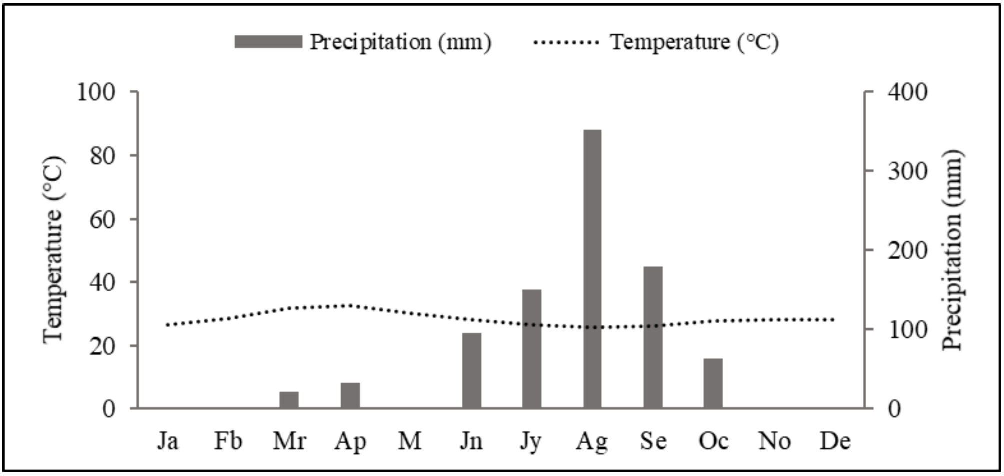

Figure 7. Monthly average temperature and precipitation data during the study period.

4.2 Infestation

Fall armyworm adults were captured throughout the year. In the three sites, the adult catches showed two peaks. The first peak was recorded in December and January (dry season) and the second in July and August (rainy season). In contrast, low densities were recorded between March and June. At the site where the highest number of adults was recorded (Bama), the monthly average number per trap was 15.5 ± 3.1 (1st peak) and 17.5 ± 2.5 (2nd peak) (Figure 8).

The zero-inflated regression models revealed that there is significant difference in moth presence between months at different sites (P-value < 0.001). In addition, when moths were present, captures were significantly negatively correlated with temperature (P-value < 0.001) and rainfall (P-value = 0.008).

The proportion of *S. frugiperda* infested maize field reached 80% in the rainy season and 94% in the dry season. However, the percentage of infested plants per field in the rainy season (26.2%) was lower than in the dry season (44.9%).

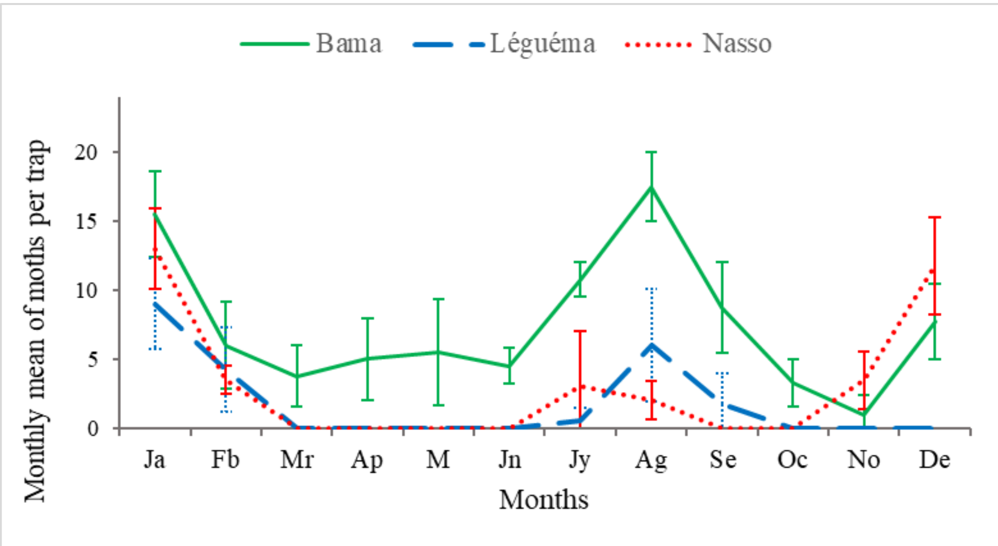

Figure 8. Monthly mean number of fall armyworm catches per trap during one year of sampling in three maize production areas. Data are means ± standard deviation.

4.3 Fall armyworm host plants and development

All ten plant species tested in the laboratory allowed the fall armyworm to develop and complete its life cycle. However, the diet greatly influenced various developmental parameters (Table 5), including the durations of the larval (K = 216.9; df = 9; P < 0.001), pupal (K = 59.3; df = 9; P < 0.001) and adult (K = 78.5; df = 9; P < 0.001) stages. Maize (15.1±0.7 days) and pearl millet (14.7±0.9 days) were the most favorable for larva development while tomato was the poorest host, leading to the longest larva development (30.1±3.1 days). Larval development included 6 stages with pearl millet, cowpea, groundnut, cotton, maize and onion while 7 stages were recorded on the other crops. The duration of pupal development was similar on all crops (between 8 and 9 days), except for cotton where it was longer (11 days). The duration of development to adult stage was longest on okra (14.0±4.4 days) than on maize (10.1±1.3 days), cowpea (9.0±1.4 days) and onion (9.2±1.3 days). The longevity of the fall armyworm was shorter when the larvae were fed on maize and pearl millet (36.8±0.6 and 36.7±1.0 days respectively) rather than tomato (51.8±2.2 days).

Larval diet greatly affected survival of larvae and fecundity of adults of the fall armyworm (Table 6). In the larval stage, the survival rates on okra and groundnut (82.5±14.6% and 80.0±6.1%, respectively) were higher than on cotton (5.0±6.1%). Pupal emergence rates were statistically similar for all crops (77.5 - 100%). No egg laying was recorded with adults from cotton because larvae survival was low and emerged adults were males only. In contrast, egg laying was recorded for female adults from the nine others crops. A significant difference between the mean numbers of eggs laid per female was recorded (df=8; P<0.001).

Table 5. Mean duration ± standard deviation (days) of larvae, pupae, and adults of the fall armyworm fed on different crops under controlled conditions. For a given column, different letters on the means indicate significant differences among crops according to the Kruskal-Wallis test followed by Pairwise Wilcox Test.

Crops	**Developmental time**		**Adult lifespan**
	Larvae	**Pupae**	
Maize	15.1±0.7 d	8.8±1.0 b	10.1±1.3 abcd
Pearl millet	14.7±0.9 d	8.9±0.8 b	10.3±1.2 abcd
Cowpea	20.2±1.2 a	8.8±0.7 b	9.0±1.4 d
Sorghum	18.8±1.4 b	9.7±1.1 b	9.6±1.6 abd
Okra	24.3±4.1 e	9.5±1.4 b	14.0±4.4 e
Groundnut	16.8±1.3 c	8.8±0.8 b	9.5±1.4 ad
Rice	20.2±2.8 ab	9.5±1.1 b	11.8±2.1 bce
Tomato	30.1±3.1 f	8.8±0.5 b	11.2±0.9 c
Onion	19.0±1.9 b	9.5±0.8 b	9.2±1.3 d
Cotton	20.1±1.5 ab	10.9±0.9 a	10.7±0.9 abc
P-value	< 0.001	< 0.001	< 0.001

A principal component analysis was performed to compare 9 crops (except cotton where there was no oviposition) using the following criteria: larval and adult development time, larval-adult survival rate and number of eggs laid (Figure 9). With the exception of onion for which fecundity is very high despite the average survival rate, only larvae fed on maize, pearl millet and groundnut showed high survival and fecundity with a short larval and adult life span.

Table 6. Survival rate and fecundity of the fall armyworm fed on different crops under controlled conditions. For a given column, different letters on the data indicate significant differences among crops (GLM, Binomial family for survival rate and Poisson family for fecundity; Tukey test, $p < 0.05$). n.a. refers to non-applicable. Data are means ± standard deviations.

Crops	Survival rate (%) Larvae to Pupae	Larvae to Adults	Fecundity (eggs/female)
Maize	72.5±10.2 de	72.5±10.2 cd	1009.8±73 f
Pearl millet	67.5±17.2 ce	65.0±19.7 bd	727.6±160 e
Cowpea	67.5±14.7 ce	62.5±12.2 bc	527.5±123 b
Sorghum	62.5±15.0 cd	57.5±12.6 bc	646.4±136 d
Okra	82.5±14.6 e	72.5±3.5 cd	454.8±48 a
Groundnut	80.0±6.1 e	80.0±6.1 d	1000.4±161 f
Rice	55.0±10.2 c	55.0±10.2 b	596.8±66 c
Tomato	20.0±8.9 b	15.0±5.4 a	722.3±46 e
Onion	72.5±9.1 de	50.0±15.1 b	1428.0±232 g
Cotton	5.0±6.1 a	5.0±6.1 a	n.a.
P-value	< 0.001	< 0.001	< 0.001

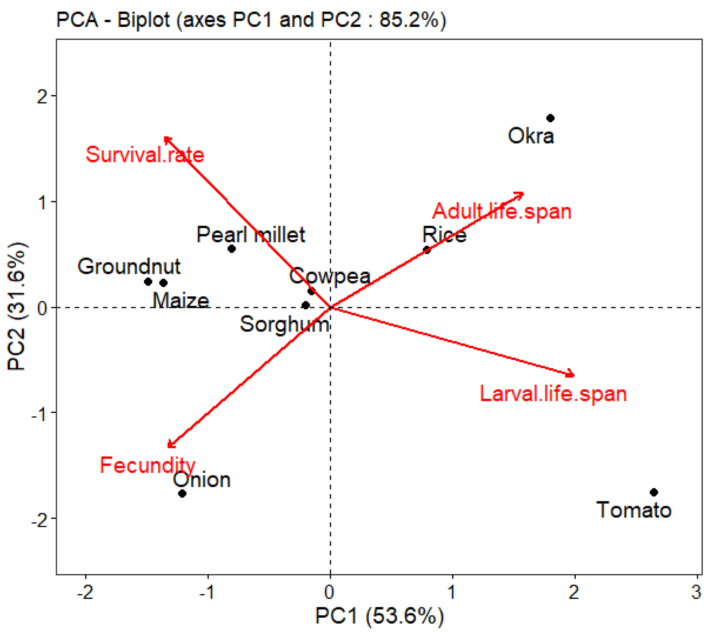

Figure 9. Principal component analysis among the developmental variables of fall armyworm in different host species.

5. *Discussion*

Maize production occurs mainly during the rainy season, but can also be settled during the dry season in irrigated perimeters, market gardens or lowlands in Western Burkina Faso. After the rains, maize planting is usually performed in June and July. Based on the moth catches at this period, maize seedlings should be carefuly monitored as they are very susceptible to damage from fall armyworm larvae. The increase in fall armyworm populations was synchronized with the major maize production periods at all sites in both the dry and rainy seasons. Adult catches reach their higher peak in August. This period generally corresponds to the 6 - 12 leaf stage of maize (V6 – V12) after which catches become less important. The same trends were observed in the dry season after maize planting. Similar results were obtained in a study conducted in Ghana during two successive rainy seasons (Nboyine *et al.*, 2020). For effective management of fall armyworm, it is important to concentrate insecticide applications when maize plants have not reached the flowering stage. Generally, pre-flowering maize leaves are more tender and susceptible to larval damage (particular for neonates) compared to older leaves. A high density of larvae per maize plant indicates that the larvae have not reached the advanced stages, as cannibalism within this species usually reduces the number to one larva per plant (Ren *et al.*, 2020). We also confirm that larva density decreases as the maize leaves begin to dry and the acorns develop (Pannuti *et al.*, 2016).

This study reports that the presence of maize at any time of the year plays an important role in the abundance of the fall armyworm. The mean annual temperature (29°C) is favorable for fall armyworm development (Prasanna *et al.*, 2018). We showed that during the dry season, maize fields were more affected by the insect than during the rainy season (as regard to the proportion of infested plants), probably as a result of (i) the low availability of alternative hosts in the dry season, and (ii) the abundance of host plants and natural enemies in the rainy season (Cammell & Knight, 1992). A similar trend was observed in Mozambique, where the percentage of infested fields and infested plants per field was higher during the dry season (Caniço *et al.*, 2020b). Therefore, crop diversity is very important to reduce fall armyworm populations and to attract and maintain natural enemies that play an important role in the regulation of the pest. In the mid dry season (March-May) in the absence of maize, male adults of the fall armyworm were caught in low numbers. The insect would be able to feed on alternative plants, such as pearl millet (Favetti *et al.*, 2017). Therefore, better detections can be achieved by monitoring the surrounding crops and non-crop plants.

In this study, we identified ten host plants of fall armyworm that allow it to develop and complete its life cycle. Although the fall armyworm is a highly polyphagous pest, its development is greatly impacted by the consumed plant (da Silva *et al.*, 2017). With larva-to-adult survival rates ranging between 65 and 80%, mean fecundity of 700 - 1000 eggs per female, and a longevity of 36.7±1.0, 36.8±0.6 and 37.8±0.1 days; pearl millet, maize, and groundnut were respectively the most favorable hosts for fall armyworm development. As a result, three to four generations could occur on long-cycle maize, pearl millet and groundnut. In terms of control decisions, early planting and short-cycle varieties could allow farmers to avoid heavy infestations at the end of the cycle. Fall armyworm larvae typically complete six larval instars (Prasanna *et al.*, 2018), but they may complete seven and very rarely eight depending on temperature and availability of the host plant (Luginbill, 1928). In addition, several studies have shown that the older stages were the longest (Hutasoit *et al.*, 2020; Wu *et al.*, 2021), most voracious (Luginbill, 1928; Ren *et al.*, 2020) and least susceptible to insecticides (Ghidiu & Andaloro, 1993). Therefore, the early larval stages of fall armyworm should be the focus of the integrated management program. Using effective products, the best time to apply pesticide treatments is the first days after the emergence of neonates. Effective integrated management of this pest in Burkina Faso and areas with similar climatic conditions requires close monitoring of the pest in crops associated with maize or planted after maize harvests. Early detection (e.g., with pheromone traps), use of short-cycle varieties, and early planting will reduce fall armyworm damage.

Conclusion du chapitre 4

Il ressort de cette étude que les conditions climatiques au Burkina Faso sont favorables à la chenille légionnaire d'automne, qui persiste toute l'année avec une abondance particulière de papillons pendant les principales périodes de production du maïs. Quelle que soit la période de production (saison sèche ou saison des pluies), les populations de ravageurs évoluent pour atteindre leurs pics lorsque les plantes sont aux stades 6-12 feuilles, avant la floraison. Après ce stade, les populations de *S. frugiperda* diminuent systématiquement. Par conséquent, une gestion efficace devrait concentrer les pulvérisations d'insecticides aux périodes les plus sensibles (stades de croissance végétative). Par ailleurs, la durée de développement de l'insecte étant plus courte sur les meilleures plantes hôtes, 4 à 5 générations pourraient se succéder pendant la production et augmenter les pertes de rendement sur les cultures à cycle long. Il conviendrait donc d'utiliser des variétés à cycle court et de faire des semis précoces pour éviter les fortes populations du ravageur en fin de cycle.

5

Susceptibilité aux insecticides chimiques et biologiques

Introduction au chapitre 5

Avant l'arrivée de la chenille légionnaire d'automne en Afrique, il n'existait pas de molécules officiellement enregistrées contre ce ravageur dans les pays membres du Comité Sahélien des Pesticides (Bénin, Burkina Faso Cap-Vert, Côte d'Ivoire, Gambie, Guinée, Guinée-Bissau, Mali, Mauritanie, Niger, Sénégal, Tchad et Togo) et même au-delà. Les réponses immédiates suite à l'invasion de la chenille légionnaire d'automne ont consisté en l'approvisionnement et l'application d'une diversité d'insecticides chimiques par les différents gouvernements africains sans une évaluation préalable de leur efficacité. Malheureusement, de nombreux échecs de traitement ont été rapidement notés sur le terrain.

En effet, la chenille légionnaire d'automne est connue pour avoir développé une résistance à de nombreux insecticides utilisés sur son continent d'origine, et qui sont actuellement utilisés en Afrique ; c'est notamment le cas des carbamates et des pyréthrinoïdes. Les effets néfastes de l'utilisation abusive et fréquente des insecticides chimiques sur les ennemis naturels et la santé humaine ne sont plus à démontrer. Il est donc important de rechercher des insecticides qui contrôlent efficacement la chenille légionnaire d'automne afin de réduire les quantités d'insecticides utilisées et les risques liés à leur application fréquente. Par ailleurs, les bioinsecticides occupent une place importante dans les programmes de recherche de méthodes de lutte alternatives aux insecticides chimiques. Les bioinsecticides présentent l'avantage d'être généralement moins toxiques pour l'homme et les ennemis naturels.

A l'heure actuelle, il existe très peu d'informations sur le niveau de sensibilité et de résistance de la chenille légionnaire d'automne aux différents insecticides chimiques dans les zones nouvellement envahies, bien que la lutte chimique demeure la principale méthode. L'objectif de ce chapitre est d'établir une liste positive d'insecticides disponibles localement pouvant contrôler efficacement la chenille légionnaire d'automne. Suivant le protocole IRAC N° 020, nous avons réalisé un test de susceptibilité du ravageur, en utilisant des insectes collectés dans plusieurs zones de production de maïs au Burkina Faso, et en utilisant la plupart des substances actives disponibles. Les articles qui composent ce chapitre portent sur les insecticides chimiques et bioinsecticides respectivement.

Baseline toxicity data of different insecticides against the fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) and control failure likelihood estimation in Burkina Faso

Cette section est une adaptation de l'article suivant :

Ahissou, B. R., Sawadogo, W. M., Bokonon-Ganta, A. H., Somda, I., Kestemont, M.-P., & Verheggen, F. J. (2021). Baseline toxicity data of different insecticides against the fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) and control failure likelihood estimation in Burkina Faso. *African Entomology, 29*(2), 435–444. https://doi.org/10.4001/003.029.0435

1. *Abstract*

The fall armyworm (*Spodoptera frugiperda*) is a worldwide maize pest originating from the American continent. It invaded Africa during 2016, causing important economic damages, forcing African countries to take urgent actions to tackle this new invasive pest. In Burkina Faso, several chemical insecticides were promoted, but farmers have quickly and repeatedly reported control failures. In this work, we collected seven fall armyworm populations in as many maize-producing areas of Burkina Faso.

Following the approved IRAC leaf bioassay protocol, we evaluated the susceptibility of third instar larvae to seven commercially available insecticide formulations, including various modes of action: methomyl and chlorpyriphos-ethyl (acetylcholinesterase inhibitors), deltamethrin and lambda-cyhalothrin (sodium channel modulators), emamectin benzoate and abamectin (chloride channel activators) and *Bacillus thuringiensis* (a microbial disruptor of insect midgut membranes). Lethal concentrations (LC_{50}), resistance ratios (RR_{50}) and relative toxicity were calculated for each population and active ingredient.

LC_{50} values for all *S. frugiperda* populations were, in order of importance: emamectin benzoate (0.33–0.38 μg/l), methomyl (18–73 mg/l), abamectin (58–430 mg/l), chlorpyrifos-ethyl (199–377 mg/l), deltamethrin (70–541 mg/l) and lambda-cyhalothrin (268–895 mg/l). LC_{50} of the *B. thuringiensis* formulation ranged from 430 to 614 MIU/l. Lambda-cyhalothrin was the least efficient of the tested chemical pesticides, and emamectin benzoate the most efficient (relative toxicity ×2 712 969). Methomyl (×49), abamectin (×15), deltamethrin (×13), chlorpyriphos-ethyl (×4) were also more toxic than lambda-cyhalothrin.

Based on these results, we conclude that emamectin benzoate, methomyl and chlorpyriphos-ethyl insecticides are the most efficient for the control of the fall armyworm in Burkina Faso. We discuss the importance to implement a national-level

resistance survey for this major pest, which would allow rapid and efficient adaptation of the control strategy.

2. Introduction

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a major insect pest of various crops, but mainly maize. Native to America, *S. frugiperda* was first reported on the African continent in January 2016 (Goergen *et al.*, 2016). From West Africa, it rapidly spread across the continent (Prasanna *et al.*, 2018) and currently continues spreading to Asia (Maino *et al.*, 2021; Sharanabasappa *et al.*, 2018). Besides its main host plant, it is reported to develop on rice, sorghum, sugarcane, cabbage, beet, groundnut, soybean, onion, cotton, millet, tomato, and potato (Goergen *et al.*, 2016), threatening nutritional security of millions of agricultural households in Africa (Prasanna *et al.*, 2018). For instance, the estimated national mean loss of maize in Ghana was 22–67 %, in Zambia 25–50 % (Day *et al.*, 2017), in Ethiopia and Kenya 32–47 % (Kumela *et al.*, 2019).

Due to the widespread and sometimes indiscriminate use of insecticides in the Americas, *S. frugiperda* populations rapidly developed resistance to organochlorines, organophosphates, carbamates and pyrethroids (Diez-Rodriguez & Omoto, 2001; Young & McMillian, 1979; Yu, 1991; 1992; Yu *et al.*, 2003). Resistance to *Bacillus thuringiensis* maize have also been reported in Brazil, Puerto Rico and the U.S.A. (Flagel *et al.*, 2018). As a result, farmers have increased frequencies and doses of insecticide applications, leading to field control failures in Brazil, Puerto Rico and Mexico (Carvalho *et al.*, 2013; Gutiérrez-Moreno *et al.*, 2019; León-García *et al.*, 2012).

In Africa, barely any alternatives to insecticides are being used. Most African countries had no insecticide formulations specifically recommended or registered for the protection of maize against this new pest (Sisay *et al.*, 2019a). Farmers were advised to apply formulations despite their questionable and unproven efficacy (Harrison *et al.*, 2019; Sisay *et al.*, 2019a), including emamectin benzoate, imidacloprid, lindane, chlorpyriphos-ethyl, acetamiprid, cypermethrin, lambda-cyhalothrin (Fotso Kuate *et al.*, 2019). In Burkina Faso, for instance, more than 12 000 l of synthetic insecticides were sprayed on 14 000 ha of *S. frugiperda* infested fields, during the 2018–2019 crop season (MAAH, 2018). However, many farmers complained about the ineffectiveness of some of these products for controlling *S. frugiperda* (Sisay *et al.*, 2019a).

In this context, we decided to conduct an acute toxicity assay on *S. frugiperda*, using insects collected in all maize-production areas of Burkina Faso, and using most of the available active substances. With this information, we hope to provide the authorities with valuable information to communicate to farmers, and the scientific community about the resistance status of this pest in a newly invaded area.

3. *Material and methods*

3.1 Insects

Spodoptera frugiperda larvae were collected from maize fieds located in two provinces of the country: Houet (collected in October 2019) and Kadiogo (collected in December 2019) (Figure 10). Between 100 and 200 larvae were collected from each location (Figure 11a): Samendeni, Tolotama, Toussiana, Sambla Toukoro (Houet), Nongana, Nakamtenga and Pabré (Kadiogo). They are referred hereafter to as Sam, Tol, Tou, STo, Non, Nak and Pab populations, respectively. Maize, tomato, cabbage and other vegetable crops are grown year-around in the province of Kadiogo. Maize, sorghum and other cereals are typically grown in the province of Houet.

Larvae were placed in plastic boxes with fresh maize leaves and shipped to the laboratory at the Training and Research Centre of the University Nazi Boni (UNB) in Bobo Dioulasso, Burkina Faso (Figure 10). They were confirmed to be fall armyworm after morphological examination of the larvae and subsequent observation of the forewings of adult moths after emergence.

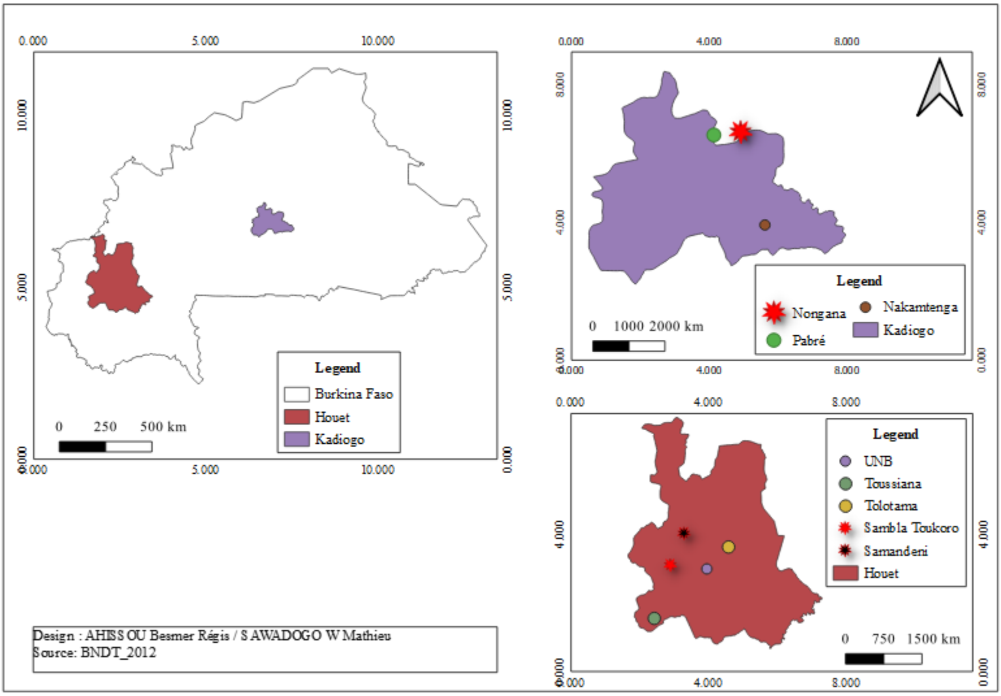

Figure 10. Sampling locations of *Spodoptera frugiperda* populations. Left: insects were collected from the two provinces of Houet and Kadiogo. Top right: collection sites in Kadiogo. Bottom right: collection sites in Houet.

Larvae were reared on maize leaves in the laboratory at 25 ± 2 °C, 60 ± 15 % relative humidity, and under a 12L:12D photoperiod. Insect development was checked every other day and fresh leaves were provided after 24 h until pupation. Pupae were collected daily and placed in a cage (60 × 40 × 40 cm) (Figure 11b, c). The bottom of the cage was covered with white paper for female egg-laying. They were fed with a sugar water solution (100 g/l) throughout their life. The white paper was removed after oviposition (Figure 11d) and cut to individualise each egg mass in separate boxes. Eggs were maintained under the same environmental conditions. Populations were reared in the laboratory and the progeny from the F1 generation was used for all bioassays.

Figure 11. Fall armyworm collection and rearing. (a) Research of larvae on maize plants, (b) chrysalids collected from the rearing in the laboratory, (c) rearing cage, (d) eggs laid on white paper.

3.2 Insecticides

According to the global list of pesticides authorised by the Sahelian Pesticides Committee (CSP) of November 2019, there is no insecticide registered for control of *S. frugiperda* in maize (CSP, 2019a). All insecticides used in this study are registered and officially intended for controlling lepidopteran larvae and other insect pests in vegetable crops. We selected the most widely used active substances: methomyl (250 g a.i./kg, Savahaler, Savana, France), chlorpyriphos-ethyl (480 g a.i./l, Pyrical 480EC, Arysta Lifescience, France), deltamethrin (25 g a.i./l, Tamega, Savana, France), lambda-cyhalothrin (25 g a.i./l, Sunhalothrin 2,5% EC, Wynca Sunshine, Mali), emamectin benzoate (19 g a.i./l, Emacot 019EC, Savana, France), abamectin (18 g a.i./l, Acarius, Savana, France) and *Bacillus thuringiensis* var. *kurstaki* (16 000 IU/mg, Bio K 16, Savana, France). The seven active ingredients tested, their IRAC group and modes of action are listed in Table 7.

Table 7. Insecticides used against fall armyworm populations. *Label rate expressed in IU/L; IRAC: Insecticide Resistance Action Committee (http://www.irac-online.org/).

Active ingredient	IRAC group	Mode of action	Label concentration (mg a.i./l)
Methomyl	1A	Acetylcholinesterase (AChE) inhibitors	937.50
Chlorpyriphos-ethyl	1B	Acetylcholinesterase (AChE) inhibitors	1 600.00
Deltamethrin	3A	Sodium channel modulators	37.50
Lambda-cyhalothrin	3A	Sodium channel modulators	83.33
Emamectin benzoate	6	Chloride channel activators	31.66
Abamectin	6	Chloride channel activators	63.00
Bacillus thuringiensis	11A	Microbial disruptors of insect midgut membranes	8×10^7 *

3.3 Insecticide assay

Insecticide assays were conducted with F1 third instars by following the IRAC standard leaf bioassay protocol (http://www.irac-online.org/methods/). Maize leaves were washed with tap water and dried before being immersed for 10 sec in the insecticide solution. They were then allowed to dry for 1 h. Each insecticide solution was freshly prepared with distilled water and Triton X-100 (0.2 g/l). A distilled water solution containing Triton X-100 (0.2 g/l) was used as control. The leaves were placed in individual Petri dishes (9 cm in diameter) containing blotting paper. A minimum of five different concentrations of the tested insecticide solution were included in the assay. A total of 40 larvae were observed per tested concentration. They were placed individually in a Petri dish, and maintained at 25 ± 2 °C, 60 ± 15 % relative humidity, and 12L:12D photoperiod. Morbidity was assessed after 48 h of exposure to insecticides (72 h in the case of *B. thuringiensis*, because mortality was only observed on the third day after inoculation). Individuals were considered dead if they failed to move when touched with a small brush, or when they showed severe intoxication symptoms such as severe growth inhibition, halted moulting, and feeding cessation.

3.4 Statistical analysis

The Abbott (1925) formula was used to correct the mortality. Concentration-mortality were subjected to probit analysis (Finney, 1971) using SPSS software, to calculate values of slope, lethal concentration (LC_{50}), and fiducial limits (95 %) for each population. Populations responses were considered equal when the confidence limits overlapped (Robertson & Preisler, 1992). Resistance ratios (RR_{50}) were determined by dividing the LC_{50} value of a given population by the LC_{50} of the most susceptible population.

Control failure likelihood (CFL) was calculated by multiplying the achieved mortality percentage (to the label concentration) by 100, dividing the product by the minimum required efficacy (%) and subtracting the result from 100 (Guedes, 2017). If the achieved mortality was higher than the required efficacy of the commercial formulation, CFL values <0 % suggest a negligible risk of control failure. The required efficacy was set at 80 %, because it is the minimum efficacy threshold required to allow registration of a synthetic insecticide (Silva *et al.*, 2011). The same reasoning was used for the biopesticide tested in this study, but with consideration of a minimum efficacy thresholds of 70 % (Guedes, 2017).

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

4. Results

4.1 Susceptibility of fall armyworms to insecticides

LC_{50} values are presented in Table 8, along with resistance ratios, for all active substances and *S. frugiperda* populations.

For the acetylcholinesterase inhibitors, the LC_{50} values ranged from 18 to 73 mg/l for methomyl, and from 199 to 377 mg/l for chlorpyrifos-ethyl. Two populations (STo and Non) were slightly less susceptible to methomyl, since they had higher LC_{50} values, leading to resistance ratios (RR50) of 1.79 and 4-fold. For chlorpyrifos-ethyl, 6 out of 7 populations of *S. frugiperda* had similar susceptibility, with RR50 between 1.34 to 1.89-fold. The fall armyworm collection from Non was less susceptible to chlorpyrifos-ethyl.

For sodium channel modulators, the LC_{50} values ranged from 70 to 541 mg/l for deltamethrin, and from 268 and 895 mg/l for lambda-cyhalothrin. Three populations (STo, Tol, Tou) were less susceptible than the others to deltamethrin, with RR50 between 5- to 7-fold. Similar susceptibility to lambda-cyhalothrin was observed among the tested populations.

For chloride channel activators, very low LC_{50} values were obtained for emamectin benzoate, ranging from 0.33 to 0.38 μg/l. We found no difference among the tested populations (the fiducial limits 95 % overlap). Abamectin LC_{50} values ranged from 58 to 430 mg/l, with the Houet populations less susceptible than the Kadiogo population ($F = 34.26$, ddl = 6, $P < 0.001$).

Table 8. Acute toxicity of some insecticide formulations against different populations of the fall armyworm from Burkina Faso. a = number of larvae tested; b = standard error; cLC_{50} expressed in µg a.i./L for emamectin benzoate and IU/L for *B. thuringiensis*; dRR_{50} = resistance ratio 50, LC_{50} value of a given population by the LC_{50} of the more susceptible population.

Insecticides	Location	n[a]	Fit of probit line				LC_{50} (95% FL) mg/1[c]	RR_{50} [d]
			Slope ± SE[b]	X^2	ddl	*P*		
Methomyl	Sam	200	3.27 ± 0.41	3.66	3	0.30	25.91 (21.80–30.45)	1
	Tol	200	3.55 ± 0.45	3.46	3	0.33	25.23 (21.49–29.45)	1
	Tou	200	3.05 ± 0.38	0.71	3	0.87	26.16 (21.81–30.96)	1
	STo	200	3.04 ± 0.36	3.26	3	0.35	32.69 (27.51–38.69)	1.79
	Non	240	1.45 ± 0.18	2.78	4	0.60	73.34 (54.56–97.45)	4.01
	Nak	200	2.23 ± 0.35	5.32	3	0.15	31.87 (21.73–41.09)	1
	Pab	200	2.22 ± 0.30	2.83	3	0.42	18.27 (13.35–23.19)	1
Chlorpyriphos–ethyl	Sam	280	8.86 ± 1.21	4.34	5	0.50	267.64 (252.92–283.42)	1.34
	Tol	200	5.64 ± 0.81	3.74	3	0.29	280.39 (255.63–316.57)	1.41
	Tou	200	6.85 ± 0.93	1.13	3	0.77	333.04 (306.40–365.98)	1.67
	STo	200	5.78 ± 0.70	0.73	3	0.87	294.62 (263.97–333.61)	1.48
	Non	200	5.46 ± 0.59	4.69	3	0.20	199.23 (179.44–220.40)	1
	Nak	200	4.41 ± 0.57	0.76	3	0.86	324.04 (286.02–371.84)	1.63
	Pab	240	3.47 ± 0.41	7.63	4	0.11	377.32 (329.57–435.42)	1.89
Deltamethrin	Sam	200	3.59 ± 0.45	3.99	3	0.26	69.95 (60.86–80.12)	1
	Tol	200	4.22 ± 0.58	7.28	3	0.06	385.88 (336.76–443.24)	5.52
	Tou	200	4.22 ± 0.58	7.28	3	0.06	358.88 (336.76–443.24)	5.13
	STo	240	11.00 ± 1.15	7.38	4	0.12	540.65 (516.43–567.42)	7.73
	Non	240	2.57 ± 0.29	4.89	4	0.30	118.02 (99.67–139.86)	1
	Nak	240	3.65 ± 0.41	3.39	4	0.50	90.86 (79.25–103.80)	1
	Pab	200	3.26 ± 0.47	5.26	3	0.15	184.39 (160.09–218.49)	2.64

Insecticides	Location	n[a]	Fit of probit line				LC$_{50}$ (95% FL) mg/1[c]	RR$_{50}$ [d]
			Slope ± SE[b]	X^2	ddl	P		
Lambda–cyhalothrin	Sam	240	2.14 ± 0.34	9.05	4	0.06	268.35 (223.32–329.25)	1
	Tol	200	8.55 ± 1.08	2.79	3	0.43	674.10 (637.42–713.87)	2.51
	Tou	200	6.61 ± 1.04	6.98	3	0.07	387.69 (355.63–414.55)	1.44
	STo	240	2.58 ± 0.38	8.70	4	0.07	513.72 (439.01–611.66)	1.91
	Non	240	5.23 ± 0.60	7.78	4	0.10	895.28 (814.41–977.15)	3.34
	Nak	240	4.55 ± 0.47	3.85	4	0.43	536.40 (479.66–596.44)	2.00
	Pab	200	3.31 ± 0.51	5.01	3	0.17	486.86 (419.32–555.71)	1.81
Emamectin benzoate	Sam	360	2.83 ± 0.32	1.53	7	0.98	0.36 (0.29–0.43)	1
	Tol	240	2.93 ± 0.33	1.29	4	0.86	0.37 (0.31–0.44)	1
	Tou	240	3.00 ± 0.35	0.75	4	0.95	0.33 (0.28–0.39)	1
	STo	200	2.89 ± 0.34	1.14	3	0.77	0.35 (0.29–0.42)	1
	Non	240	3.67 ± 0.43	8.34	4	0.08	0.33 (0.28–0.38)	1
	Nak	240	3.65 ± 0.43	8.92	4	0.06	0.33 (0.29–0.38)	1
	Pab	240	4.26 ± 0.53	8.01	4	0.09	0.38 (0.33–0.43)	1
Abamectin	Sam	200	3.12 ± 0.52	6.02	3	0.11	58.49 (49.39–67.13)	1
	Tol	200	3.75 ± 0.45	7.13	3	0.07	69.91 (61.66–79.73)	1
	Tou	200	4.81 ± 0.56	4.79	3	0.19	67.41 (60.59–74.95)	1
	STo	200	2.93 ± 0.51	7.11	3	0.07	62.34 (52.64–72.16)	1
	Non	320	4.79 ± 0.51	10.56	6	0.10	429.88 (391.02–475.24)	7.35
	Nak	240	4.19 ± 0.49	1.67	4	0.80	245.83 (220.71–277.07)	4.20
	Pab	280	4.38 ± 0.45	3.68	5	0.60	302.43 (272.70–338.09)	5.17
Bacillus thuringiensis	Sam	240	3.97 ± 0.47	3.61	4	0.46	430283534 (379409870–488993314)	1
	Tol	240	3.34 ± 0.40	1.39	4	0.85	424782228 (369261848–492489955)	1
	STo	240	4.55 ± 0.51	5.05	4	0.28	399646077 (355362294–448381180)	1
	Non	240	4.01 ± 0.48	2.23	4	0.69	443448757 (391262200–503492947)	1
	Nak	280	3.75 ± 0.47	1.94	5	0.86	614514737 (544525234–698128872)	1.54

Among the seven insecticides tested, *B. thuringiensis* var. *kurstaki* (BIO K 16) was the only biopesticide (a microbial disruptors of insect midgut membranes). Larval mortality was recorded on the third day after inoculation. The LC_{50} ranged from values were closed for all tested populations, ranging from 399 and 614 MIU/l. The overlapping fiducial limits at 95 % indicate that the susceptibility levels of the Sam, Tol, STo and Non populations were not statistically different, while Nak population showed level of resistance to *B. thuringiensis* (1.54-fold) in comparison to the other populations.

4.2 Control failure likelihood estimation

Control failure likelihood (CFL) was assessed by considering a minimum efficacy threshold of 80 % for synthetic insecticides and 70 % for the biopesticide (Table 9). Three active ingredients have negligible risks of control failure (*i.e*. their CFL values are below 0 %): methomyl, chlorpyriphos-ethyl and emamectin benzoate. This risk is higher for the other compounds, with CFL values ranging from 77 to 100 % for pyrethroids and reaching 100 % for *B. thuringiensis*, for all populations. This probability for abamectin was moderate for Sam, Tol and Tou populations (33.75 to 46.25) and very high for Non, Nak and Pab populations (100 %).

To calculate the relative toxicities among the tested chemical insecticides, lambda-cyhalothrin was set at a value of 1, since it was the least efficient. On the basis of LC_{50} values, the relative toxicity was the highest for emamectin benzoate (relative toxicity: ×2 712 969). Methomyl (×49), abamectin (×15), deltamethrin (×13), chlorpyriphos-ethyl (×4) were also more toxic than lambda-cyhalothrin.

Table 9. Control failure likehood (%) of populations of the fall armyworm using insecticides in Burkina Faso.

Insecticides	Houet			Kadiogo				Mean
	Sam	Tol	Tou	STo	Non	Nak	Pab	
Methomyl	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0
Chlorpyriphos–ethyl	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-22.5	-24.6
Deltamethrin	77.5	100.0	100.0	100.0	87.5	90.0	98.8	80.5
Lambda–cyhalothrin	81.3	100.0	100.0	97.5	100.0	100.0	100.0	97.0
Emamectin benzoate	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0
Abamectin	33.7	46.3	45.0	37.5	100.0	100.0	100.0	66.1
Bacillus thuringiensis	100.0	100.0	-	100.0	100.0	100.0	-	100.0

5. *Discussion*

Our study was performed in a context of absence of registered insecticides against the fall armyworm in West Africa. We decided to perform this study with as many active molecules as possible, to be representative of what farmers are likely to apply in their fields. We selected old and newer insecticides belonging to four modes of action: AChE inhibitors (methomyl, chlorpyriphos-ethyl), sodium channel modulators (deltamethrin, lambda-cyhalothrin), chloride channel activators (emamectin benzoate, abamectin), and microbial disruptors of insect midgut membranes (*B. thuringiensis*). Although some slight differences were observed among the tested populations, they were all in the same range of susceptibility. This could probably be explained by a limited number of introductory pathways of this pest to Burkina Faso (Early *et al.*, 2018; Otim *et al.*, 2018), the relatively short period of establishment in the country (Tizie & N'Guessan, 2017) and the similarity among the areas the populations were sampled in terms of control methods (MAAH, 2018).

Emamectin benzoate was, by far, the most efficient insecticide to control *S. frugiperda*. The fall armyworms were also relatively susceptible to the older insecticides methomyl (carbamate) and chlorpyriphos-ethyl (organophosphaste), confirming previous reports from other countries (Gutiérrez-Moreno *et al.*, 2019; Ríos-Díez & Saldamando-Benjumea, 2011). Based on our results, low risk of control failure is expected for these three insecticides. *Spodoptera frugiperda* were less susceptible to deltamethrin and lambda-cyhalothrin, despite the high doses included in our assays. Previous evidences of high resistance levels of deltamethrin and lambda-cyhalothrin were reported in Mexico, Brazil and Colombia (Carvalho *et al.*, 2013; León-García *et al.*, 2012; Ríos-Díez & Saldamando-Benjumea, 2011). In this context, failure to control fall armyworm would be very likely, as the doses required are higher than those authorised by the manufacturers, and therefore would be of serious health and environmental risk. In Benin, Adeye *et al.* (2018) reported the ineffectiveness of the binary Lambdace 25 EC (lambda-cyhalothrin 15 g/l and acetamiprid 10 g/l) on fall armyworm. In the absence of a susceptible fall armyworm population in this study, resistance factor to different insecticides were only calculated by comparing LC_{50} values and fiducial limits at 95 % to identify a significantly more susceptible population. No difference of susceptibility level to emamectin benzoate was recorded in all seven tested populations. In addition, no spatial dependence to insecticides was observed for the majority of the products tested, with exception of abamectin.

Contrasted susceptibility levels to different active substances may be observed within a pest population as the result of several factors, alone or in combination: 1) differences in crop management approaches among the regions, 2) climatic conditions (seasonal or tropical), 3) the mode of action of the insecticide, 4) the *S. frugiperda* original strain (maize or rice strains) and 5) the methods used to assess susceptibility and development of resistance to the chemicals (Ríos-Díez & Saldamando-Benjumea, 2011). Several previous studies clearly demonstrated differences in susceptibility to various insecticides among field strains of *S. frugiperda* in Mexico and Puerto Rico (Gutiérrez-Moreno *et al.*, 2019), Brazil (Campos *et al.*, 2011; Carvalho *et al.*, 2013), Colombia (Ríos-Díez & Saldamando-Benjumea, 2011), Venezuela (Morillo & Notz, 2001) and the U.S.A. (Yu, 1991; 1992).

In general, the resistance ratios were higher for pyrethroids than organophosphates and carbamates (Carvalho *et al.*, 2013; León-García *et al.*, 2012; Morillo & Notz, 2001). Resistance ratio (RR50) of the lambda-cyhalothrin selected strain in Venezuela varied from 19.4–41.9-fold between P0 and F9 generation, whereas in a methomyl selected strain the RR50 ranged from 3.1–22.1-fold in P0 to F9 (Morillo & Notz, 2001). Subsequent experiments with a population of *S. frugiperda* from Mexico also showed high resistance ratios: 1002.2-fold, 204.5-fold and 183.0-fold for deltamethrin, lambda-cyhalothrin and methomyl, respectively (León-García *et al.*, 2012). In another study, the resistance to lambda-cyhalothrin increased 10-fold in 6.5 generations compared to 11.5 generations for methomyl, which has a similar mode of action to diazinon (*i.e*. AChE inhibitors). Heritability of resistance was therefore higher for lambda-cyhalothrin, making methomyl a better option for control of fall armyworm from Colombia (Ríos-Díez & Saldamando-Benjumea, 2011), similar to our results. Genetic bases of pesticide resistance are essential to better understand the evolution of resistance and to refine resistance management strategies (Mckenzie, 2000). The heritability of *S. frugiperda* resistance to lambda-cyhalothrin has been identified as autosomal and recessive, which tends to delay inheritance (Diez-Rodriguez & Omoto, 2001). Previous evidences of the inefficiency of some pyrethroid insecticides were reported around the globe, for example in Brazil and Puerto Rico (Carvalho *et al.*, 2013; Gutiérrez-Moreno *et al.*, 2019).

The present study also shows that fall armyworm populations in Burkina Faso are highly susceptible to AChE inhibitors (methomyl, chlorpyrifos-ethyl). These old molecules showed better efficacy and lower probability of treatment failure compared to abamectin, one of the newest molecules available on the market in Burkina Faso. This is contradictory with the results recently obtained by Gutiérrez-Moreno *et al.* (2019), who reported that AChE inhibitors displayed lower potencies against fall armyworm populations from Puerto Rico and Mexico than newer molecules. For abamectin, we showed a variation in susceptibility of fall armyworm populations depending on the cropping system of the sampled area. Fall armyworm populations collected from the province of Kadiogo (with vegetable crops associated with maize) were less susceptible than those collected from the province of Houet (mainly producing cereals). This difference in susceptibility may be related to the frequency of insecticide applications, higher in vegetable crops than in cereals; maize was not treated with insecticides before the arrival of the fall armyworm in 2016 (Caniço *et al.*, 2020a). Now, abamectin is becoming increasingly important in tomato production to control major pests such as mites and leafminer *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) in Burkina Faso (Sawadogo *et al.*, 2020a; Son *et al.*, 2017a; 2018).

Emamectin benzoate was found to be highly effective against all sampled fall armyworm populations. Emamectin benzoate came out to be an effective insecticide for most armyworm species: it exhibited low or very low levels of resistance in *S. litura* (Fabricius) (Lepidoptera: Noctuidae) (Karuppaiah & Srivastava, 2013; Motaphale *et al.*, 2018; Sharma & Pathania, 2014), and *S. exigua* (Hübner) (Lepidoptera: Noctuidae) (Saeed *et al.*, 2012; Zhang *et al.*, 2014). In a recent study, emamectin benzoate also proved to be very effective against the fall armyworm, with a low level of resistance, comparable to abamectin (Gutiérrez-Moreno *et al.*, 2019). As observed in our assays, previous works reported that abamectin was less toxic for *S. litura* than emamectin benzoate (Ahmad & Mehmood, 2015; Thodsare & Srivastava, 2014). In the case of *S. exigua*, genetic studies have shown that inheritance of emamectin benzoate was autosomal, incompletely dominant, and polygenic (Che *et al.*, 2015). Consequently, continued and intensive application of this compound has contributed to rapid evolution of high resistance in field populations from China (Che *et al.*, 2013; Su & Sun, 2014). Due to their similar mode of action, *S. exigua* selected with emamectin benzoate had a high level cross-resistance to abamectin (Che *et al.*, 2015).

Biological control should become a more important part of fall armyworm management in Africa (Kenis *et al.*, 2019). Biopesticides are emerging, with *B. thuringiensis* among the most promising solutions (Deravel *et al.*, 2014). However, the number of resistant species has been increasing worldwide (Tabashnik *et al.*, 2013). In the present study, some *S. frugiperda* populations were less susceptible than others to the biopesticide *B. thuringiensis* var. *kurstaki*. The exposure duration of 3 days may have limited the expression of the full potential of this relatively slow-acting insecticide. Several studies have shown that the susceptibility to synthetic insecticides depends on the level of resistance to *B. thuringiensis*. For example, strains of *Helicoverpa armigera* (Hübner) and *H. punctigera* (Wallengren) (all Lepidoptera: Noctuidae) resistant to Cry2Ab showed small increases in susceptibility to AChE inhibitors such as methomyl and chlorpyrifos (Bird & Downes, 2014). Higher susceptibility to insecticides derived from the bacterium abamectin and spinosad was reported with a laboratory-selected strain of *H. armigera* that was resistant to Cry1Ac (Xiao *et al.*, 2016). This may also be the case for the fall armyworm for which improved susceptibility to chlorpyrifos-ethyl and methomyl has been recorded with populations showing low susceptibility to *B. thuringiensis*.

Finally, the implementation of an efficient control strategy against this pest can only be achieved through a continuous survey of its susceptibility to insecticides, to be deployed in all maize-producing regions of the country. Such a monitoring is a fundamental element of any resistance prevention programme: detecting susceptibility evolution in the laboratory allows the adaptation of the control methods before the problem becomes too serious. The establishment of a network of laboratories for insecticide susceptibility monitoring of *S. frugiperda* is essential for designing regional integrated management programmes, and to preserve the efficacy of the available active ingredients.

Susceptibility of fall armyworm *Spodoptera frugiperda* (JE Smith) to microbial and botanical bioinsecticides and control failure likelihood estimation

Cette section est une adaptation de l'article suivant :

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1. *Abstract*

The fall armyworm *Spodoptera frugiperda* (JE Smith) has become one of the most devastating pests of maize and other important economic crops in Africa since 2016. Among the alternatives to chemical insecticides, bioinsecticides are an interesting option that needs to be explored. We evaluated the susceptibility of fall armyworms collected in Burkina Faso to seven bioinsecticides available on the West African market. Bioassays were conducted following the approved IRAC 020 protocol.

We found spinetoram (LC_{80}=85.3 µg/L) and spinosad (LC_{80}=437.9 µg/L) to be the most toxic, at concentrations below those recommended by the manufacturer, and allowing control failure likelihoods close to 0%. *Bacillus thuringiensis* and products based on *Azadirachta indica* and *Carapa procera* extracts were less effective (at the manufacturers' recommended doses), even though they showed good levels of toxicity on young instars. A list of effective bioinsecticides should be communicated for sustainable management of fall armyworm in West Africa.

2. *Introduction*

The fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) is one of the most important polyphagous pests of maize and other important economic crops, in tropical and subtropical regions of the Americas. It was first reported on the African continent in 2016 (Goergen *et al.*, 2016). Favorable climatic conditions, year-round availability of host plants, high reproductive capacity, and dispersal of adults have allowed the fall armyworm to establish itself permanently in Africa (Montezano *et al.*, 2018; Prasanna *et al.*, 2018).

The fall armyworm is currently managed mainly by the application of chemical insecticides (Houngbo *et al.*, 2020; Kansiime *et al.*, 2019). Their widespread and sometimes indiscriminate use in the Americas has resulted in high levels of resistance in fall armyworm populations to the major classes of insecticides such as carbamates, organochlorines, organophosphates and pyrethroids (Gutiérrez-Moreno *et al.*, 2019). Not surprisingly, treatment failures have been reported by farmers as has already been the case in Mexico and Puerto Rico (Gutiérrez-Moreno *et al.*, 2019).

Research and development of alternatives are high on the agenda for sustainable management of this pest in West Africa (Harrison *et al.*, 2019; Prasanna *et al.*, 2018). Bioinsecticides have the advantage of being less toxic to non-target organisms and human health (Bateman *et al.*, 2018; Sisay *et al.*, 2019a). On one hand, plant extracts have demonstrated some potential insecticidal activities against the fall armyworm in field and laboratory conditions (Phambala *et al.*, 2020; Sisay *et al.*, 2019a). On the other hand, a recent analysis of national pesticide and biopesticide lists from 19 African countries identified 29 biopesticides that could be approved for use in fall armyworm management (Bateman *et al.*, 2018), subject to their efficacy being proven against this new pest. In this study, we evaluated the susceptibility of fall armyworm collected in Burkina Faso to seven bioinsecticides available on the West African market.

3. Material and methods

3.1 Insect collection and rearing

A starter colony of fall armyworm was established from a maize field located in Nasso (11°13'11"N, 4°26'11"W), Houet province in Burkina Faso. Approximately 600 fourth-instar larvae were collected in November 2020. Larvae were reared in the laboratory on maize leaves as described by Ahissou *et al.* (2021a). The F1 generation was used for all bioassays.

3.2 Insecticides

We evaluated seven commercial insecticide formulations: spinetoram (Radiant 120SC, Dow AgroSciences, recommended concentration (RC): 60 mg/L) and spinosad (Laser 480SC, Dow AgroSciences, RC: 160 mg/L), *Bacillus thuringiensis* (Bio K 16, Savana, RC: 8.10^7 IU), *Carapa procera* essential oil (16 ml/L) and various concentrations of *Azadirachta indica* extracts (HN, HNN+, HN++, Bioprotect, 14 ml/L).

3.3 Insecticide assay

Bioassays were conducted according to the adapted IRAC 020 protocol, by leaf dipping using first, second and third instar F1 larvae (http://www.irac-online.org/methods/). The first and second stages were used for plant extract-based bioinsecticides that were less toxic. They were performed as described by Ahissou *et al.* (2021a) and mortality was assessed after 72 h for all bioinsecticides except for spinetoram and spinosad (48 h). Each insecticide was tested using at least five concentrations, after dilution with distilled water containing Triton X-100 (0.2 g/L). Non-treated maize leaves were collected, washed with tap water and dried (Figure 12a). Then, they were immersed for 10 seconds in the insecticide solution and left to dry for 1 h. Control leaves were treated only with a solution of Triton in water. Leaves were placed in individual Petri dishes (9 cm in diameter) containing blotting paper. A total of 40 larvae were individually exposed to each concentration of each tested product (Figure 12b).

Figure 12. Susceptibility test for fall armyworm. (a) Maize leaf cutting, (b) larvae exposed to different insecticides in Petri dishes.

3.4 Statistical analysis

Data were corrected for control mortality (Abbott, 1925) and subjected to probit analysis (Finney, 1971) using SPSS software, to calculate slope values, lethal concentrations (LC_{50}; LC_{80}), and fiducial limits (95%). Control failure likelihood (CFL) was calculated by multiplying the achieved mortality (AM) percentage (to the label concentration) by 100, dividing the product by the minimum required efficacy (RE) (e.g. 70%) and subtracting the result from 100 (Guedes, 2017). Additionally, an ANOVA was performed to compare mortality rates between different concentrations of a bioinsecticide (Tukey's test, $P<0.05$).

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

4. *Results*

The observed control mortality rate was found to be less than 3% and was used to correct mortality. For the seven bioinsecticides tested, the theoretical values were not significantly different from the observed values, so the Probit model was considered appropriate (Table 10 and 11). The LC_{50} and LC_{80} values and their confidence intervals and CFL are presented in Table 10.

For each bioinsecticide, the observed mortality rates were always affected by the tested concentrations ($P<0.001$) (Table 11).

Table 10. Susceptibility level of fall armyworm to seven bio-insecticides. L: insect stage; a: number of larvae tested; bLC_{50} and cLC_{80} expressed in: µg a.i./L (spinosad, spinetoram), IU/L (*B. thuringiensis*), ml/L (HN, HN+, HN++, *C. procera*); SE: standard error.

Insecticides	L	n[a]	LC_{50} (95% FL)[b]	LC_{80} (95% FL)[c]	Fit of probit line			CFL
					Slope ± SE[d]	X^2 (ddl)	*P*	
Bacillus thuringiensis	L1	200	$2.7x10^8$ (2.29-3.14).10^8	$4.5x10^8$ (3.9-5.4).10^8	-	5.4 (3)	0.15	74.3
	L2	200	$4.7x10^8$ (4.33-5.10).10^8	$6.3x10^8$ (5.8-6.9).10^8	-	1.0 (3)	0.80	99.9
	L3	240	$6.2x10^8$ (5.66-6.72).10^8	$8.5x10^8$ (7.9-9.4).10^8	-	0.9 (4)	0.92	100.0
Carapa procera	L1	200	63.0 (55.9-71.0)	93.6 (83.7-108.9)	0.03 ± 0.004	1.4 (3)	0.70	99.9
	L2	200	151.5 (134.2-174.2)	222.8 (195.7-267.5)	0.01 ± 0.002	3.5 (3)	0.32	100.0
HN	L1	200	11.9 (10.2-13.7)	19.0 (16.7-22.7)	0.12 ± 0.017	7.6 (3)	0.05	14.3
	L2	200	19.1 (17.0-21.7)	28.3 (25.1-33.7)	0.09 ± 0.013	3.5 (3)	0.32	50.0
	L3	280	115.8 (105.2-127.3)	167.7 (153.3-187.7)	0.02 ± 0.002	2.9 (5)	0.72	99.9
HN+	L1	200	172.2 (154.5-185.3)	224.9 (211.2-245.2)	0.02 ± 0.002	7.3 (3)	0.06	100.0
	L2	200	205.9 (178.5-234.3)	324.2 (286.5-389.3)	0.01 ± 0.001	0.7 (3)	0.87	100.0
HN++	L1	200	172.2 (154.5-185.3)	224.9 (211.1-245.2)	0.02 ± 0.002	7.3 (3)	0.06	100.0
	L2	200	206.8 (185.9-228.1)	294.8 (268.1-335.5)	0.01 ± 0.001	2.6 (3)	0.47	100.0
Spinetoram	L3	200	54.1 (46.3-62.4)	85.3 (75.6-98.9)	27.0 ± 3.2	4.7 (3)	0.19	-42.9
Spinosad	L3	200	322.0 (290.5-352.7)	437.9 (403.1-484.7)	7.2 ± 0.84	2.2 (3)	0.54	-42.9

Table 11. Mean percent mortality of fall armyworm larvae after bioinsecticide application. L: insect stage; C: concentrations expressed in: µg a.i./L (spinosad, spinetoram), IU/L (*B. thuringiensis*), ml/L (HN, HN+, HN++, *C. procera*); mortality (%): for a given bioinsecticide, different letters indicate significant differences between concentrations using Tukey's test $p < 0.05$.

Insecticides	L	C [a]	% [b]
Spinosad	L3	120	10.3 a
		240	23.1 b
		360	61.5 c
		480	84.6 d
		600	100.0 e
Spinetoram	L3	12	10.3 a
		24	23.1 b
		48	48.7 c
		90	74.4 d
		120	100.0 e
HN	L1	3.75	5.1 a
		5	28.2 b
		10	48.7 c
		15	69.2 d
		20	76.9 d
HN	L2	5	12.8 a
		10	15.4 a
		15	30.8 b
		20	64.1 c
		27.5	74.4 c
HN	L3	20	2.6 a
		25	7.7 a
		75	33.3 b
		100	35.9 b
		125	53.9 c
		150	74.4 d
		200	89.7 e
Bacillus thuringiensis	L1	1×10^8	10.3 a
		1.8×10^8	38.5 b
		2.4×10^8	51.3 c
		3.2×10^8	64.1 d
		5.6×10^8	87.2 e
Bacillus thuringiensis	L2	2×10^8	7.7 a
		3.2×10^8	23.1 b
		4.4×10^8	38.5 c
		5.6×10^8	66.7 d
		7×10^8	92.3 e

Insecticides	L	C [a]	% [b]
Bacillus thuringiensis	L3	2.8×10^8	7.7 a
		3.2×10^8	15.4 a
		4.4×10^8	28.2 b
		6.8×10^8	59.0 c
		8×10^8	76.9 d
Carapa procera	L1	25	7.7 a
		100	20.5 b
		175	43.6 c
		200	59.0 d
		250	84.6 e
Carapa procera	L2	100	2.6 a
		150	18.0 b
		200	23.1 b
		250	53.9 c
		350	69.2 d
HN+	L1	150	23.1 a
		175	64.1 bc
		200	74.4 bc
		250	84.6 c
		300	97.4 d
HN+	L2	25	7.7 a
		175	43.6 bc
		200	51.3 bc
		225	56.4 c
		325	76.9 d
HN++	L1	25	5.1 a
		100	23.1 b
		175	59.0 c
		200	74.4 d
		250	84.6 d
HN++	L2	100	10.3 a
		150	30.8 b
		200	51.3 c
		250	71.8 d
		350	87.2 e

Spinetoram and spinosad were the most toxic of the insecticides tested with LC_{80} values of 85.3 µg/L and 437.9 µg/L respectively. These values are 99% lower than recommended by the manufacturer.

Bacillus thuringiensis LC_{50} and LC_{80} values increased significantly with the developmental stage of the fall armyworm, as the confidence intervals did not overlap. Lethal concentration values were 5.6 to 10.6 times higher than the manufacturer's recommended dose, so the CFL is very high (74.3-100%).

Plant extract-based insecticides tested were less toxic to the fall armyworm larvae. Lethal concentrations values were 6 to 23 times higher than the manufacturers' recommended concentrations, meaning that the CFL is high.

5. *Discussion*

Our study was conducted in a context of lack of insecticides registered by the Sahelian Pesticides Committee (CSP) against the fall armyworm in West Africa, although chemical control is currently the main method of controlling this new pest (Houngbo *et al.*, 2020; Kansiime *et al.*, 2019). In addition, the poor use of personal protective equipment when handling chemical insecticides and other poor practices related to their use (Prasanna *et al.*, 2018; Tambo *et al.*, 2020) expose maize farmers who were not used to them before the arrival of the fall armyworm (Caniço *et al.*, 2020a) to several health risks. We decided to carry out this study by choosing molecules of low toxicity registered by the CSP on other insect pests, but also bioinsecticides formulated from several botanical species that have each demonstrated insecticidal activity. We have selected formulations belonging to different modes of action: spinosyns spinetoram and spinosad (nicotinic acetylcholine receptor), *B. thuringiensis* (microbial disruptor of insect midgut membranes), *A. indica* and *C. procera* extracts (compounds of unknown or uncertain mode of action).

In the present study, spinetoram (LC_{80}=85.3 µg/L) and spinosad (LC_{80}=437.9 µg/L) insecticides have the best efficacy profiles against fall armyworm at concentrations significantly lower than manufacturers' recommendations. The high slope values (7.26 to 27.03) mean that a small increase in insecticide concentration is sufficient to significantly increase larval mortality, suggesting that the fall armyworm population is very sensitive to these molecules. At the dose recommended very limited treatment failure should be observed. Similar results were obtained in Brazil, China, Mexico and Puerto Rico (Gutiérrez-Moreno *et al.*, 2019; Lira *et al.*, 2020). With CFL close to zero, both spynosins are more effective than chemical insecticides such as abamectin (CFL=66%), deltamethrin (CFL=80%), and lambda-cyhalothrin (CFL=96%) (Ahissou *et al.*, 2021a) which are widely used against this pest in West Africa (Ahissou *et al.*, 2021c; Kansiime *et al.*, 2019). However, it would not be surprising to see in the near future the emergence of resistance to these molecules, as it has already been observed in Brazil, Mexico and Puerto Rico (Gutiérrez-Moreno *et al.*, 2019; Lira *et al.*, 2020; Okuma *et al.*, 2018) or a cross-resistance between both spynosins in Brazil (Lira *et al.*, 2020).

For the plant extract-based insecticides tested, the required LC_{80} values were much higher than the manufacturers' recommended concentrations with better results on smaller larvae. However, it is interesting to note that the leaves treated with the botanical insecticides were not consumed by the larvae. Azadirachtin and *C. procera* are powerful food deterrents and insect growth regulators (Isman, 2006; Seigler, 1998). Their use should be recommended — as it is the case of *Azadirachtin* in China (Zhao *et al.*, 2020) — in fall armyworm IPM programs in combination with other compatible methods.

With high LC_{80} values ranging from 4.48×10^8 to 8.50×10^8 IU/L and low slope values (<0.001), fall armyworm showed resistance to *B. thuringiensis* var *kurstaki* with a CFL between 74 - 100%. This is consistent with the hypothesis that some Bt-resistant lepidopterans are highly susceptible to spinosad (Xiao *et al.*, 2016), as is the case in this study.

6. Conclusion

In conclusion, we recommend extending these results to farmers, which show that some bioinsecticides are very effective and could play an important role in IPM programs against fall armyworm. Apart from superior insecticidal activity relative to some chemical insecticides, such bioinsecticides have the advantage of being less toxic to non-target organisms.

Conclusion du chapitre 5

Dans ces deux études, nous rapportons les niveaux de sensibilité de différentes populations de *S. frugiperda* du Burkina Faso à une diversité d'insecticides chimiques et de bioinsecticides disponibles localement. Dans l'ensemble, les niveaux de sensibilité sont similaires entre les différentes populations de *S. frugiperda* et nos résultats indiquent que l'émamectine benzoate (mode d'action IRAC : Groupe 6), le méthomyl, le chlorpyrifos-éthyl (Groupe 1A/1B), le spinétorame et le spinosad (Groupe 5) présentent les meilleurs profils d'efficacité pour le contrôle du ravageur.

La résistance de la chenille légionnaire d'automne aux insecticides évolue très rapidement aux champs, lorsque des générations successives du ravageur sont soumises à des insecticides ayant le même mode d'action. En conséquence, leur gestion devient plus difficile et nécessite des doses et fréquences d'application d'insecticides plus importantes. Pour retarder ou ralentir cette menace quasi permanente à la durabilité de la lutte chimique, il faudrait alterner les insecticides de différents modes d'action entre des fenêtres de traitement de 30 jours (durée moyenne d'une génération du ravageur). En outre, la surveillance de la sensibilité du ravageur doit se poursuivre en permanence pour détecter tout changement à temps avant que le problème ne devienne trop grave.

6

Ennemis naturels de la chenille légionnaire d’automne

Introduction au chapitre 6

La lutte biologique est une alternative de gestion hautement souhaitable pour contrôler la chenille légionnaire d'automne à long terme. Cependant, son succès doit être fondé sur une connaissance approfondie de la diversité et de l'abondance des ennemis naturels locaux. La chenille légionnaire d'automne est attaquée par une diversité d'ennemis naturels, notamment des parasitoïdes, prédateurs et des entomopathogènes (champignons, bactéries, virus et nématodes). Le complexe d'ennemis naturels est un facteur de mortalité important de la chenille légionnaire d'automne sur son continent d'origine.

Les ennemis naturels locaux qui contrôlent d'autres espèces du genre *Spodoptera* présentes en Afrique peuvent élargir leur niche en s'adaptant à la chenille légionnaire d'automne comme nouvel hôte ou nouvelle proie. L'objectif de ce chapitre est de rechercher des ennemis naturels associés à la chenille légionnaire d'automne et des stratégies pour leur maintien dans les champs de maïs. Dans la première partie, nous avons inventorié les ennemis naturels associés à ce ravageur dans les champs de maïs. Dans la deuxième partie, nous évaluons le potentiel de prédation des œufs et larves de la chenille légionnaire d'automne par les perce-oreilles qui sont les prédateurs majoritaires. Ce chapitre se termine par une étude comparative de la sélectivité de différents insecticides chimiques et biologiques sur les perce-oreilles et leur proie afin d'identifier les produits compatibles avec une stratégie de lutte intégrée.

Natural enemies of the fall armyworm *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) in Burkina Faso

Cette section est une adaptation de l'article suivant :

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1. *Abstract*

The fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) is a voracious pest that preferentially feeds on cereals and other crops of economic importance. Native to America, it has recently invaded sub-Saharan African countries where it is currently threatening food security. There is limited knowledge of the natural enemies of the fall armyworm in Africa. In this study, we aimed to identify arthropods, fungi and entomopathogenic nematodes that naturally control this pest in Burkina Faso. Insect samplings, including larvae and egg masses, were conducted in 47 maize farms from October 2019 to November 2020.

About 20 species of parasitoids, predators and entomopathogenic fungus associated with the fall armyworm were identified. The overall parasitism rate was 10.5%. Nematodes (Mermithidae) were the most frequent parasites (73.2% of the parasitized larvae). Identified parasitoids included Hymenopterans [*Coccygidium luteum* (Brullé), *Chelonus bifoveolatus* (Szépligeti)] and Dipterans (*Drino* sp.). Predators included Areneae and insects belonging to the following families: Carabidae (*Calleida* sp.), Coccinellidae [*Cheilomenes sulphurea* (Olivier)], Forficulidae [*Diaperasticus erythrocephalus* (Olivier), *Forficula senegalensis* (Serville)], Formicidae [*Pheidole megacephala* (Fabricius) and others], Mantidae, Pentatomidae and Reduviidae (*Rhynocoris* sp.). The most abundant predators were members of the Forficulidae (51%), Formicidae (15%) and Coccinellidae (13%). We advocate for the development of conservation biological control since this approach can be simple and cost-effective to control this pest.

2. *Introduction*

Native from tropical America, *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae), commonly known as fall armyworm invaded West Africa in early 2016 (Goergen *et al.*, 2016). It is a major insect pest of maize and other cereals that has spread rapidly across the African continent (Montezano *et al.*, 2018; Prasanna *et al.*, 2018) and then to Asia where it was first reported in India (Sharanabasappa *et al.*, 2018; Shylesha *et al.*, 2018). In the absence of control measures, the fall armyworm can cause estimated maize yield losses of 8 - 20 million tons in 12 African countries per year (Day *et al.*, 2017). Following serious infestations in West Africa, fall armyworm management has been based primarily on the use of chemical insecticides, despite their questionable and unproven efficacy (Ahissou *et al.*, 2021a; Harrison *et al.*, 2019; Sisay *et al.*, 2019a) or unregistered for use on this new threat (Sisay *et al.*, 2019a). The adverse effects of some chemical insecticides on human health, the environment, and living organisms (Son *et al.*, 2017b) makes biological control a more desirable alternative to control this pest in the long term (Harrison *et al.*, 2019).

The beneficial action of competitors, pathogens, parasitoids and predators in the control of pests and their damage is termed biological control (Nafiu *et al.*, 2014). Four types of biological control strategies applied in pests control programs may be identified: natural (no human intervention), augmentative (periodical release of mass-reared natural enemies), classical (importation of an exotic natural enemy), and conservation biological control (Nafiu *et al.*, 2014; Prasanna *et al.*, 2018; van Lenteren *et al.*, 2018). Conservation biological control, i.e. the conservation of existing natural enemies in an environment, can be simple and cost-effective, through the manipulation of environment, cropping systems, and locally available techniques to enhance their efficacy (Harrison *et al.*, 2019; Nafiu *et al.*, 2014). It provides the possibility of minimizing pest outbreaks in an ecologically and economically cost effective manner using locally available natural enemies (Barbosa & Benrey, 1998). However, its promotion should be based on a comprehensive knowledge of the diversity and abundance of natural enemies existing locally.

The fall armyworm is attacked by various natural enemies including insect parasitoids species (Molina-Ochoa *et al.*, 2003; Sisay *et al.*, 2018), diverse taxa of predators (Harrison *et al.*, 2019; Koffi *et al.*, 2020; Wyckhuys & O'Neil, 2006) and entomopathogens such as fungi, bacteria, viruses and nematodes (Molina-Ochoa *et al.*, 2003; Shylesha *et al.*, 2018; Tendeng *et al.*, 2019). Natural enemy complex is reported as important mortality factors for the fall armyworm (up to 42%) in its native continent (Wheeler *et al.*, 1989). Natural enemies native to West Africa are already controlling other species of *Spodoptera* present in the area, including *Spodoptera exempta* (Walker), *S. littoralis* (Boisduval), *S. litura* (Fabricius), *S. exigua* (Hübner) (all Lepidoptera: Noctuidae). They may widen their niche by adapting to *S. frugiperda* as a novel host or prey (Koffi *et al.*, 2020; Sharanabasappa *et al.*, 2019).

Presently, little information is available on natural enemies of the fall armyworm in Africa (Agboyi *et al.*, 2020) and Asia (Firake & Behere, 2020). Although, some recent studies reported natural enemies of fall armyworm in Tanzania, Kenya and Ethiopia (Sisay *et al.*, 2018), Senegal (Tendeng *et al.*, 2019), Benin, Ivory Coast and Ghana (Agboyi *et al.*, 2020; Kenis *et al.*, 2019; Koffi *et al.*, 2020), Niger (Laminou *et al.*, 2020), Mozambique (Caniço *et al.*, 2020a) and India (Firake & Behere, 2020; Sharanabasappa *et al.*, 2019; Shylesha *et al.*, 2018). These studies indicated that the natural enemy complex associated with fall armyworm varies between countries, even though some species (i.e., *Coccygidium* spp., *Chelonus* spp., *Campoletis* spp., *Metopius* spp., *Trichogramma* spp., *Telenomus* sp., *Hexamermis* sp. and earwigs) have been widely reported in many parts of the world.

In Burkina Faso, such information is lacking from the scientific literature, although *S. frugiperda* is extremely active in the country. Farmers have a detailed knowledge of most of the arthropod present in their field. However, they usually cannot identify the beneficial role of many of them (Dicko *et al.*, 1998). In this study, we documented the natural enemies of fall armyworm and evaluated their contributions to pest mortality.

3. Materials and methods

3.1 Sampling sites and methods

This study investigated the natural enemies of fall armyworm larvae by collecting its larvae and eggs, and by counting and identifying all species of predatory arthropods in maize fields in Burkina Faso. A total of 47 maize fields were sampled from two producing provinces of the country: Houet (11°20'N, 4°15'W) and Kadiogo (12°20'N, 1°30'W) (Figure 13) from October 2019 to November 2020. Provinces of Houet and Kadiogo were selected based on reported presence of fall armyworm combined with maize production in the Sudanian and Sahelo-Sudanese agro-ecological zones, respectively. Maize, sorghum, and other cereals are typically grown in the province of Houet. Agriculture in the province of Kadiogo is characterized by intensive horticulture: maize, tomato, cabbage, and other vegetable crops are grown year-around.

In the different fields, the presence of fresh frass and feeding injury on whorls and leaves helped locate sites with fall armyworm infestation. Only maize fields in which plants were in stages V5 (2 fully deployed leaves) to R (tasseling and silking) were sampled (Prasanna *et al.*, 2018). Among the plants having visible fall armyworm attack symptoms, 25 were randomly selected. Stalks, whorls, and both upper and lower surfaces of plant leaves were inspected. All fall armyworm egg masses and larvae found on the selected maize plants were collected. In addition, some entomopathogenic nematodes were directly observed on maize leaves and were collected with a fine brush. Predators present on the different parts of the plant were counted. The predation of fall armyworm was confirmed by direct observation in the field. Each field was visited once during the study period and location details such as latitude, altitude and longitude were taken using GPS. All samples were brought to the laboratory at the Training and Research Center of the University Nazi Boni (UNB) in Bobo Dioulasso (Burkina Faso) for rearing and identification.

3.2 Rearing of fall armyworm and natural enemies

Fall armyworm egg masses were maintained separately in rearing containers until the emergence of larvae or egg parasitoids. All collected insects were kept individually in the laboratory on maize leaves at 26±2°C, 71±14% relative humidity, and 12:12 photoperiod. Fall armyworm larvae development was checked every daily and fresh leaves were replaced after 24 h until pupation. They were observed until the emergence of fall armyworm imago, parasitic nematodes or parasitoids. Emerged parasitoids were preserved in 90% ethanol and later identified morphologically. Parasitic nematodes were grouped per date of collection in 250 ml transparent plastic boxes containing moistened sand.

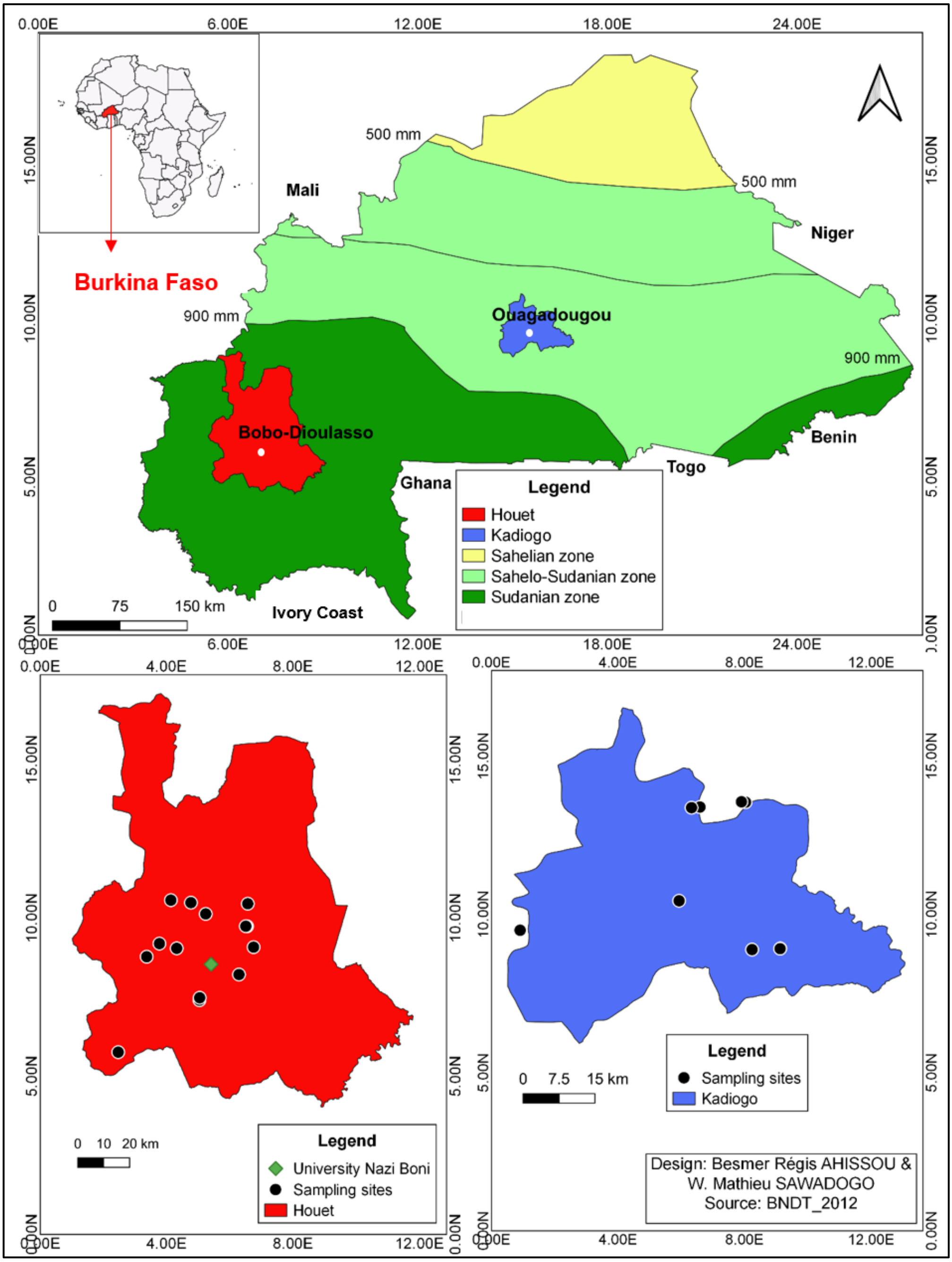

Figure 13. Sampling locations in Houet and Kadiogo provinces (Burkina Faso).

Arthropod predators were observed and counted in the field. However, in doubtful cases, a sample of the predators were brought to the laboratory and exposed to fall armyworm eggs and to first, second, third and fourth (L1, L2, L3 and L4) instar larvae as prey, to check their predatory potential. All predators were then preserved in 90% ethanol until identification.

3.3 Identification of natural enemies of the fall armyworm

Parasitic nematodes were sent for morphological identification in the Laboratory of Diagnosis and Integrated Management of Plant Bio-agressors at the University of Parakou (Benin). The determination keys and description proposed by Baker & Capinera (1997); Firake & Behere (2020) and Tendeng *et al.* (2019) were used for their identification. For parasitoids, various determination keys were used to identify Braconidae (Braet *et al.*, 2012; Sharkey, 1992; van Achterberg, 1990) and Tachinadae (Crosskey, 1968; O'Hara & Cerretti, 2016). For predators, the checklist of the earwigs of Chad (Dermaptera) (Girod & Lassalle, 2017) and determination keys proposed by Brindle (1967) and Waller *et al.* (1999) were used to identify Forficulidae. Online databases provided by Global Biodiversity Information Facility (GBIF: https://www.gbif.org/) and annotated list of ladybirds of Reunion Island (Nicolas *et al.*, 2015) were used to identify Coccinellidae and Carabidae. The determination keys proposed by Kwadjo *et al.* (2012) was used to identify Reduviidae.

3.4 Entomopathogenic fungi isolation and Koch's postulates

Cadavers of fall armyworm showing natural symptoms of entomopathogenic fungi were encountered and brought to the laboratory. Each cadaver was placed in a Petri dish containing Potato Dextrose Agar (PDA) medium and incubated at 25±2°C and 12: 12 h (UV: dark) photoperiod for 7–14 days. After the incubation, the fungal conidia were harvested by scraping the conidial layers formed on the surface of the plates using a sterilized scalpel. To confirm the causal agent of the death of the fall armyworm, we evaluated the pathogenicity of isolated entomopathogenic fungi by confirming the Koch's postulates. The fungal conidia were dissolved in 0.05% Tween-20 solution and was inoculated to fall armyworm larvae (L3 and L5) by two methods. A larva dipping in an inoculum solution and a standard leaf dipping bioassay. A total of 40 larvae were observed per instar and method.

3.5 Relative abundance and parasitism rates

The number of fall armyworm collected was corrected by subtracting the number that died from injury or unknown causes during the first few days after collection before calculating percent parasitism (Molina-Ochoa *et al.*, 2004). Unknown death causes may include possible bacteria, viruses, or the effects of chemical pesticides. Mortality due to parasitoids and nematodes was reported elsewhere. The relative abundance (RA) of each species was determined by dividing the number of individuals of a given species i (Ni) by the total number of all individuals collected (Nt) and expressing this value as a percentage (Agboyi *et al.*, 2020). To assess RA, all predators were separated from the parasite group (i.e., parasitoids and nematodes). For the entomopathogenic fungi, numbers of field-infected larvae and total fall armyworm larvae collected were recorded and converted to percentage infection.

$$RA = \frac{Ni}{Nt} \times 100$$

Gregarious parasitoids emerging from a single larva were considered as being only one. Parasitism rate (PR) of each parasitoid species was calculated by dividing the number of larvae parasitized (Lp) by the total number of fall armyworm larvae collected (TL) and by expressing this value as a percentage (Pair *et al.*, 1986).

$$PR = \frac{Lp}{TL} \times 100$$

4. Results

Despite its recent introduction into West Africa, we recorded a total of 20 species of natural enemies associated with the fall armyworm, including parasitoids (5), predators (13), a parasitic nematode (1) and an entomopathogenic fungus (1) in Houet and Kadiogo provinces of Burkina Faso (Table 12). A total of 23 fall armyworm egg masses were collected, but no egg parasitoids were detected. Out of 684 fall armyworm larvae collected, 47 died without any emergence of parasites or parasitoids. From the remaining 637 larvae, 67 contained parasitic nematodes and parasitoids. Parasitic nematodes (Nematoda: Mermithidae) were by far the most abundant species with RA estimated at 73.2%. All other larval parasitoids were found to be less abundant (RA < 5%) (Table 13). The overall parasitism rate was 10.5% (Table 14).

The predator complex is made of Araneae, and several insect families including Carabidae, Coccinellidae, Forficulidae, Formicidae, Mantidae, Pentatomidae and Reduviidae. This complex was dominated numerically by Forficulidae (51%), followed by Formicidae (15%) and Coccinellidae (13%). All other predators were found to be less abundant (RA < 5%). A total of thirteen species of predators were observed associated with different stages of fall armyworm (Table 15). In addition, nine cadavers of fall armyworm infected with fungi were found in seven maize fields.

Table 12. Provinces with the collected natural enemies of fall armyworm in Bukina Faso.

Province	Natural enemies
Houet	Araneae, *Calleida* sp., Carabidae, *Cheilomenes sulphurea*, *Chelonus bifoveolatus*, *Coccygidium luteum*, *Diaperasticus erythrocephalus*, *Drino* sp., Parasitic nematode, *Forficula senegalensis*, Mantidae, Pentatomidae, *Pheidole megacephala* and other ants (Formicidae), *Rhynocoris* sp., Unidentified gregarious endoparasitoid, Entomopthogenic fungi on cadavers of fall armyworm
Kadiogo	Ants (Formicidae), Araneae, Carabidae, *C. sulphurea*, *D. erythrocephalus*, *F. senegalensis*, Mantidae, Pentatomidae, *Rhynocoris* sp., Unidentified fly (Diptera), Entomopthogenic fungi on cadavers of fall armyworm

4.1 Parasitic nematodes

Fifty-two larvae were parasitized by parasitic nematodes (Nematoda: Mermithidae) (Figure 14). All fall armyworm larvae died after nematode emergence. In the field, one parasitic nematode emerged from fall armyworm larva was directly found in maize leave (Figure 14b).

Table 13. Host stages attacked and relative abondance (RA) of parasitoid and parasite of fall armyworm, recorded in maize fields located in Burkina Faso

N°	Order, family and species of parasitoid or parasite	Type	RA (%)
	Diptera		
	Tachinidae		
1	*Drino* sp.	Larval parasitoid	4.2
2	Unidentified sp.	Larval parasitoid	2.8
	Hymenoptera		
	Braconidae		
3	*Chelonus bifoveolatus* (Szépligeti)	Egg–larval parasitoid	8.5
4	*Coccygidium luteum* (Brullé)	Larval parasitoid	4.2
	Nematoda		
5	Mermithidae	Larval and pupal parasite	73.2
6	Unidentified gregarious endoparasitoid	Larval parasitoid	1.4

The parasitism rate was calculated to be 8.2% (Table 14). The mermithids are white, 140-258 mm in length (Figure 14d), and were living for more than 200 days in the laboratory. After reproduction in moistened sand in laboratory, infective juveniles of less than 10 mm in length were obtained (Figure 14c).

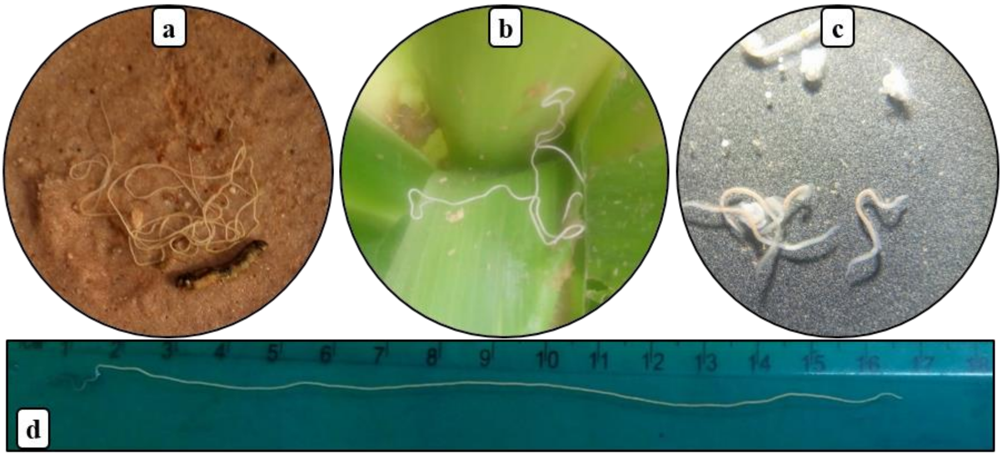

Figure 14. Mermithid nematode emerged from fall armyworm larvae. (a) nematode in soil, (b) nematode emerged from host on maize leaf, (c) infective juveniles of mermithid, (d) ruler graduated in cm used to measure nematodes.

4.2 Parasitoids

From all samples of fall armyworm larvae collected, five species of parasitoids belonging to Hymenoptera (2), Diptera (2) and an unidentified gregarious larval endoparasitoid emerged (adults had not emerged from the parasitoid pupae) (Figure 15a-f). These are *Coccygidium luteum* (Brullé), *Chelonus bifoveolatus* (Szépligeti) (both Braconidae), *Drino* sp. (Tachinidae), an unidentified diptera fly. Except for *C. bifoveolatus*, an egg-larval parasitoid, the others are exclusive larval parasitoids (Table 13). The present field survey data showed that *C. bifoveolatus* (0.9%) and *C. luteum* (0.5%) were the most abundant parasitoids in fall armyworm infested maize fields (Table 14).

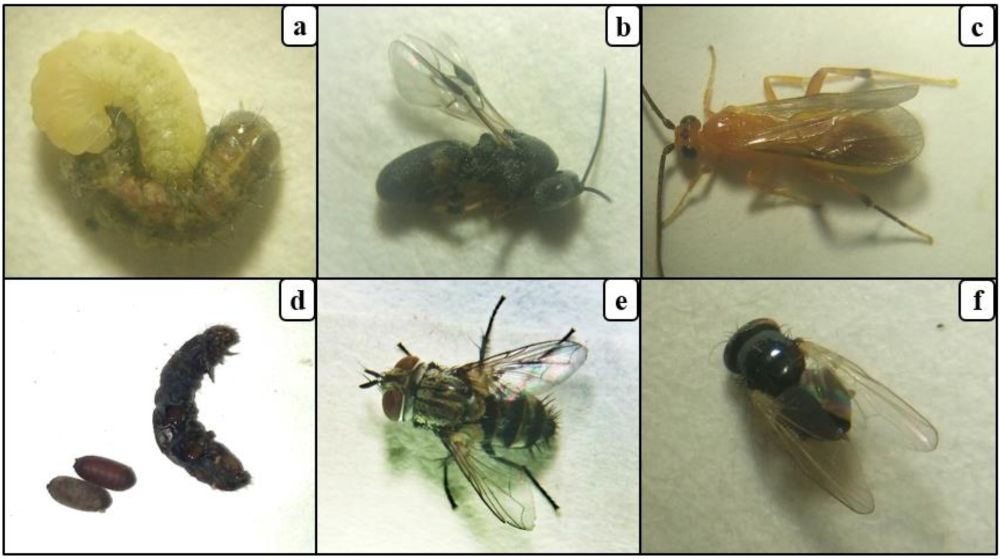

Figure 15. Parasitoids of fall armyworm in Burkina Faso. (a) larva of *Chelonus bifoveolatus* sucking the hemolymph from fall armyworm larva, (b) adult of *C. bifoveolatus*, (c) *Coccygidium luteum*, (d) pupae of gregarious larval endoparasitoid, (e) *Drino* sp., (f) unidentified Diptera.

4.3 Predators

In this study, a total of 736 arthropod predators belonging 13 species were recorded (Table 15). Earwigs represented up to 51% of the total predator complex identified from the maize fields. In many fields, earwigs are the most frequently encountered species, especially when free from insecticidal spray. All species found were Forficulidae of the species *Diaperasticus erythrocephalus* (Olivier) and *Forficula senegalensis* (Serville) (Figure 16a-c). These two forficulidae are predators and were collected from late-stage maize fields, particularly in the whorl and ears of maize.

We report the predation of fall armyworm larvae by the ant *Pheidole megacephala* (Fabricius) (Hymenoptera: Formicidae). Five additional ant species were observed on maize plants infested by fall armyworm (Figure 16d, e). They were observed in all surveyed maize fields.

Table 14. Parasitism rate (mortality rate) of fall armyworm attributed to various parasites, parasitoids, and other factors in Burkina Faso. † Possible bacterial or viral agents and unknown death causes.

Species	Parasitim rate (%)
Mermithid nematode	8.2
Chelonus bifoveolatus (Szépligeti)	0.9
Coccygidium luteum (Brullé)	0.5
Drino sp.	0.5
Unidentified sp. Diptera	0.3
Unidentified gregarious endoparasitoids	0.2
Total parasitism rate	10.5
Other mortality†	7.4
Total mortality	17.9

Table 15. Host stages attacked and relative abondance (RA) of predators of fall armyworm, recorded in maize fields located in Burkina Faso

N°	Order, family, and species of predator	Host stages attacked	RA (%)
1	Araneae	Larvae	5.4
	Coleoptera		
	Carabidae		
2	*Calleida* sp.	Larvae	1.5
3	Unidentified sp. 1	Larvae	0.8
4	Unidentified sp. 2	Larvae	0.4
	Coccinellidae		
5	*Cheilomenes sulphurea* (Olivier)	Larvae	12.6
6	Unidentified coccinelid	Larvae	1.1
	Dermaptera		
	Forficulidae		
7	*Diaperasticus erythrocephalus* (Olivier)	Eggs and larvae	26.8
8	*Forficula senegalensis* (Serville)	Eggs and larvae	24.3
	Hemiptera		
9	Pentatomidae	Larvae	2.3
	Reduviidae		
10	*Rhynocoris* sp.	Larvae	4.9
	Hymenoptera		
	Formicidae		
11	*Pheidole megacephala* (Fabricius)	Larvae	5.6
12	Unidentified spp.	Larvae	10.2
	Mantodea		
13	Mantidae	Larvae	4.1

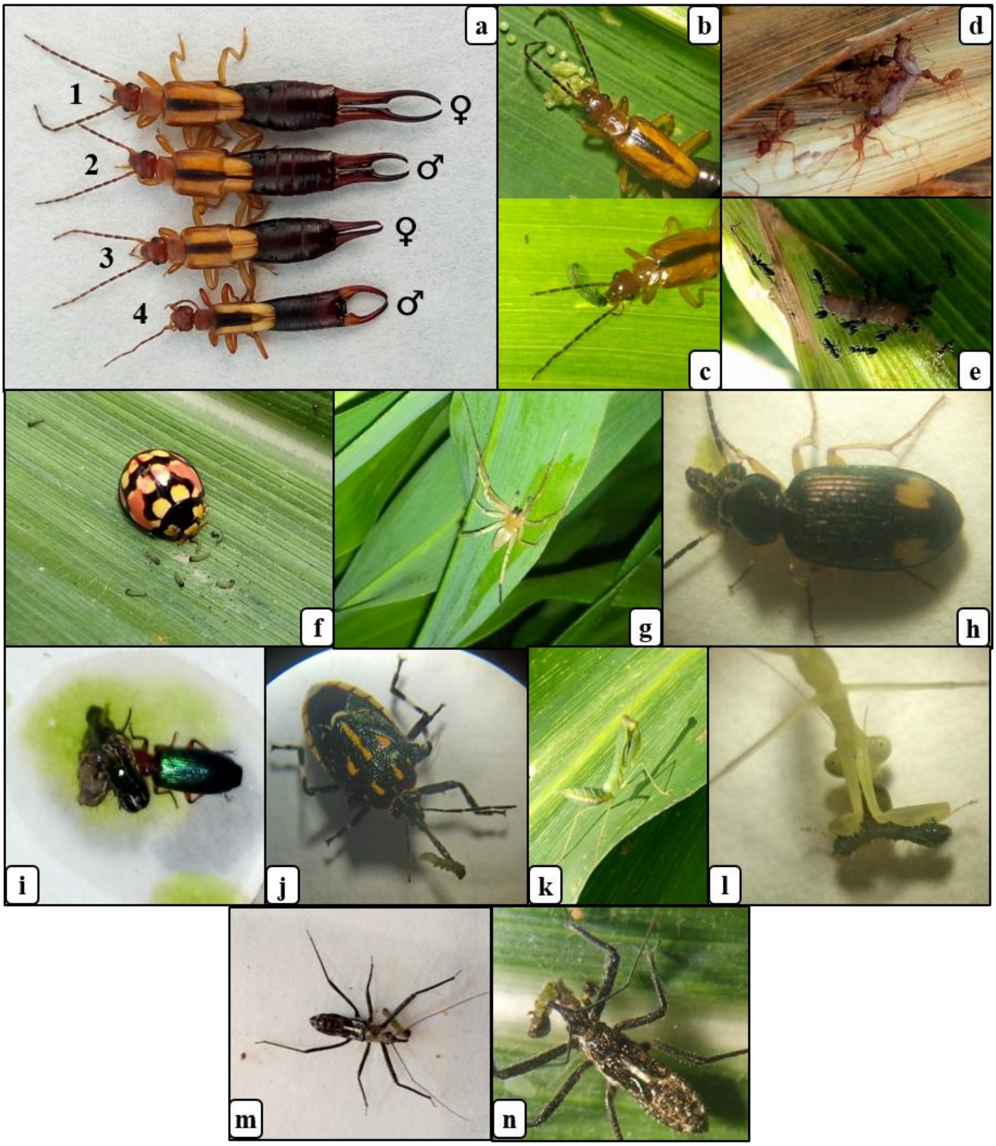

Figure 16. Predators of fall armyworm in Burkina Faso. (a) earwigs (1 and 2 = *Forficula senegalensis*, 3 and 4 = *Diaperasticus erythrocephalus*), (b, c) fall armyworm eggs and larvae attacked by earwig, (d, e) fall armyworm larvae attacked by ants, (f) fall armyworm larvae attacked by *Cheilomenes sulphurea*, (g) spider on a maize plant, (h) carabidae predator, (i) *Calleida* sp. eating fall armyworm larvae, (j) pentatomid predator eating a larva, (k, l) mantidae predator, (m, n) *Rhynocoris* sp. eating fall armyworm larvae.

Ladybirds constituted 13.7% of all predators recorded in maize fields. Two species were found: *Cheilomenes sulphurea* (Olivier) and unidentified coccinelid (Coleoptera: Coccinellidae). Coccinellids were found active in fall armyworm infested maize fields and *C. sulphurea* was observed feeding on fall armyworm neonate larvae (Figure 16f). The predators *Calleida* sp., two unidentified species (all Coleoptera: Carabidae) (Figure 16h, i), *Rhynocoris* sp. (Hemiptera: Reduviidae) (Figure 16m, n), and the order Areneae were found directly feeding on fall armyworm larvae in maize fields. Predation on fall armyworm larvae by Mantidae and Pentatomidae was not directly observed on maize plants. However, field collected specimens placed in boxes together with fall armyworm larvae were observed to devour them immediately (Figure 16j-l).

4.4 Entomopathogenic fungus

A total of 9 fall armyworm larvae infected with entomopathogenic fungus were collected from the fields (Figure 17a), representing 1.4% of larval infection. After incubating these cadavers on PDA medium (Figure 17b), one fungus species was observed. Pathogenicity using Koch's postulates of fungi associated with fall armyworm collected in maize field revealed that the fungus was pathogenic to larvae. Mortality of larvae was recorded between 4 - 7 days after pathogenicity test (Figure 17d). Identification and detailed description of the fungal strain is required.

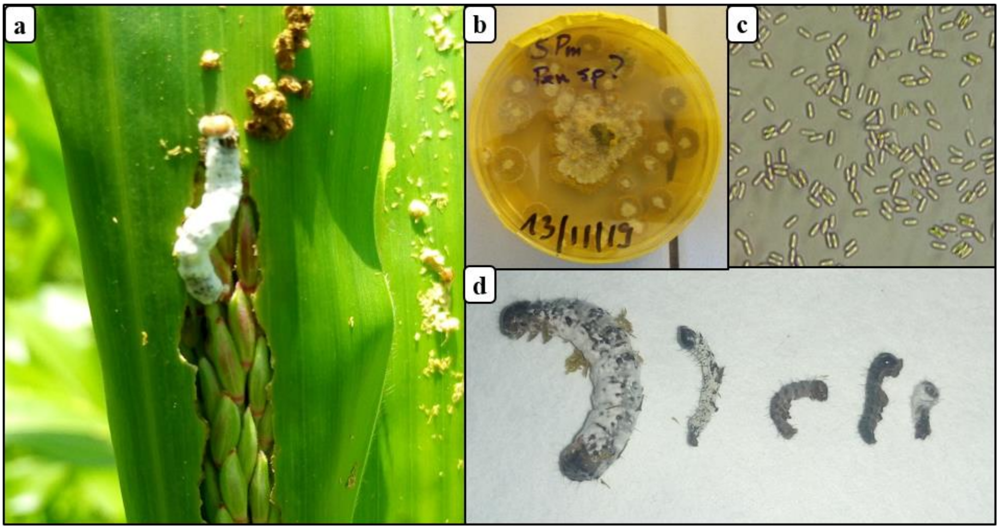

Figure 17. Entomopathogenic fungus of fall armyworm in Burkina Faso. (a) fall armyworm larva killed by an entomopathogenic fungus on maize, (b) momified fall armyworm larvae on PDA media, (c) conidia of entomopathogenic fungus, (d) fall armyworm larvae (3rd to 5th instar) killed by entomopathogenic fungus in the laboratory.

5. *Discussion*

This study confirms the association of 20 species of natural enemies with the fall armyworm in Burkina Faso. Among them, 10 species were the first records of predation or parasitism on the fall armyworm in Burkina Faso. These were *C. bifoveolatus*, *C. luteum* (Hymenoptera: Braconidae), *Drino* sp. (Diptera: Tachinidae), *D. erythrocephalus*, *F. senegalensis* (Dermaptera: Forficulidae), *P. megacephala* (Hymenoptera: Formicidae), *C. sulphurea* (Coleoptera: Coccinellidae), *Calleida* sp. (Coleoptera: Carabidae), *Rhynocoris* sp. (Hemiptera: Reduviidae) and parasitic nematode (Nematoda: Mermithidae).

The parasitic nematode parasitism rate in Burkina Faso was lower than previous results in Senegal (13.7%) where adult nematodes are shorter, 100 to 120 mm (Tendeng *et al.*, 2019). Based on images shown by Tendeng *et al.* (2019) and Firake & Behere (2020), these were likely also the same parasitic nematode recently recovered from fall armyworm in Senegal and India, that the authors identified as *Hexamermis* sp. and *Hexamermis* cf. *albicans* (Siebold), respectively (all Nematoda: Mermithidae).

Parasitism rates of 30 and 9.8% of fall armyworms by *Hexamermis* were recorded in Nicaragua (Van Huis, 1981) and Honduras (Wheeler *et al.*, 1989) respectively. Mermithid species feed on the insect host's haemolymph and then emerge to complete development outside it. Infective juveniles of mermithids climb on plants in moist conditions, and infect hosts that feed on the plant (Nickle, 1981). We also hypothesize that the soil placed into infested whorls of maize by growers, or which accidentally enters the whorl during manual weeding, may contain nematodes that infect the larvae. Additional studies are needed to identify and understand the ecological relationship between parasitic nematodes and the fall armyworm with a view toward artificial rearing for field applications.

Fall armyworm larvae are susceptible to various parasitoids, corroborating earlier field reports in West Africa: Senegal (Tendeng *et al.*, 2019), Benin and Ghana (Agboyi *et al.*, 2020; Koffi *et al.*, 2020). Many *Chelonus* species are generally solitary egg-larvae koinobiont endoparasitoids that attack Lepidoptera including *S. littoralis*, *S. exigua*, *S. frugiperda* and *Heliothis virescens* Fabricius (Grossniklaus-Bürgin *et al.*, 1994). *Chelonus* spp. have recently been reported in the fall armyworm in several countries, *C. curvimaculatus* Cameron in Kenya (Sisay *et al.*, 2018), *Chelonus* sp. in Senegal (Tendeng *et al.*, 2019) and *C. bifoveolatus* in Benin and Ghana (Agboyi *et al.*, 2020; Koffi *et al.*, 2020).

The braconid *C. luteum* is widely distributed in Africa and was firstly reported in association with the fall armyworm in Africa (Ethiopia, Kenya and Tanzania) (Sisay *et al.*, 2018; Sisay *et al.*, 2019b). This internal solitary koinobiont parasitoid was later reported in Benin and Ghana (Agboyi *et al.*, 2020; Koffi *et al.*, 2020) and Mozambique (Caniço *et al.*, 2020a). Several tachinid species in association with the fall armyworm were recently found in similar surveys conducted in several countries. *Palexorista zonata* (Curran) was recorded in East Africa (Ethiopia, Kenya) (Sisay *et al.*, 2018; Sisay *et al.*, 2019b) and *Drino quadrizonula* Thomson was recorded in West Africa (Benin, Ghana) (Agboyi *et al.*, 2020). However, according to the recent classification of the Tachinidae of the Afrotropical region (O'Hara & Cerretti, 2016), *D.*

quadrizonula is closely related to *P. zonata*. This species is prevalent in sub-Saharan Africa, and is known to attack a species of moth larvae such as: *S. exigua*, *S. exempta* and other noctuidae (Crosskey, 1968).

On the other hand, some unidentified species of Tachinidae were reported in Ghana (Koffi *et al.*, 2020), Mozambique (Caniço *et al.*, 2020a) and India (Firake & Behere, 2020). These results suggest that these species are adapted to West African countries and can be good biological control agents of fall armyworm in West Africa. Considering the performance of parasitoids as biocontrol agents against fall armyworm in other parts of the world (Kenis *et al.*, 2019; Sisay *et al.*, 2018; Wheeler *et al.*, 1989), further studies are needed to evaluate their usefulness against fall armyworm in West Africa.

Most earwigs are generalist predators usually considered major component of the biological control complex agents for insect pests (Cruz, 2007; Prasanna *et al.*, 2018). Earwigs (i.e. *Doru luteipes* (Scudder) and *Euborellia anulipes* (Lucas)) are used in biological control programs for maize and sorghum pests in Brazil (Cruz, 2007). In Africa, earwigs are commonly reported as predators of aphids and stem borers in cereals (i.e. maize and rice) (Prasanna *et al.*, 2018). In India, the earwig *Forficula* sp. was commonly found in maize whorls attacking different stages of fall armyworm (Firake & Behere, 2020; Sharanabasappa *et al.*, 2019; Shylesha *et al.*, 2018). The potential of these earwigs to predate on fall armyworm eggs and larvae needs to be investigated.

In a similar study in Ghana, *P. megacephala* was the most abundant and dispersed predator of fall armyworm (Koffi *et al.*, 2020). In Africa, *Pheidole* spp. are sufficiently common and widespread to suppress insects such as *H. armigera* (Van Den Berg *et al.*, 1993). Similar to the present study, other coccinellids have recently been reported as predators of the fall armyworm in other countries: *Harmonia octomaculata* Fabricius and *Coccinella transversalis* Fabricius in India (Sharanabasappa *et al.*, 2019). However, Mantidae and Pentatomidae are known as common fall armyworm predators and have been reported in numerous previous studies (Firake & Behere, 2020; Wyckhuys & O'Neil, 2006).

Entomopathogenic fungus can be effective in controlling fall armyworm populations (Firake & Behere, 2020; Prasanna *et al.*, 2018). Recently, larvae infected with the entomofungal pathogen *Metarhizium* (=*Nomuraea*) *rileyi* (Clavicipitaceae) were collected from some maize infested fields in India (Firake & Behere, 2020; Sharanabasappa *et al.*, 2019; Shylesha *et al.*, 2018). Moreover, *Beauveria bassiana* (Balsamo) Vuillemin was also recorded infesting fall armyworm larvae (Firake & Behere, 2020). Although fall armyworm cadavers showing natural symptoms of entomopathogenic fungi have been encountered in several fields in Africa, there are no published results in the scientific literature on the different entomopathogenic fungi associated with this new pest.

Temporal and spatial differences in fall armyworm parasitism and microbial infection may be caused by climate variability, agronomic practices, crop type and stage of cultivation (Ruiz-Nájera *et al.*, 2007). However, we hypothesize that this low parasitism rate of the fall armyworm is attributable to recent introductions of the parasite in Burkina Faso. Consequently, we believe that fall armyworm parasitism will increase provided that maize management includes options that conserve natural enemies. A balanced relationship between fall armyworm and its indigenous natural enemies may take considerable time to achieve, but the implementation of cultural practices that promote their action should be advocated (Caniço *et al.*, 2020a).

6. Conclusion

An interesting conclusion of this study is that most natural enemies are abundant in maize fields and their potential should be exploited to control the fall armyworm. The indiscriminate use of chemical insecticides against fall armyworm negatively affects the natural enemies and can undermine the management strategies of smallholder farmers who rely heavily on natural enemies. The use of selective insecticides, protection of natural enemies from the harmful effects of insecticides and the development of more comprehensive integrated pest management strategies for the management of fall armyworm in Burkina Faso are therefore crucial.

Earwig predation potential and selectivity of insecticides used against fall armyworm on the predator in West Africa

Cette section est une adaptation de l'article suivant :

Ahissou, B. R., Sawadogo, W. M., Sankara, F., Bonzi, S., Bokonon-Ganta, A. H., Somda, I., & Verheggen, F. J. Earwig predation potential and selectivity of insecticides used against fall armyworm on the predator in West Africa. *In prep.*

1. *Abstract*

The fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) has become a major pest of staple cereal crops in Africa since 2016. Several natural enemies including earwigs are commonly observed being associated with this pest in maize fields. However, their populations are threathened by the common use of insecticides.

In this study, we evaluated the potential of earwig *Diaperasticus erythrocephalus* (Olivier) to consume fall armyworm eggs and larvae. In addition, we also compared the selectivity of different insecticides on this predatory species as well as on its prey in order to help identifing products compatible with an integrated pest management strategy.

Our results suggest that earwigs play an important role in the regulation of fall armyworm, as a single individual consum a mean of 90.3±16.5 eggs and 36.4±8.7 larvae per day. We found emamectin benzoate and spinetoram to be effective to control the fall armyworm while not affecting its predator. On the other hand, chlorpyrifos-ethyl, methomyl and spinosad are highly toxic to the predator. We discuss the potential of these results in the development of integrated pest management program. In particular, we recommend training farmers on natural enemy recognition and conservation practices.

2. *Introduction*

Over the last decade, the fall armyworm *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) has become one of the most important damageous invasive pests worldwide. Native to the tropical and subtropical regions of the Americas, it has seen its global distribution expand widely across the continents of Africa and Asia (Maino *et al.*, 2021; Goergen *et al.*, 2016). It threatens the production of staple cereal crops and consequently nutritional food security and livelihoods of millions of farmers (Goergen *et al.*, 2016). In maize, its main host, the fall armyworm is mainly managed by the application of chemical insecticides (Houngbo *et al.*, 2020; Tambo *et al.*, 2020), despite repeated demonstrations of resistance (Ahissou *et al.*, 2021a).

A diversity of natural enemies have been identified in Senegal (Tendeng *et al.*, 2019), Benin, Côte d'Ivoire, Ghana (Agboyi *et al.*, 2020; Dassou *et al.*, 2021; Kenis *et al.*, 2019; Koffi *et al.*, 2020), Niger (Laminou *et al.*, 2020) and Burkina Faso (Ahissou *et al.*, 2021b). Although the natural enemy complex associated varies among countries, some species (i.e., *Coccygidium* spp., *Chelonus* spp., *Trichogramma* spp., *Telenomus* sp., earwigs and ants) have been widely reported in many countries. In Burkina Faso, the predator complex was numerically dominated by predators and particularly Forficulidae (*Diaperasticus erythrocephalus* (Olivier) and *Forficula senegalensis* (Serville) (Ahissou *et al.*, 2021b). Because of their potential, their conservation is an important tactic to promote biological control and natural regulation of fall armyworm.

Earwigs (Dermaptera: Forficulidae) are known to be the most important predator of eggs and larvae of fall armyworm in maize fields in Brazil (Cruz, 2007; Figueiredo *et al.*, 2006). However, management decisions that focus exclusively on reducing insect pests (as with the case of chemical insecticides) may also eliminate predators, and thus lead to pest control failure (Guedes *et al.*, 2016). An alternative to keep these predators in the field is to use selective insecticides only. Some studies have reported that broad-spectrum insecticides such as carbamates, organophosphates and pyrethroids are highly toxic to earwigs (Campos *et al.*, 2011; Zotti *et al.*, 2010). The research of more selective insecticides is therefore warranted to allow compatibility and complementarity of chemical and biological control methods, which is vital to the success of integrated pest management programs against fall armyworms.

The predation potential of earwigs in the control of fall armyworm in Africa is not documented. The same is true for the selectivity of various insecticides widely used against the pest. To fill this knowledge gap, we evaluated the predation capacity of the earwig *D. erythrocephalus* on fall armyworm eggs and larvae under laboratory conditions using insects collected in Burkina Faso. We also comparatively evaluated the selectivity of different commercially available chemical and biological insecticides on adult earwigs and their prey to identify products compatible with an integrated pest management strategy against fall armyworm. We hope to provide authorities and farmers with precious information to choose the most appropriate insecticides to incorporate into the biological control of fall armyworm in recently invaded areas.

3. Material and methods

3.1 Sources of insects

Both earwig and fall armyworm colonies were collected from a maize field located in province of Houet and shipped to the laboratory at the University Nazi Boni (UNB) in Bobo Dioulasso, Burkina Faso. Approximately 60 earwigs were reared in transparent plastics boxes (20 × 10 × 10 cm) with openings covered with thin white cloth for ventilation. They were fed with a diet made with maize powder (10g) and insect remains consisting of dead pupae and adults of the fall armyworm (50g). 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 to laboratory conditions for 1 month before testing.

Fall armyworm larvae were fed daily on fresh maize leaves until pupation. Pupae were daily collected and placed in a cage (60 × 40 × 40 cm) along with a white paper for female oviposition. Fall armyworm adults were fed a sugar water solution (100 g/L). After oviposition, the white paper was removed and cut to individualize each egg mass in separate boxes. The F1 generation of fall armyworms was used for all bioassays. Both insects were reared under controlled conditions at 25±2°C, 60±15% relative humidity, and a 12L:12D photoperiod.

3.2 Insecticides

We evaluated the survivability of earwigs to ten commercial insecticide formulations used against fall armyworm in maize fields. These were chemical insecticides (NAR = Normal Application Rate): abamectin 18 g a.i./L (Acarius® EC, Savana, France, NAR = 1 L/ha), chlorpyriphos-ethyl 480 g a.i./L (Pyrical™ 480 EC, Arysta Lifescience, France, NAR = 1 L/ha), deltamethrin 25 g a.i./L (Tamega® EC, Savana, France, NAR = 0.5 L/ha), emamectin benzoate 19 g a.i./L (Emacot® 019 EC, Savana, France, NAR = 0.5 L/ha), lambda-cyhalothrin 25 g a.i./L (Sunhalothrin® 2,5% EC, Wynca Sunshine, Mali, NAR = 0.5 L/ha), methomyl 250 g a.i./Kg (Savahaler® WP, Savana, France, NAR = 1.5Kg/ha). Biopesticides were also included in the assay and included spinetoram 120 g a.i./L (Radiant™ 120 SC, Dow AgroSciences, NAR = 100 ml/ha), spinosad (Laser™ 480 SC, Dow AgroSciences, NAR = 100 ml/ha), *Bacillus thuringiensis* 16,000 IU/mg (Bio K® 16 WP, Savana, France, NAR = 1.5Kg/ha) and *Azadirachta indica* extracts (HN, Bioprotect, Burkina Faso, NAR = 5 L/ha). The ten active ingredients, their IRAC group and modes of action are listed in Table 16.

Table 16. Insecticides used against earwigs and fall armyworm populations. Group numbers and mode of action are those of IRAC, the Insecticide Resistance Action Committee (https:/www.irac-online.org/modes-of-action/)

Active ingredient	IRAC group	Chemical subgroup	Mode of action
Methomyl Chlorpyriphos-ethyl	1A 1B	Carbamates Organophosphastes	Acetylcholinesterase (AChE) inhibitors
Deltamethrin Lambda-cyhalothrin	3A 3A	Pyrethroids	Sodium channel modulators
Spinetoram Spinosad	5 5	Spinosyns	Nicotinic acetylcholine receptor (nAChR) allosteric modulators
Abamectin Emamectin benzoate	6 6	Avermectins	Chloride channel activators
Bacillus thuringiensis	11A	*Bacillus thuringiensis*	Microbial disruptors of insect midgut membranes
Azadirachta indica	UN	Azadirachtin	Compounds of unknown or uncertain MoA

3.3 Predation on eggs and larvae of fall armyworm

Fall armyworm 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. Egg predation rate was determined by individually placing ten male and female *D. erythrocephalus* earwigs in each Petri dish containing between 130 - 150 eggs and which was sealed with parafilm. To evaluate the predation capacity on the larval stages of the fall armyworm, the same protocol was used by introducing 60 L1, 30 L2, 10 L3 in each Petri dish containing fresh maize leaves where a male or female earwig was subsequently added. The controls consisted of Petri dishes containing fresh maize leaves and either eggs or larvae only. Five replicates were done for each sex. The boxes were maintained under the same conditions as those described above. After 24 h of exposure, each Petri 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.

3.4 Susceptibility of earwigs and fall armyworm

Bioassays were conducted according to the adapted IRAC 020 protocol, by leaf dipping using adult earwig *D. erythrocephalus* collected and third instar F1 larvae of the fall armyworm (http://www.irac-online.org/methods/). Each insecticide was diluted at least five times using distilled water containing Triton X-100 (0.2 g/L) for fall armyworm. Regarding the survival of earwigs, only the recommended dose of the 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 left to dry for 1 h. Control leaves were treated only with a solution of Triton in water. Leaves were placed in individual Petri dishes (9 cm in diameter) containing blotting paper. A total of 40 insects were individually exposed to each concentration with 4 replications. All bioassays were conducted under controlled laboratory conditions at 25±2°C, 60±15% relative humidity, and a photoperiod 12L:12D. Earwig survival was assessed for 24 h, 48 h, and 72 h, and the diet was added daily to each Petri dish. Mortality of fall armyworm larvae was assessed after 72 h for all insecticides. Insects were considered dead if they failed to move when touched with a small brush, or when they showed severe intoxication symptoms such as severe growth inhibition, halted moulting, and feeding cessation.

3.5 Data analysis

Data on the number of fall armyworm eggs and larvae consumed by adult earwigs, as well as data on earwig survival to insecticides, were subjected to a generalized linear models (GLMs) procedure, binomial distribution. 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 fall armyworm population were corrected for control mortality (Abbott, 1925). They were subjected to probit analysis (Finney, 1971), to calculate values of slope, lethal concentration (LC_{50} and LC_{80}), and fiducial limits (95%). Control failure likelihood (CFL) was calculated using Guedes (2017) formula. 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. The required efficacy was set at 80%, as the minimum efficacy threshold required to allow registration of insecticides. Finally, the 'prcomp' function was used to perform Principal Component Analysis (PCA) and Biplot is generated by using the 'fviz_pca_biplot' function in the 'factoextra' package for R. In the Biplot, the lines represent the measured variables and the points represent the evaluated insecticides. Except for the probit analyses performed in SPSS 25.0 statistical package for Windows, all other analyses were performed in R statistical software (R Core Team, 2021) using the RStudio-2021.09.2 interface.

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

4. *Results*

4.1 Predation on eggs and larvae of fall armyworm

The consumption capacity of earwig varied significantly with the developmental stage of the prey tested (fall armyworm eggs or larvae) and the sex of the predator ($P<0.001$). Daily egg consumption by female earwigs (98.2 ± 17.6) was significantly higher than that of males (82.4 ± 10.3) ($P<0.001$) (Figure 18). Adult females also consumed significantly more L1 larvae (38.6 ± 8.2) than males (34.3 ± 8.7) ($P=0.03$). In contrast, no significant difference was observed in consumption between female and male earwigs when fed fall armyworm L2 and L3 larvae.

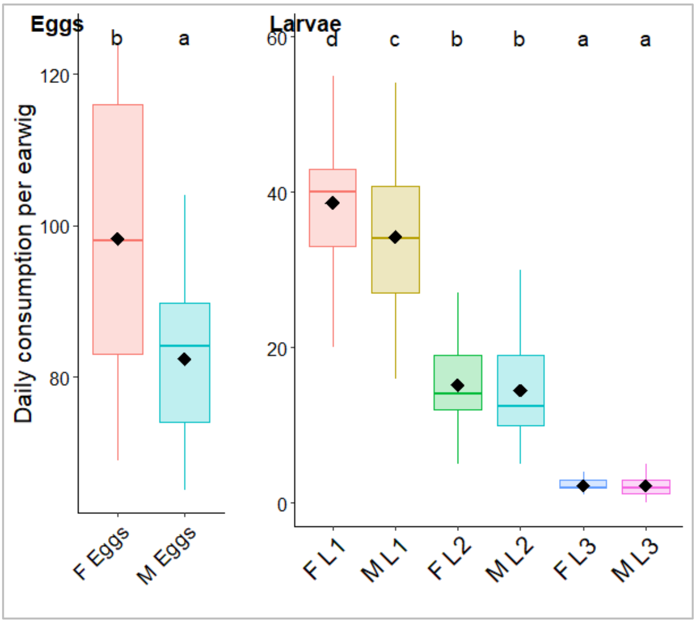

Figure 18. Predation of earwigs female (F) and male (M) on fall armyworm eggs and larvae (L1, L2 and L3). Different letters indicate significant differences (GLM; Tukey test, p < 0.05). Figure shows the means (black lozenges), SE (boxes) and SD (whiskers).

4.2 Survival rate of earwigs to insecticides and control failure likehood (CFL)

No mortality was recorded for the control treatments. Survival of earwigs after 24, 48 and 72 hours of exposure to insecticides varied significantly according to the insecticides.

(1) The insecticides chlorpyriphos-ethyl, methomyl and spinosad were very toxic for the earwigs which all died only after 24 hours exposure (Table 17). With a zero CFL, these products would eliminate earwigs from maize fields at the recommended dose.

(2) The insecticides lambda-cyhalothrin and spinetoram were moderately toxic to earwigs at all exposure times with a survival rate between 41.9-65.6%. The CFL values of 57.0 and 27.4 respectively, suggest that at the manufacturer's recommended rates, these products could provide moderate suppression of earwigs in maize fields (43 – 72.6%).

(3) The insecticides abamectin, emamectin benzoate, deltamethrin, *A. indica* and *B. thuringiensis* did not affect earwig survival (100%) at all exposure times. With an CFL of 100, all earwigs could survive in maize fields to applications of these products at the manufacturer's recommended rates.

Table 17. Survival rates of earwigs at recommended doses of fall armyworm insecticides after exposure for 24, 48 and 72 hours.

Insecticides	Survival rate (%)			CFL
	24h	48h	72h	
Abamectin	100.0	100.0	100.0	100.0
Azadirachta indica	100.0	100.0	100.0	100.0
Bacillus thuringiensis	100.0	100.0	100.0	100.0
Deltamethrin	100.0	100.0	100.0	100.0
Emamectin benzoate	100.0	100.0	100.0	100.0
Lambda-cyhalothrin	78.1	66.8	65.6	57.0
Spinetoram	53.7	44.4	41.9	27.4
Chlorpyriphos-ethyl	0.0	0.0	0.0	-25
Methomyl	0.0	0.0	0.0	-25
Spinosad	0.0	0.0	0.0	-25

4.3 Susceptibility of fall armyworms to insecticides

The natural mortality observed in the control treatments was below 5% and was used to correct the insecticide mortality. For all insecticides tested, the theoretical values were not significantly different from the observed values, so the Probit model was considered appropriate (Table 18).

Table 18. Susceptibility level of fall armyworm to ten insecticides. [a]*n* = number of larvae tested; [b]LC_{50} and [c]LC_{80} expressed in mg a.i./L (abamectin, deltamethrin, lambda-cyhalothrin, chlorpyriphos-ethyl and methomyl), µg a.i./L (emamectin benzoate, spinosad and spinetoram), IU/L (*B. thuringiensis*), ml/L (*Azadirachta indica*); [d]SE = standard error.

Insecticides	n[a]	LC_{50} (95% FL)[b]	LC_{80} (95% FL)[c]	Fit of probit line			CFL
				Slope ± SE[d]	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)	2671 ± 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)	6.9 ± 0.7	11.4 (4)	0.02	-25.0
Spinetoram	200	51 (18-79)	80 (56-129)	28.5 ± 2.9	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

Spinosyns: Spinetoram and spinosad were highly toxic insecticides to fall armyworm with LC_{80} values of 80.0 µg/L and 420.0 µg/L, respectively (Table 18). These values are 99% lower than those recommended by the 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 fall armyworm population is very sensitive to both molecules. At the dose recommended, very limited treatment failure should be observed.

Carbamates and organophosphates: The LC_{80} values for methomyl (74.3 mg/L) and chlorpyrifos-ethyl (417.4 mg/L) were lower than the recommended doses by 92% and 74%, 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 fall armyworm at the recommended rates.

Avermectins: The LC_{80} values of emamectin benzoate and abamectin were 0.82 µg/L and 115.1 mg/L, respectively. Since their confidence limits do not overlap, abamectin has a lower toxicity than emamectin benzoate. At the doses recommended by the manufacturers of these insecticides, the CFL is 47.5% for abamectin and -25 for emamectin benzoate.

Pyrethroids: Deltamethrin and lambda-cyhalothrin were less toxic to fall armyworm with similar LC_{80} values (confidence limits overlap) of 655.0 mg/L and 764.9 mg/L, 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) and *B. thuringiensis* (13.0 x 10^8 IU/L) 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 fall armyworm from fields are high (100%).

4.4 Comparative selectivity of insecticides on earwigs and fall armyworm

The objective is to identify active ingredients that are toxic to fall armyworm and simultaneously selective or less toxic to earwigs for integrated pest management. The PCA performed by combining the control failure likelihoods of the different insecticides on the fall armyworm and the predator allowed us to group the insecticides. Insecticides in the blue box are selective or less toxic to earwigs and those in the red box are toxic to the fall armyworm (Figure 19). The combination allows the insecticides to be grouped into different classes.

(1) The insecticides emamectin benzoate and spinetoram, which are highly toxic to the fall armyworm but have no (or very little) effect on the predator (in blue on the biplot) (Figure 19). Their use in maize fields infested with fall armyworm will eliminate this pest, while preserving the earwigs present.

(2) The insecticides chlorpyrifos-ethyl, methomyl and spinosad are highly toxic to the fall armyworm, but are not selective to the predator (green in the biplot). Their use in maize fields may eliminate the fall armyworm and the earwigs present.

(3) The insecticides deltamethrin, lambda-cyhalothrin, abamectin, deltamethrin, *A. indica*, and *B. thuringiensis* that are not toxic to either the fall armyworm or the

predator (red in the biplot). At the recommended rates for these, the control failure likelihood in maize fields is very high for fall armyworm.

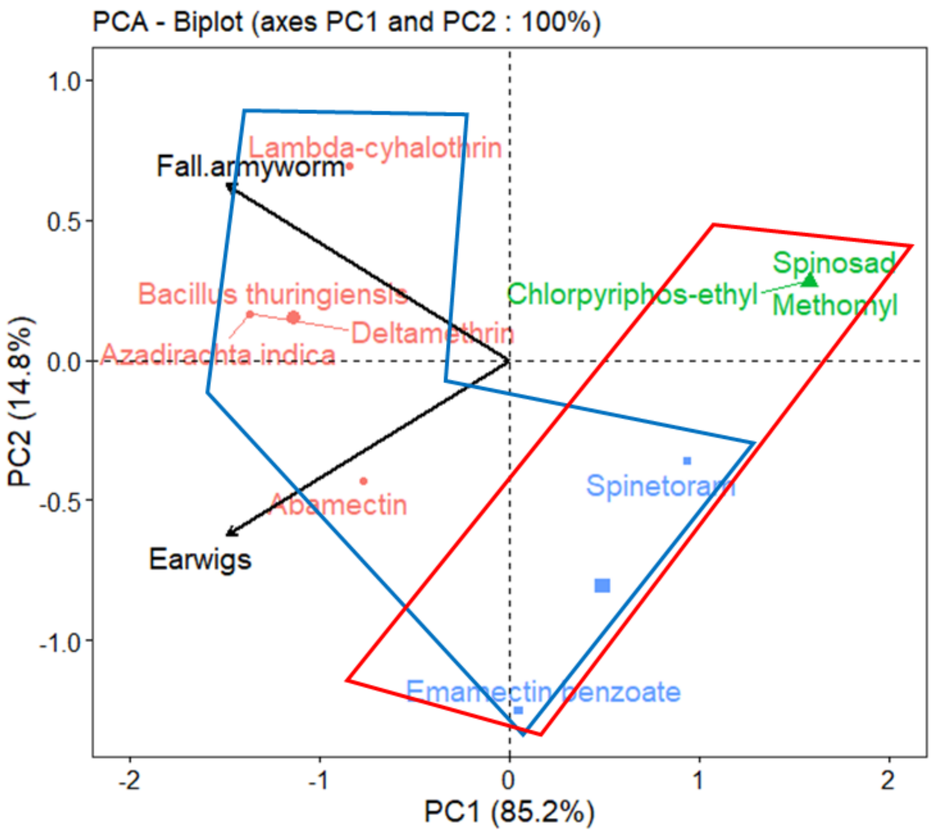

Figure 19. Principal component analysis of the effectiveness of insecticides on fall armyworm and earwigs. Arrowed lines represent the two insects used including fall armyworm (to be eliminated) and earwigs (to be preserved). In blue: insecticides highly toxic to fall armyworms and selective for earwigs. In green: insecticides highly toxic to fall armyworms and earwigs. In red: insecticides not toxic to the fall armyworms and earwigs.

5. *Discussion*

Our study was conducted in a context of associations of several natural enemies with the fall armyworm in West Africa after its invasion (Ahissou *et al.*, 2021a; Agboyi *et al.*, 2020; Koffi *et al.*, 2020). Among the predator complex identified in Burkina Faso, earwigs were by far the most abundant, especially in un-treated maize fields with chemical insecticides (Ahissou *et al.*, 2021b). Most of them are generalist predators that are considered to be major components of biological control agents for insect pests (Prasanna *et al.*, 2018; Cruz, 2007). Their conservation and promotion in the field is therefore an important strategy to promote biological control of arthropod pests.

Earwig *D. erythrocephalus* consumed an average of 90 eggs and 36 larvae of the fall armyworm per day in the present study. Similar results were found in Brazil and Argentina for *Euborellia annulipes* (Lucas) on fall armyworm eggs (da Silva *et al.*, 2009a; b) and *Doru luteipes* (Scudder) on fall armyworm larvae (Romero Sueldo *et al.*, 2010; Reis *et al.*, 1988). They are recommended for additional releases for biological control of fall armyworm in Brazil (Cruz, 2007). Clearly, these results show that earwigs could play an important role in the regulation of the fall armyworm in maize fields in Africa, particularly by consuming fall armyworm egg masses and early larval stages that are gregarious. Additional studies are needed to test the effectiveness of certain agricultural practices and plants in attracting earwigs in the field to contribute to biological control. For example, spraying a sugar solution on maize results in 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 (*M. minutiflora*, *D. uncinatum*, *D. intortum*) and trap crops (*P. purpureum*, *S. vulgare*) (Cook *et al.*, 2007).

Unfortunately, the performance of earwigs under natural conditions cannot be optimal if chemical insecticides are used in maize fields. Among the insecticides available on the local market, chlorpyrifos-ethyl, methomyl and the bioinsecticide spinosad are not selective for the predator. Their use should be avoided as much as possible and replaced by other insecticides more respectful of natural enemies. In contrast, emamectin benzoate, abamectin, deltamethrin, *A. indica* and *B. thuringiensis* showed interesting selectivity and safety profiles on earwigs, followed by lambda-cyhalothrin and spinetoram which were moderately toxic. The results confirm previous studies that reported that organophosphates and carbamates are generally broad-spectrum compounds with low selectivity for earwigs (Campos *et al.*, 2011; Zotti *et al.*, 2010), but not for the pyrethroids in this study.

However, all insecticides with a better profile against earwigs are not effective against fall armyworm and vice versa. The following insecticides were found to be effective on fall armyworm: emamectin benzoate, chlorpyrifos-ethyl, methomyl, spinetoram and spinosad, confirming previous work in Burkina Faso (Ahissou *et al.*, 2021a; 2022a). The widespread treatment failures mentioned by producers could therefore 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), or to resistance to these molecules. Given that high levels of fall armyworm resistance to these molecules have been reported in the Americas (Gutiérrez-Moreno *et al.*, 2019), 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.*, 2021a).

Several studies on insecticide selectivity involving predators and their prey have shown that predators are resistant to many insecticides and can be used as a biological control in conjunction with insecticides (Campos *et al.*, 2011; Lima *et al.*, 2020; Sawadogo *et al.*, 2022). Among insecticides that are effective in controlling fall armyworm in the present study, chlorpyrifos-ethyl, methomyl, and spinosad are highly toxic for the predator, while emamectin benzoate and spinetoram are selective. The latter two could therefore be used in fall armyworm integrated pest management programs in combination with earwigs or without affecting those available in the field. Azadirachtin insecticide, which was effective on the early stages of the fall armyworm, could also be used because of its selectivity towards the predator. This result is contradictory for both spinosad and methomyl, which had a better safety profile towards adult earwigs *D. luteipes*, while being effective against fall armyworm (Campos *et al.*, 2011). 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.

6. Conclusion

Earwigs could be excellent biological control agents for fall armyworm if they are present especially before egg laying and/or hatching. Alternatively, one way to keep these predators in maize fields to take advantage of their regulatory potential is to use only selective insecticides (such as emamectin benzoate and spinetoram) when the fall armyworm population reaches the economic threshold. These products can be safely used in maize when necessary, making chemical control compatible with the preservation of natural biological control.

Conclusion du chapitre 6

Malgré son introduction récente en Afrique, cette étude confirme l'association de plusieurs ennemis naturels avec la chenille légionnaire d'automne, dont des parasitoïdes (5), des prédateurs (13), un nématode parasite (Mermithidae) et un champignon entomopathogène. Ces résultats montrent que les agents de biocontrôle du continent ont élargi leur gamme d'hôtes en s'associant à la chenille légionnaire d'automne. Ils pourraient donc jouer un rôle important dans la régulation naturelle de ce ravageur et représentent une alternative durable et très prometteuse aux insecticides chimiques.

La mise en œuvre de pratiques agricoles et de méthodes de lutte favorisant leur maintien est donc indispensable dans les champs de maïs (lutte biologique de conservation). Par exemple, les insecticides chimiques sélectifs ou peu toxiques pour les ennemis naturels doivent être privilégiés dans les programmes de lutte. En outre, des études approfondies sur les facteurs locaux (gestion des cultures), les paysages (cultures et habitats non cultivés) qui favorisent les communautés de ces ennemis naturels et leur multiplication à grande échelle en vue d'un lâcher sont nécessaires pour un contrôle durable de la chenille légionnaire d'automne.

7

Discussion générale, perspectives et conclusion générale

Discussion générale et perspectives

Cette nouvelle espèce invasive a mis en évidence la nécessité de mener de nombreuses recherches pour une meilleure compréhension et une gestion durable du ravageur dans le contexte spécifique des zones nouvellement envahies. Les travaux menés au Burkina Faso au cours de cette thèse ont permis de générer des informations et des données importantes pour le développement et l'optimisation des stratégies de lutte contre la chenille légionnaire d'automne en Afrique de l'Ouest en particulier, mais aussi au-delà.

1. Changements de pratiques de gestion des insectes suite à l'invasion de la chenille légionnaire d'automne

La présente étude montre que l'invasion récente de la chenille légionnaire d'automne en Afrique constitue une menace pour la sécurité alimentaire, nutritionnelle et les revenus des producteurs agricoles en raison des dommages importants causés aux cultures. Bien que polyphage, ce ravageur a une préférence pour le maïs, qui est un aliment de base en Afrique et dont l'importance n'est plus à démontrer (Prasanna *et al.*, 2018). La plupart des agriculteurs interrogés ont reconnu et signalé les dommages causés par le stade larvaire de la chenille légionnaire d'automne sur le maïs principalement. Les infestations de 40 à 70 % signalées par les producteurs pourraient réduire considérablement le rendement du maïs en Afrique de l'Ouest. Au Nicaragua, des infestations de 55 à 100% des plantes de maïs peuvent entraîner des pertes de rendement allant de 15 à 73% (Hruska & Gould, 1997). Elles sont estimées entre 22 - 67 % au Ghana (Day *et al.*, 2017) et 40 - 49 % au Bénin (Houngbo *et al.*, 2020), ce qui représente une perte de revenu très importante. Ces pertes pourraient exacerber les difficultés socio-économiques des producteurs de maïs : remboursement des crédits d'intrants contractés auprès des institutions de microfinance et des commerçants, paiement de leurs employés, prise en charge des frais de scolarité de leurs enfants. Des situations similaires ont été signalées chez les maraîchers du Burkina Faso qui ont subi de plein fouet les conséquences de l'invasion de *T. absoluta* qui ravage la production de tomate (Sawadogo *et al.*, 2020c).

Les producteurs qui dépendaient principalement de l'action des ennemis naturels pour la régulation des insectes ravageurs du maïs ont dû urgemment investir dans l'acquisition et l'application d'insecticides chimiques (dont l'efficacité n'a pas été prouvée sur le continent) pour contrer cette menace (Ahissou *et al.*, 2021c; Caniço *et al.*, 2020a). Bien qu'une diversité de méthodes de lutte ait été mise en œuvre par les producteurs, la lutte chimique demeure prédominante. La même observation a été faite dans d'autres pays africains (comme la Zambie, le Ghana (Kansiime *et al.*, 2019; Rwomushana *et al.*, 2018), le Bénin (Houngbo *et al.*, 2020), le Kenya et l'Éthiopie (Kumela *et al.*, 2019)).

Dans un contexte d'inexistence d'insecticides chimiques homologués contre la chenille légionnaire d'automne, le choix des produits à utiliser demeure une véritable problématique. Par conséquent, les agriculteurs essayent la diversité des insecticides chimiques distribués par les différents gouvernements (Abrahams *et al.*, 2017b;

Tambo *et al.*, 2020) et ceux disponibles sur le marché pour lutter contre le ravageur. A cela s'ajoutent, les mauvaises pratiques d'utilisation des insecticides chimiques (utilisation des insecticides chimiques réservés pour la production cotonnière, non-respect des doses prescrites et du calendrier de traitement, non-respect des règles d'hygiène conseillées lors des traitements phytosanitaires) (Caniço *et al.*, 2020a) et leurs conséquences sur la santé humaine et l'environnement (Damalas & Eleftherohorinos, 2011; Desneux *et al.*, 2007). Il est donc important de former les producteurs qui ne peuvent généralement pas lire les notices sur les bonnes pratiques d'utilisation des produits phytosanitaires.

Par ailleurs, l'utilisation intensive et continue des insecticides chimiques conduit généralement au développement de la résistance dans les populations de ravageurs (Barzman *et al.*, 2015). Les insecticides couramment utilisés contre la chenille légionnaire d'automne appartiennent aux familles d'insecticides pour lesquelles des niveaux de résistance élevés ont été rapportés dans son aire d'origine (Gutiérrez-Moreno *et al.*, 2019; Yu, 1991). Cependant, aucune étude n'a encore été menée en ce sens en Afrique de l'Ouest. Etant donné que plusieurs échecs de traitements ont été signalés par les producteurs de maïs, il serait dès lors opportun d'identifier si les populations de chenille légionnaire d'automne sont résistantes aux insecticides utilisés. Malheureusement, les agriculteurs réagissent aux échecs des traitements par une augmentation des fréquences et doses d'insecticides, ce qui entraine une évolution de la résistance.

Outre le risque de développement de la résistance chez la chenille légionnaire d'automne, l'utilisation abusive des insecticides chimiques constitue une menace pour ses ennemis naturels présents dans les champs de maïs et pourrait altérer les services de régulation naturelle (Barzman *et al.*, 2015). Ces ennemis naturels constituent une première ligne de défense contre les insectes ravageurs du maïs et leur élimination pourrait accélérer le changement de statut de ravageurs secondaires de plusieurs autres espèces telles que *B. fusca*, *H. armigera* et *S. littoralis* (Van den Berg *et al.*, 2022). Par ailleurs, les ennemis naturels pourraient jouer un rôle important de régulation de la chenille légionnaire d'automne, comme c'est le cas en production de maïs de subsistance au Honduras, (Wyckhuys & O'Neil, 2006).

Bien que les producteurs soient conscients de l'existence de la plupart des arthropodes présents dans leur champ, ils ne peuvent généralement pas identifier le rôle bénéfique de beaucoup d'entre eux. En conséquence, les ennemis naturels ne sont pas épargnés lors des applications insecticides et les pratiques de préservation ne sont pas également mises en œuvre. Or, la conservation des ennemis naturels existants dans un environnement peut être simple et rentable, grâce à la manipulation de l'environnement, des systèmes de culture et des techniques disponibles localement pour améliorer leur efficacité.

La formation continue des agriculteurs est impérative pour améliorer leurs connaissances et compétences pour assurer une gestion durable des insectes ravageurs. Il est donc important de mener des études socioculturelles pour générer des recommandations de lutte intégrée flexibles pour répondre aux situations locales. Par ailleurs, la communication des résultats de recherche aux agents de vulgarisation et producteurs doit être améliorée par le biais de divers outils (parcelles de démonstration, champs-écoles de producteurs, posters, émissions de radio, etc.), tout en tenant compte des outils de communication modernes (applications mobiles et plateformes). Les producteurs devraient être formés sur l'impact des insecticides chimiques sur leur santé, surtout dans un contexte de faible utilisation d'équipements de protection et de respect des bonnes pratiques phytosanitaires.

2. *Dynamique annuelle de la chenille légionnaire d'automne et plantes hôtes*

Cette étude rapporte que la température moyenne annuelle et la pluviométrie au Burkina Faso sont favorables à la chenille légionnaire d'automne qui persiste toute l'année. Le suivi de la dynamique des populations montre qu'il n'y a pas de différence significative de prolifération entre la saison sèche et la saison de pluies (Ahissou *et al.*, 2022b). Une étude menée au Mozambique a montré que la chenille légionnaire d'automne est présente aussi bien en saison sèche qu'en saison des pluies, mais que les niveaux d'infestation et de dégâts sont plus élevés en saison sèche (Caniço *et al.*, 2020b). Cependant, la présence du maïs dans le paysage joue un rôle important dans l'abondance de la chenille légionnaire d'automne. Les zones de production de maïs tout au long de l'année en saisons sèche et pluvieuse, comme à Bama dans la province du Houet sont plus infestées par le ravageur. Ceci serait dû à la disponibilité du maïs, au chevauchement et à l'explosion exponentielle de plusieurs générations de l'insecte dans la zone. Le maïs, le petit mil et d'autres cultures qui sont très propices au développement de l'insecte (cycle court, survie élevée) pourraient permettre à 4 ou 5 générations de se succéder pendant la production et augmenter les pertes de rendement sur les cultures à cycle long. En conséquence, l'utilisation de variétés à cycle court et des semis précoces dans les zones où la production se fait uniquement en saison de pluies pourraient permettent d'éviter les fortes populations de la chenille légionnaire d'automne en fin de cycle.

Par ailleurs, les pics de pullulation de la chenille légionnaire d'automne sont synchronisés avec les principales périodes de production de maïs tant en saison sèche qu'en saison des pluies. Ces périodes correspondent généralement aux stades 6 - 12 feuilles du maïs (avant la floraison) après lesquels les captures deviennent moins importantes. Les femelles pondent généralement sur des plantes qui permettent la survie de leur progéniture. Des résultats similaires ont été obtenus dans une étude menée au Ghana pendant deux saisons des pluies successives (Nboyine *et al.*, 2020). Il est donc important de concentrer les applications insecticides avant le stade de floraison, car les feuilles sont encore tendres et plus sensibles aux dommages causés par les larves, contrairement aux feuilles qui durcissent et commencent à sécher avec le développement (Pannuti *et al.*, 2016). Par ailleurs, la période de floraison du maïs est caractérisée par une abondance d'ennemis naturels et de pollinisateurs (Ferrante *et al.*, 2017) qui devraient être préservés autant que possible de l'effet des traitements insecticides. Bien que la présente étude n'ait pas permis d'établir une relation entre l'abondance des adultes de la chenille légionnaire d'automne et les niveaux de dommages sur le maïs ; l'utilisation des pièges à phéromones permet de détecter rapidement le ravageur. Comme les derniers stades larvaires de la chenille légionnaire d'automne sont plus voraces (Luginbill, 1928; Ren *et al.*, 2020), plus longs (Hutasoit *et al.*, 2020; Wu *et al.*, 2021) et moins sensibles aux insecticides (Ahissou *et al.*, 2022a; Ghidiu & Andaloro, 1993), la détection des premiers stades larvaires devrait faire l'objet d'un programme de gestion intégrée efficace. Par ailleurs, une meilleure détection devrait prendre en compte toutes les cultures associées au maïs.

En outre, la chenille légionnaire d'automne a une grande capcité de migration et sa gestion nécessite des systèmes efficaces d'alerte précoce et de détection à grande échelle. A cet effet, plusieurs applications mobiles et plateformes ont été mises en place pour aider les producteurs à détecter rapidement et recevoir des informations importantes pour la lutte contre ce ravageur. Disponibles en plusieurs langues et faciles à utiliser, les applications FAMEWS et PlantVillage NURU sont facilement accessibles pour les producteurs disposant d'un smartphone (Njuguna *et al.*, 2021).

Compte tenu de la complexité de la dynamique de la chenille légionnaire d'automne (et de tous les insectes ravageurs), les études visant à établir une relation entre l'abondance de la chenille légionnaire d'automne et les niveaux de dégâts sur le maïs sont essentielles pour déterminer les seuils d'application des insecticides. Ces études doivent également prendre en compte l'influence des différents ennemis naturels présents dans la régulation du ravageur. En outre, l'Afrique de l'Ouest a probablement connu plusieurs entrées de la chenille légionnaire d'automne provenant de différentes sources. La région continue de présenter un risque élevé d'introductions de nouvelles populations de chenille légionnaire d'automne, avec des traits de résistance et une gamme d'hôtes plus larges, ce qui pourrait compliquer les efforts d'atténuation présentement mis en place (Nagoshi *et al.*, 2022). Il est donc nécessaire de renforcer les systèmes de surveillance phytosanitaire aux différents points d'entrée, afin de rendre la région moins vulnérable aux futures invasions de la chenille légionnaire d'automne et d'autres espèces.

3. Susceptibilité de la chenille légionnaire d'automne aux insecticides homologuées et bioinsecticides

En réponse à l'invasion de la chenille légionnaire d'automne en Afrique, plusieurs insecticides chimiques disponibles localement ont été utilisés massivement, bien qu'ils ne soient pas forcément efficaces pour lutter contre ce ravageur. Plusieurs échecs de traitement ont d'ailleurs été rapportés, ce qui amène les producteurs à augmenter les quantités d'insecticides (augmentation des fréquences et doses d'application) pour contrer ce ravageur. En conséquence, l'identification de produits efficaces contre la chenille légionnaire d'automne est primordiale pour prévenir l'utilisation excessive des insecticides chimiques. Pour y parvenir, nous avons mené des travaux pour évaluer la sensibilité de la chenille légionnaire d'automne aux insecticides chimiques et bioinsecticides disponibles localement, ce qui nous a permis d'obtenir une liste positive de produits pouvant lutter efficacement contre ce ravageur actuellement (Ahissou *et al.*, 2021a; 2022a). Il s'agit de l'émamectine benzoate, le méthomyl, le chlorpyriphos-éthyl, le spinétorame et le spinosad qui sont déjà homologués par le Comité Sahélien des Pesticides sur d'autres cultures et insectes ravageurs dans la région.

Les avermectines sont des insecticides de nouvelle génération et figurent actuellement parmi les plus efficaces contre les insectes ravageurs. L'émamectine benzoate et l'abamectine se sont révélées très efficaces contre les populations de *S.*

frugiperda de Porto Rico (Gutiérrez-Moreno *et al.*, 2019) et de *T. absoluta* du Burkina Faso (Sawadogo *et al.*, 2022). Contrairement à ces résultats, seul l'émamectine benzoate a présenté un meilleur profil d'efficacité contre la chenille légionnaire d'automne dans cette étude. Depuis l'invasion de la chenille légionnaire d'automne, l'émamectine benzoate fait partie des insecticides les plus efficaces utilisés par les producteurs de maïs en Afrique de l'Ouest. Par conséquent, il sera important de prévenir le développement de la résistance par une rotation rationnelle et un calendrier approprié des pulvérisations pour une utilisation durable de ce produit.

Le spinétorame et le spinosad qui ne sont vraisemblablement disponibles que pour la production cotonnière au Burkina Faso sont également très efficaces contre la chenille légionnaire d'automne. Le profil de sécurité environnementale très favorable du spinosad, qui est un mélange de spinosynes d'origine naturelle, et du spinétorame, qui est un produit spinosyne semi-synthétique, en fait des bioinsecticides utilisés en agriculture biologique (Bateman *et al.*, 2018; Campos *et al.*, 2014; Sparks *et al.*, 2021b). Des études antérieures ont également rapporté que ces insecticides sont hautement toxiques pour les populations de *S. frugiperda*, avec de faibles valeurs de CL_{80} pour le spinétorame au Brésil, en Chine, au Mexique et à Porto Rico (Gao *et al.*, 2021; Gutiérrez-Moreno *et al.*, 2019; Lira *et al.*, 2020; Zhao *et al.*, 2020) et pour le spinosad au Brésil, au Mexique et à Porto Rico (Campos *et al.*, 2011; Gutiérrez-Moreno *et al.*, 2019; Lira *et al.*, 2020; Storch *et al.*, 2017). Dans une étude menée au Bénin, le spinétorame et l'émamectine benzoate ont montré une bonne efficacité au champ avec des taux de réduction des plants de maïs attaqués par *S. frugiperda* de 70 et 55% respectivement (Bonni *et al.*, 2020). En outre, les concentrations sublétales de spinosynes ont également un effet négatif sur les insectes en prolongeant significativement la durée de vie des larves et en réduisant le poids de la chenille légionnaire d'automne (Gao *et al.*, 2021) et de *S. exigua* (Wang *et al.*, 2013) avec le spinétorame et le spinosad respectivement.

Contrairement aux résultats obtenus sur les populations de *S. frugiperda* de Porto Rico et du Mexique (Gutiérrez-Moreno *et al.*, 2019), le méthomyl (carbamate) et le chlorpyriphos-éthyl (organophosphate) sont plus performants que l'abamectine sur les populations collectées au Burkina Faso dans cette étude. Ces anciennes molécules présentent une plus faible probabilité d'échec du traitement par rapport à l'abamectine qui est l'une des plus récentes molécules disponibles sur le marché au Burkina Faso (Ahissou *et al.*, 2021a). Des preuves antérieures de niveaux élevés de résistance au méthomyl et au chlorpyrifos-éthyl ont été signalées au Brésil, au Mexique et à Porto Rico (Carvalho *et al.*, 2013; Gutiérrez-Moreno *et al.*, 2019; León-García *et al.*, 2012). Il ne serait pas surprenant de voir dans un avenir proche l'émergence de résistances à ces molécules en Afrique de l'Ouest, comme cela a été observé en Amérique.

Par contre, les pyréthrinoïdes (lambda-cyhalothrine et deltaméthrine), l'abamectine et le bioinsecticide à base de *B. thuringiensis* qui sont les insecticides les plus utilisés (à l'exception de l'émamectine benzoate) par les agriculteurs contre la chenille légionnaire d'automne se sont révélés inefficaces contre les populations du ravageur collectées au Burkina Faso (Ahissou *et al.*, 2021a). Les valeurs des concentrations létales (CL_{80} : efficacité minimale acceptée) sont généralement 7 – 17 fois supérieures aux doses recommandées par le fabricant, ce qui expliquerait les échecs de traitement sur le terrain d'une part et met en évidence les quantités d'insecticides et les risques liés à l'utilisation de ces produits pour éliminer ce ravageur d'autre part. Parallèlement, les pyréthrinoïdes font partie des molécules pour lesquelles une forte résistance de la chenille légionnaire d'automne a été enregistrée au Brésil, en Colombie et au Mexique (Carvalho *et al.*, 2013; León-García *et al.*, 2012; Ríos-Díez & Saldamando-Benjumea, 2011).

Dans cette étude, les bioinsecticides à base d'extraits de plantes (*A. indica*) sont généralement efficaces sur les premiers stades larvaires. Les doses recommandées par les fabricants sont inférieures aux valeurs de CL_{80} (efficacité minimale acceptée) nécessaires pour contrôler efficacement la chenille légionnaire d'automne. Pour mieux gérer ce ravageur, nous suggérons des efforts de surveillance pour détecter les premiers stades larvaires qui sont plus sensibles aux insecticides chimiques et bioinsecticides. Par ailleurs, les niveaux d'efficacité élevés obtenus avec l'*A. indica* au Bénin (Adeye *et al.*, 2018), au Malawi (Phambala *et al.*, 2020) et en Ethiopie (Sisay *et al.*, 2019a) seraient liés à la quantité d'azadirachtine variable dans les différents produits utilisés. En effet, les fluctuations saisonnières ont un impact sur la disponibilité et la quantité des métabolites secondaires produits par les plantes de Neem et Eucalyptus, et donc sur leur efficacité (Akiode *et al.*, 2021). Par conséquent, collecter et utiliser directement les différentes parties de ces plantes insecticides, sans tenir compte des quantités de métabolites, ne permet pas d'avoir des résultats stables dans le temps et l'espace. Sans une harmonisation des protocoles de production des biopesticides, les problèmes de dosage (sous-dosage ou surdosage) ne permettent pas d'avoir une idée exacte de l'efficacité des produits, et par conséquent leur homologation et adoption par les producteurs seront difficiles. Il est donc essentiel d'investir dans les infrastructures et les compétences technologiques nécessaires à la recherche et au développement des biopesticides efficaces en Afrique de l'Ouest.

4. *Gestion de la résistance aux insecticides chimiques*

La résistance résulte généralement de l'exposition répétée de plusieurs générations de ravageurs aux insecticides ayant le même mode d'action. Elle augmente avec une utilisation excessive ou une mauvaise application des insecticides (Barzman *et al.*, 2015; Gutiérrez-Moreno *et al.*, 2019; Sparks *et al.*, 2021b). La chenille légionnaire d'automne est connue pour avoir développé une résistance élevée aux insecticides appartenant aux familles chimiques des avermectines (groupe 5), carbamates (groupe 1A), organophosphorés (groupe 1B), pyréthrinoïdes (groupe 3A), et au *B. thuringiensis* (groupe 11A) dans son aire d'origine (Gutiérrez-Moreno *et al.*, 2019; Yu, 1991). Etant donné la forte probabilité que la chenille légionnaire d'automne soit arrivée en Afrique avec cette résistance, il est urgent de mettre en œuvre des stratégies de gestion de la résistance aux insecticides qui sont encore efficaces afin de retarder ou prévenir l'évolution de la résistance d'une part et rendre à nouveau sensibles les populations d'insectes ayant développées une résistance d'autre part.

Dans la pratique, la rotation, l'association et la réduction de la fréquence d'application des matières actives ayant des modes d'action différents donnent des résultats plus efficaces et durables. Dans cette étude, les produits efficaces contre la chenille légionnaire d'automne appartiennent à trois modes d'action différents : groupe 6 (émamectine benzoate), groupe 1A/1B (méthomyl et chlorpyriphos-éthyl respectivement) et groupe 5 (spinétorame et spinosad) (Ahissou *et al.*, 2021a; 2022a) qui peuvent être alternés. Une stratégie judicieuse d'utilisation en rotation basée sur différents modes d'action devrait être recommandée aux agriculteurs afin de ralentir le développement de la résistance à ces insecticides. Compte tenu de la durée moyenne d'une génération (30 jours), les générations successives de l'insecte ne devraient pas être traitées avec des produits ayant le même mode d'action. Conformément aux directives du Comité d'Action contre la Résistance aux Insecticides (IRAC), il est fortement recommandé d'utiliser des matières actives ayant des modes d'action différents pour des applications successives ou entre fenêtres de traitement de 30 jours (Figure 20). Par ailleurs, il faut prévoir 60 jours entre les applications d'insecticides d'un même mode d'action au-delà de la fenêtre de 30 jours. En conséquence, l'utilisation de l'émamectine benzoate pour toutes les applications pendant tout le cycle du maïs en raison de son efficacité actuelle (comme c'est le cas dans la région) risque de conduire rapidement au développement de la résistance dans un avenir prévisible (Figure 20). Par exemple, la sensibilité des populations brésiliennes de *S. frugiperda* à l'émamectine benzoate a considérablement diminué entre 2003 et 2021, avec des taux de résistance multipliés par plus de 400 (Muraro *et al.*, 2022).

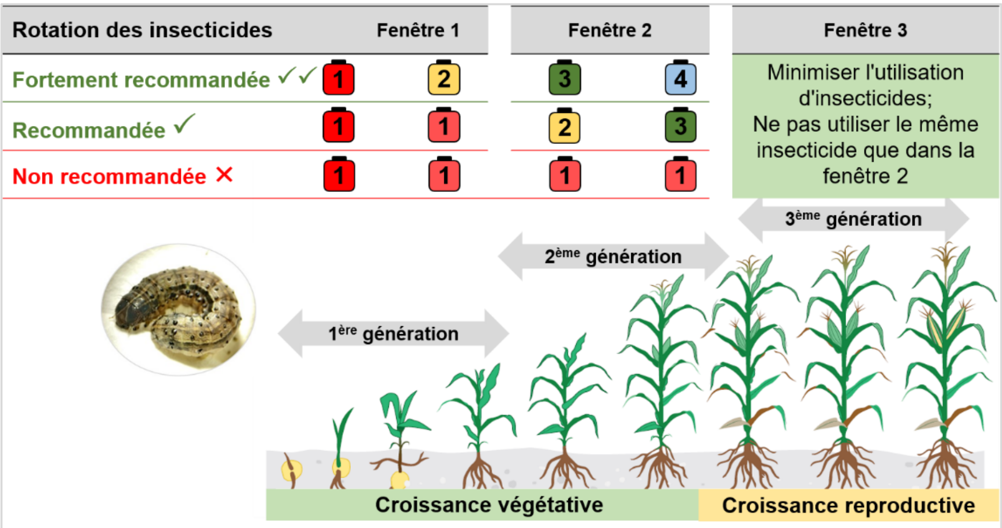

Figure 20. Programme de rotation des insecticides selon les modes d'action pour retarder le développement de la résistance chez la chenille légionnaire d'automne. Les combinaisons de chiffres et de couleurs dans les lignes représentent des insecticides ayant des modes d'action différents. (Adapté des recommandations du Comité d'Action contre la Résistance aux Insecticides : https:/www.irac-online.org/).

A l'heure actuelle, la lutte contre la chenille légionnaire d'automne et les principaux ravageurs des cultures repose essentiellement sur l'utilisation des insecticides chimiques en Afrique de l'Ouest. Il est donc essentiel de mettre en place (et continuellement mettre à jour) une liste positive d'insecticides chimiques et bioinsecticides homologués pour gérer efficacement les doses et fréquences d'application afin de réduire les quantités de produits appliquées et les risques environnementaux associés. Par ailleurs, la mise en place d'un réseau de laboratoires pour le suivi et la gestion de la résistance aux insecticides est essentielle pour concevoir des programmes régionaux de gestion, et pour préserver l'efficacité des matières actives disponibles. Des travaux supplémentaires sont également nécessaires pour déterminer les seuils à partir desquels la lutte chimique est indispensable.

5. Ennemis naturels de la chenille légionnaire d'automne

Les ennemis naturels indigènes des espèces nuisibles existantes apparentées constituent la première défense contre les nuisibles envahissants. Malgré son introduction récente en Afrique de l'Ouest, nous avons enregistré un total de 20 espèces d'ennemis naturels associés à la chenille légionnaire d'automne, y compris des parasitoïdes (5), des prédateurs (13), un nématode parasite (Mermithidae) et un champignon entomopathogène au Burkina Faso (Ahissou *et al.*, 2021b). Des travaux similaires ont rapporté l'association de plusieurs espèces de *Chelonus*, *Coccygidium* et *Drino* présents en Afrique de l'Ouest avec la chenille légionnaire d'automne au Sénégal (Tendeng *et al.*, 2019), au Bénin et au Ghana (Agboyi *et al.*, 2020; Koffi *et al.*, 2020) et au Mozambique (Caniço *et al.*, 2020a). Le taux de parasitisme était de 10,5 % et le complexe dominé par les nématodes, suivi des Braconidae et Tachinidae. Le complexe des prédateurs est dominé par les Forficulidae (51%), Formicidae (15%) et Coccinellidae (13%). Ces résultats montrent que les agents de biocontrôle présents sur le continent ont élargi leur gamme d'hôtes en s'associant à la chenille légionnaire d'automne et pourraient jouer un rôle important dans la régulation naturelle de ce ravageur.

Etant donné que l'établissement d'une relation équilibrée de contrôle entre les ennemis naturels indigènes et la chenille légionnaire d'automne ne soit pas immédiate (Caniço *et al.*, 2020a), les pratiques culturales favorisant leur action doivent être mises en œuvre afin d'optimiser le potentiel de la lutte biologique. En effet, les niveaux d'infestation du ravageur sont maintenus en dessous des seuils économiques au Honduras en raison de la diversité et du potentiel des ennemis naturels associés au ravageur (Wyckhuys & O'Neil, 2006). Pour y parvenir, il sera essentiel d'éviter l'application systématique et généralisée d'insecticides chimiques à large spectre qui sont également toxiques pour certains ennemis naturels. Par ailleurs, des méthodes simples pour attirer certains parasitoïdes et prédateurs consistent à appliquer de l'eau sucrée et de la soupe de poisson sur les feuilles de maïs (Canas & O'Neil, 1998; Harrison *et al.*, 2019). Les travaux menés en Éthiopie ont également rapporté une augmentation des prédateurs généralistes et la prédation des œufs de la chenille légionnaire d'automne en associant *P. vulgaris* au maïs (Kebede *et al.*, 2018). Il est également nécessaire de former les agriculteurs à la reconnaissance de ces précieux ennemis naturels qui sont parfois considérés à tort comme des ravageurs à éliminer à tout prix.

Plusieurs ennemis naturels indigènes qui contrôlent les insectes ravageurs du maïs et d'autres élargissent progressivement leur gamme d'hôtes en s'associant à la chenille légionnaire d'automne. Il est donc crucial d'élaborer des méthodes de lutte biologique avec ces prédateurs, parasitoïdes, nématodes et agents entomopathogènes locaux et de mettre en place des approches agroécologiques pour renforcer leur efficacité. Le rapport coût-efficacité des différents ennemis naturels doit être également pris en compte pour faciliter leur adoption. Par ailleurs, l'impact de la lutte chimique sur ces ennemis naturels doit être mieux évalué pour améliorer la lutte intégrée contre la chenille légionnaire d'automne.

6. *Perce-oreilles : Potentiel de prédation et sensibilité aux insecticides*

Pour optimiser la lutte biologique, il est crucial d'évaluer le potentiel de régulation des ennemis naturels et les paramètres pouvant affecter leur efficacité. Les perce-oreilles sont les prédateurs les plus abondants dans les champs de maïs, en particulier dans les champs non traités (Ahissou *et al.*, 2021b). En conditions de laboratoire, ils peuvent consommer jusqu'à 90 œufs ou 36 jeunes larves de chenille légionnaire d'automne par jour. Ces résultats montrent que les perce-oreilles pourraient jouer un rôle important dans la régulation de la chenille légionnaire d'automne dans les champs de maïs en Afrique de l'Ouest, notamment en consommant les masses d'œufs du ravageur et les premiers stades larvaires qui sont grégaires. Au Brésil, les perce-oreilles *E. annulipes* et *D. luteipes* sont recommandés pour des élevages en masse et des lâchers supplémentaires pour la lutte biologique contre la chenille légionnaire d'automne (Cruz, 2007).

Parmi les insecticides efficaces contre la chenille légionnaire d'automne, seuls l'émamectine benzoate et le spinétorame sont sélectifs pour les perce-oreilles, contrairement au chlorpyrifos-éthyl, méthomyl et spinosad qui leur sont très toxiques. En conséquence, les produits sélectifs pourraient être utilisés dans les programmes de lutte intégrée contre la chenille légionnaire d'automne sans affecter les perce-oreilles présents dans les champs de maïs. Par ailleurs, les bioinsecticides à base d'*A. indica* qui sont efficaces sur les premiers stades de *S. frugiperda* pourraient également être utilisés en raison de leur sélectivité vis-à-vis des prédateurs. La chenille légionnaire d'automne étant capable de développer rapidement une résistance aux insecticides chimiques, leur utilisation abusive et indiscriminée risque d'éliminer les ennemis naturels et empêcher la lutte biologique. Toutefois, des travaux supplémentaires sont également nécessaires pour évaluer les effets potentiels à long terme et la sécurité de ces composés pour les perce-oreilles et d'autres ennemis naturels sur le terrain.

7. *Lutte intégrée contre la chenille légionnaire d'automne et d'autres insectes importants*

La lutte intégrée est la meilleure stratégie pour gérer efficacement la chenille légionnaire d'automne en Afrique de l'Ouest. Individuellement, les différentes méthodes de lutte contre les insectes nuisibles n'offrent qu'une efficacité limitée. En revanche, le choix de méthodes complémentaires et compatibles dans le temps et l'espace permet une gestion optimale. La lutte intégrée contre la chenille légionnaire d'automne n'est pas une solution ''toute faite'', mais une combinaison de stratégies qui tient compte de la dynamique de l'insecte, du stade phénologique des plantes attaquées, de l'abondance des ennemis naturels, de la disponibilité de variétés résistantes, des bioinsecticides et des insecticides chimiques efficaces. Compte tenu de son potentiel de propagation, la gestion de ce ravageur devrait se faire de manière coordonnée à grande échelle et non sur une parcelle. Les différents résultats obtenus permettent d'intervenir à plusieurs niveaux.

- Pour la prévention, des semis précoces et des variétés à cycle court permettraient d'éviter de fortes infestations en fin de cycle, notamment dans les zones où la production ne se fait que pendant la saison des pluies.
- Pour la surveillance et la détection précoce, des pièges à phéromones suivis d'observations visuelles pourraient aider à confirmer rapidement la présence du ravageur et surtout des premiers stades larvaires qui sont plus faciles à éliminer.
- Pour la lutte curative, des bioinsecticides à base d'*A. indica* qui sont efficaces sur les premiers stades larvaires pourraient être utilisés en premier lieu. Enfin, l'émamectine benzoate, le spinétorame, le spinosad, le chlorpyrifos-éthyl et le méthomyl devraient être utilisés en dernier recours, en veillant à alterner les modes d'action pour les traitements successifs.
- En tenant compte du stade phénologique de la plante, les applications d'insecticides devraient être concentrées au stade végétatif du maïs. Après la floraison, le maïs est moins sensible et plusieurs ennemis naturels sont abondants à ce stade de développement. Si nécessaire, les insecticides à utiliser doivent être sélectifs ou moins toxiques pour les principaux ennemis naturels.
- Une attention particulière devrait être accordée aux ennemis naturels pour optimiser la lutte biologique qui est très prometteuse dans la région.

En outre, la lutte intégrée devrait également prendre en compte d'autres insectes ravageurs qui endommagent les cultures principalement associées au maïs. C'est le cas de *T. absoluta*, qui cause des dégâts importants sur la tomate. Dans les associations de cultures (tomate et maïs), les agriculteurs pourraient utiliser certains insecticides efficaces contre les deux ravageurs afin de réduire les applications d'insecticides. Il s'agit de l'émamectine benzoate, du spinosad, du spinétorame et du chlorpyrifos ethyl qui sont efficaces sur les populations de *T. absoluta* au Burkina Faso (Sawadogo *et al.*, 2022). Ces auteurs ont également signalé l'importance de *Gynandropsis gynandra* (L.) Briq (Capparaceae) pour la préservation de *Nesidiocoris tenuis* Reuter (Hemiptera : Miridae) qui est un prédateur de *T. absoluta* et des mouches blanches. Cette plante pourrait également servir d'hôte à certains ennemis naturels de la chenille légionnaire d'automne.

Conclusion générale

La chenille légionnaire d'automne est un ravageur envahissant qui a été signalé en Afrique pour la première fois en 2016. Elle a exacerbé les pertes de rendement des cultures céréalières de base, notamment le maïs, déjà menacées par d'autres stress, en particulier ceux induits par le changement climatique. Face à cette menace pour la sécurité alimentaire et les moyens de subsistance de millions d'agriculteurs, les réponses mises en place s'étaient appuyées essentiellement sur les connaissances et expériences de gestion du ravageur issues de son continent d'origine. Cependant, elles n'ont pas permis d'arrêter le ravageur qui s'est propagé très rapidement sur une grande partie du continent africain et même au-delà. Cette thèse a donc été initiée pour combler le gap de connaissances sur la chenille légionnaire d'automne dans le contexte Ouest africain, afin d'optimiser les mesures mises en place urgemment.

Les premières réponses pour supprimer le ravageur se sont essentiellement focalisées sur l'utilisation des insecticides chimiques, malgré leur efficacité douteuse et non prouvée. L'évaluation de la susceptibilité de la chenille légionnaire d'automne nous a permis d'obtenir une liste positive de produits pouvant lutter efficacement contre ce ravageur actuellement : émamectine benzoate, chlorpyriphos-éthyl, méthomyl, spinétorame et spinosad. Cependant, il est important d'utiliser des produits de différents modes d'action pour traiter les générations successives du ravageur (intervalle de 30 jours) pour prévenir le développement de la résistance. Les produits à base d'extraits d'*A. indica* ont également montré une bonne efficacité sur les premiers stades du ravageur, bien qu'une augmentation des concentrations recommandées soit nécessaire.

Le suivi de la dynamique des populations montre que la chenille légionnaire d'automne persiste toute l'année en raison de sa capacité de développement sur la diversité de cultures disponibles en saison sèche et pluvieuse. Cependant, les applications insecticides devraient être concentrées avant la floraison du maïs, où les populations de la chenille légionnaire d'automne sont les plus importantes dans les champs.

La lutte biologique de conservation est également prometteuse en raison de la diversité de parasitoïdes, des prédateurs, de champignon entomopathogène et de nématode parasite qui se sont associés à la chenille légionnaire d'automne. Il est donc important d'utiliser judicieusement les insecticides chimiques, et particulièrement ceux qui sont sélectifs pour ces ennemis naturels ; comme c'est le cas de l'émamectine benzoate, le spinétorame et les produits à base d'*A. indica* pour les perce-oreilles.

La communication des informations et résultats obtenus auprès des producteurs, vulgarisateurs et chercheurs à travers différents outils (parcelles de démonstration, champs écoles de producteurs, posters et émissions radio en langues locales, manifestations scientifiques, etc.) est nécessaire pour comprendre le comportement de la chenille légionnaire d'automne en Afrique de l'Ouest et permettrait d'établir des recommandations pour une gestion intégrée et durable de ce ravageur.

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Annexes

Publications, communications scientifiques et autres

Publications scientifiques

1. *Articles publiés*

Ahissou B. R., Sawadogo W. M., Bonzi S., Kambiré F. C., Somda I., Bokonon-Ganta A. H. & Verheggen F. J. Farmers' knowledge, perceptions, and management practices of the fall armyworm (*Spodoptera frugiperda* Smith) in Burkina Faso. *Accepted in Biotechnology, Agronomy and Society and Environment.*

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1. Présentations orales

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2. Posters

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Autres annexes

Supplementary material

Farmers' perception of the new invasive pest, fall armyworm *Spodoptera frugiperda* (Smith) and management practices in Burkina Faso

Objective: evaluate the knowledge, perceptions and management practices of the fall armyworm in maize production in Burkina Faso.

Period: August to November 2020.

IDENTIFICATION: LOCALITY AND FARMER CHARACTERISTIC

1. Province	....
2. Commune	....
3. Name of farmer	....
4. Telephone number	....
5. Gender	○ M ○ F
6. Age	....

7. What is your level of education?		
○No Literate	○Primary	○ Secondary
○ Higher	○Literate in local languages	

8. What are the main crops?		
○ Maize	○ sorghum	○ rice
○ groundnut	○ pearl millet	○ cowpea
If other, specify		

9. What is the size of your maize field (ha)?
○ ....

10. How long have you been involved in maize production?	
○ Less than 5 years	○ 5 - 10 years
○ 10 - 15 years	○ More than 15 years

11. What is your cropping system?	
○Monoculture (maize)	○ Maize and ....

12. How many maize crop cycle per year?		
○ 1	○2	○3

13. What is the method of weeding and the number of times per cycle?		
○ Manual	○chemical	○both

14. Do you belong to a farmer organization?	
○ Yes	○ No

15. Do you collaborate with research and other structures?	
○ Yes	○ No

16. Have you followed a training in plant protection?
○ No training taken
○ Use of chemical pesticides
○ Preparation and use of biopesticides
○ Recognition of pests and diseases
○ Recognition of natural enemies
○ If other, specify ....

KNOWLEDGE AND MANAGEMENT OF FALL ARMYWORM

17. Are you familiar with the fall armyworm? (Show eggs, larvae and adults to producer)?	
○ Yes	○ No

18. How do you recognize this pest?
○ Egg mass
○ Inverted "Y" on the head
○ Characteristic damage on maize plants
○ If other, specify ....

19. Which crops are affected by the pest?		
○Maize	○Rice	○Sorghum
○ Groundnut	○ If other, specify	

20. When did this insect infest your field?		
○ 2020	○ 2019	○ 2018
○ 2017	○ 2016	○ 2015
If other, specify		

21. Have you attended training on the recognition and management of fall armyworm?	
○ Yes	○ No

22. If Yes, who conducted the training?
○ Ministry of Agriculture
○ Farmer organization
○ NGOs
○ If other, specify ....

23. Do you do pesticide treatments before the fall armyworm arrives?	
○ Yes	○ No

24. What is the infestation level of your maize field? (Help farmer to estimate)	
○Low (<10% of plants)	○Medium (10 - 40%)
○ High (40 - 70%)	○Very high (> 70%)

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25. In your perception, what is percentage of loss? (Help farmer to estimate in %)
○ ....

26. What chemical pesticides do you use against the fall armyworm?
○ ....

27. How many chemical treatments do you use in maize cycle against this pest?
○ ....

28. What do you do if pesticides are not effective?
○ Increase the dose of pesticide
○ Increase the frequency of treatment
○ Mix pesticides
○ If other, specify ....

29. How do you choose chemical pesticides?
○ Advice from pesticide sellers
○ Advice from agricultural officer
○ Advice of another producer
○ Reading the pesticide label
○ Personal experience
○ If other, specify ....

30. What biopesticides do you use against Spodoptera frugiperda?
○ Neem
○ Chilli pepper
○ Tobacco
○ If other, specify ....

31. What preventive methods, physical and other management practices for fall armyworm do you use?
○ Early planting
○ Fertilization
○ Intercropping
○ Crop rotations
○ Handpicking of egg masses and larvae
○ Detergent, soap
○ Application of sand
○ Application of ash
○ If other, specify ....

32. Do you know of any natural enemies of fall armyworm? (Show photos of natural enemies to farmer)?
○ Ants
○ Spiders
○ Earwigs
○ Praying mantises
○ Birds
○ Mummified larvae
○ If other, specify ....

33. What are you doing to preserve these natural enemies?
○ Spare natural enemies when treating
○ Do not treat if natural enemies are abundant
○ Create refuges for natural enemies
○ Do nothing to preserve them
○ If other, specify ....

SAFETY AND MANAGEMENT OF PESTICIDES

34. In your opinion, what are the harmful effects of chemical pesticides?
○ Poisoning of humans
○ Toxicity to animals and useful insects
○ Pollution of water and soil
○ None
○ If other, specify ....

35. How do you protect yourself during pesticide application?
○ Ordinary clothes
○ Personal protective gear
○ Nose mask
○ Gumboots
○ Glasses
○ Shirtless (without shirt)
○ If other, specify ....

36. What symptoms do you notice after pesticide application?
○ Eyes or skin irritation
○ Headache
○ Vomiting
○ Stomach ache
○ General fatigue
○ No symptoms
○ If other, specify ....

37. What do you do if you experience symptoms?
○ Do nothing
○ Go to the hospital
○ Drink milk (before and after application)
○ Wash with soap
○ Rest in the shade
○ Wash or scrub with lemon or potash
○ If other, specify ....

38. Do you have a particular comment?
○ ....

Thank for your participation in this survey.

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