**UNIVERSITY FOR DEVELOPMENT STUDIES**

# EVALUATION OF SYNTHETIC INSECTICIDES FOR CONTROL OF FALL ARMYWORM (*SPODOPTERA FRUGIPERDA,* J.E. SMITH) IN THE GUINEA SAVANNAH AGRO ECOLOGY OF GHANA

**BY**

**JERRY KUUNEBIER SOYEL**

**(UDS/MCS/0009/17)**

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FACULTY OF AGRICULTURE

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BY

JERRY KUUNEBIER SOYEL

B.Sc. (AGRIBUSINESS)

(UDS/MCS/0009/17)

THESIS SUBMITTED TO THE DEPARTMENT OF AGRONOMY, FACULTY OF AGRICULTURE, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN CROP SCIENCE

NOVEMBER, 2020

# DECLARATION

I hereby declare that this thesis is the results of my own research conducted and no part of it has been presented for another degree in this University or elsewhere. Work of others which served as useful information has been duly acknowledged.

**Jerry Kuunebier Soyel** ........................... ..................

(Student) Signature Date

**Supervisors'**

We hereby declare that the preparation and presentation of this thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

**Dr. Benjamin K. Badii** ....................... .... ...............

(Principal Supervisor) Signature Date

## ABSTRACT

The Fall Armyworm (FAW), *Spodoptera frugiperda* (J.E Smith) is an alien invasive insect pest in tropical Africa. The recent spread of the pest to Ghana has triggered rampant spraying of all sorts of synthetic insecticides to control the pest. Studies were conducted to evaluate nine synthetic insecticides belonging to different chemical groups for their efficacy against the FAW in maize. The effects of the insecticides on larval mortality were evaluated in laboratory bioassay at 12 hr. to 96 hr. of exposure, and subsequently in the field to assess their efficacy and impact on maize yield. Completely randomized design (CRD) and randomized complete block design (RCBD) were used for the laboratory and field experiments, respectively. There were significant differences among the treatments. From the laboratory results, the highest larval mortality (100%) was recorded on Emamectin Benzoate 12g/L + Acetamiprid 64g/L (Ema star) and Emamectin Benzoate 12g/L + Imidacloprid 50g/L (Dean) treatments. This was followed by those of Emamectin Benzoate 1.9% (Wv) EC + Nonhazardous Ingredient 98.1% (Attack) and Chlorpyrifos 400g/L + Deltamethrin 24g/L EC (Pyrinex quick) which recorded 96% and 50% mortality, respectively. The least mortality (13%) was observed in Imidacloprid 250g/L + Bifenthrin 50g/L (Galil), Azadirachtin (Neemazal) and Teflebenzuron 75g/L + Alphacypermethrin 75 g/L (Normax). Results of the field trial indicated that Emamectin Benzoate 12g/L + Acetamiprid 64g/L (Ema star) significantly reduced population of FAW and number of infested whorls compared to those of the control and the other insecticide treatments. However, mortality from Emamectin Benzoate 12g/L + Acetamiprid 64g/L (Ema star) treatment was not significantly different from that of Emamectin Benzoate 12g/L + Imidacloprid 50g/L (Dean). Moreover, there were significant differences in maize yield among the insecticide treatments. Maize plants sprayed with Emamectin Benzoate 12g/L + Acetamiprid 64g/L (Ema star) and Emamectin Benzoate 12g/L + Imidacloprid 50g/L (Dean) yielded almost three times the yield of the control and the other insecticide treatments Azadirachtin (Neemazal), Teflebenzuron 75g/L + Alphacypermethrin 75 g/L (Normax) and Imidacloprid 250g/L + Bifenthrin 50g/L (Galil). Therefore, Emamectin Benzoate 12g/L + Acetamiprid 64g/L (Ema star) and Emamectin Benzoate 12g/L + Imidacloprid 50g/L (Dean) were the most recommended insecticides for the control of FAW and for maximum productivity of maize in the savanna ecology of Ghana.

## ACKNOWLEDGEMENTS

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## DEDICATION

I dedicate this work to all my family members.

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# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background

The Fall Armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), is a moth native to the humid and sub humid areas of the Americas, Argentina, and the Caribbean. It is a key insect pest of maize in Brazil and other countries (Knipling, 1980; Pashley *et al.*, 1985). This migrant and economically important pest causes considerable losses in maize, sorghum, forage grasses, turf grasses, rice, cotton, and peanut production (Sparks, 1979). The first report of its presence on the African continent was in January 2016 in south-west Nigeria and shortly after in Ghana Benin, Sao Tome and Togo (Goergen *et al.*, 2016; Cock *et al.*, 2017). The pest has since spread across Sub-Saharan Africa except in Djibouti and Lesotho (FAO, 2018). Caterpillars of *S. frugiperda* appear much to be destructive to maize in West and Central Africa than other African *Spodoptera* species (Goergen *et al.*, 2016). In Ghana, it was first reported on maize in the Eastern region in April 2016, but now present in all the other regions and still spreading within the regions (Abraham *et al.*, 2017). Although the FAW is an extremely polyphagous insect pest that can feed on over 80 plant species (Prasanna *et al.*, 2018), major crop attacked in Africa is maize. Maize is regarded as a significant crop and a prime staple food crop in Africa. The attack of the worm threatens the food security of millions in SubSaharan Africa (SSA) (Rwomushana *et al.*, 2018; Prasanna *et al.*, 2018). The FAW could possibly account for losses projected at 8.3 to 20.6 m tons of maize per year valued at US$2481–6187 m in 12 maize producing nations in Sub-Saharan Africa (SSA).

This figure could account for almost 20% of the overall production in the region (Abraham *et al.*, 2017).

## 1.2 Problem statement

The *Spodoptera frugiperda* displays a strong appetite for plant species in the family, Poaceae. Other economically important crops that are attacked and damaged by FAW include sugar cane, beet, tomato, potato, cotton and pasture grasses (Abraham *et al.*, 2017; Day *et al.*, 2017). However, maize is the main host in Ghana. The caterpillar causes injury to the plant by damaging the leaves. The young caterpillars principally feed on the epidermal tissue of the leaf leaving holes in the leaves, which is the characteristic damage symptom of FAW (Day *et al.*, 2017). Feeding on undeveloped plants via the leaf whorl causes dead heart. At the reproductive stage of the maize the caterpillar feeds on the cob and kernels inside reducing yield and quality (Capinera, 2002).

The primary management strategy for agricultural pest especially FAW is the use of chemical insecticide. However, there are reported cases of resistance development of FAW against numerous chemical insecticides (Yu, 1991; Abrahams *et al*., 2017). According to Abrahams *et al.* (2017), the resistance of FAW to chemicals has been reported to mode-of-action categories 1A (Carbamates) 1B (Organophosphates), and 3A (Pyrethroids-Pyrethrins).

The estimates indicate that key maize producing countries in Africa combined will possibly lose yields between 8.3 and 20.6 million tonnes per year of the total expected production of 39 million tonnes per year. This denotes a range of 21-53% of the yearly production of maize averaged over three years in these countries. The worth of these losses was valued at between US$2.48 billion and US$6.19 billion (Day *et al.,* 2017).

In Ghana, 1,400 hectares of farmland was initially affected in May 2017 and eventually increased to more than 112,000 hectares of farmland attacked by the pest (Tamakloe, 2018). Out of a total 249,054 hectares of maize attacked by the FAW, 234,807 hectares was recovered by using chemical insecticide. It was estimated that Ghana may lose up to $163 million in 2017 as a result of the invasion (Tamakloe, 2018). This suggests the need for screening synthetic insecticide to sustainably control this invasive pest.

## 1.3 Justification

Consequent to the introduction of FAW in Ghana, chemical insecticides have been the common control measure used to manage maize fields. Even though synthetic insecticides play a significant role in managing the pest, there are reports of insecticide resistance in the pest populations elsewhere (Yu, 1991). This therefore calls for integrated pest management to successfully control FAW. According to Durmuşoğlu *et al.,* (2015), chemical synthetic insecticides are still considered the mainstay of agricultural pest control. The government of Ghana procured 72,774 liters of liquid pesticides and 4, 320 milligrams of powdered pesticides for application in the affected areas (MoFA, 2017) in attempt to curb this invasive pest despite the unavailability of adequate information on the efficacy of the chemicals on the pest.

Apart from the pesticides supplied by the government, farmers often use any synthetic insecticides on the market that is believed to instantly suppress the pest during outbreaks. In most cases these pesticides are for a broad spectrum of insect pests of vegetables and legumes. Hence there is inadequate information on the efficacy of these synthetic pesticides on the Ghanaian market in control of fall armyworm. Farmers use doses higher than the manufacturer recommended dose and repeated applications, because there were reports of insecticides not effective on the worm. The repeated application with higher doses will eventually lead to resistance build-up and accumulation of residues with consequent environmental health issues (Sisay *et al.,* 2019).This and many other factors calls for attention to screen these synthetic insecticide for their efficacy to manage the pest and preserve life of users and the environment.

### 1.4 Objectives

This study sought to evaluate nine major insecticides recommended for the control of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) in the Guinea Savanna Agro ecological zone of Ghana.

1. To evaluate the efficacy of the insecticides on the larval mortality under laboratory condition.
2. To evaluate the efficacy of the insecticides on larval mortality and the impact on the yield of maize under field condition.

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 Description of fall armyworm

The fall armyworm *Spodoptera frugiperda* (Insecta: Lepidoptera: Noctuida) (J.E. Smith) is a very difficult insect pest to control in field maize. It comes from the order of lepidoptera. The term "armyworm" relates to the immense invasive actions of the species larval stage.

A diagram representing scientific classification of Genus Spodoptera

Domain: Eukaryota
    Kingdom: Metazoa
        Phylum: Arthropoda
            Subphylum: Uniramia
                Class: Insecta
                    Order: Lepidoptera
                        Family: Noctuidae
                            Genus: Spodoptera
                                Species: frugiperda
                                        Scientific Name: Spodoptera Frugiperda

The scientific name, *Spodoptera frugiperda*, discusses the grey-patterned wings of the moths and the fruit destroying habits of the caterpillars. The common name is fall armyworm because of the mass movements of the caterpillars in the Fall

(Wikipedia). The fall armyworm has several features that make it difficult to control. The adult females of FAW are highly fertile and can lay in excess of

1000 eggs during their lifetime (Nagoshi *et al.*, 2018). The fact that they can attack several plant species makes control problematic. The most damaging reports from its innate range are for maize causing large economic damage. The moth is a strong flyer, flying across continents. Another remarkable trait of the larva is that they practice cannibalism. (Nagoshi *et al.*, 2018).

The persistent abundance of the fall armyworm during the past several years has increased efforts to achieve a more comprehensive understanding of the ecology of this pest so that effective monitoring and control strategies can be developed. Information concerning the way parasites affect the population dynamics of this pest is essential if these natural mortality agents are to become significant components of an integrated management program (Ashley, 1979).

## 2.2 Origin and distribution of fall armyworm

The fall armyworm is innate to humid areas of the western hemisphere from the United States to Brazil and Argentina (Sarmento *et al.*, 2002; Ferreira *et al.*, 2010). According to Visser (2017), the *Spodoptera* genus has 31 species in the world. This species *Spodoptera frugiperda* is innate to the American continent with eight species in the African continent. Existence of fall armyworm populations throughout winter months in the United States is only detected in Southern Florida and Southern Texas (Pair *et al.*, 1991; Nagoshi *et al.*, 2017). *Spodoptera frugiperda* has an extraordinary dispersion capacity (Johnson 1987), a feature that is known to have advanced as part of its life history (Nagoshi and Meagher 2008). Through yearly movements, it can travel northwards from its dominant area in the warmer parts of Central and South America. It moves over

2000 km across the USA, Canada and southwards, reaching the northern parts of Argentina and Chile (Pair *et al*.,

1986; Johnson 1987; Nagoshi *et al.*, 2017). By means of its recent invasion into Africa, *S. frugiperda* stretched its dispersal to districts outside the tropics of the Americas and the Caribbean (Pogue 2002).

The pest at present has been identified in over 30 countries including Cape Verde, Madagascar, São Tomé and Príncipe, and the Seychelles (Rose *et al*. 1975). The pest is a multigenerational pest in Africa owing to its favorable agro-ecological conditions (Rose *et al*. 1975). As a new pest it will pose some degree of risk to the agricultural environment. Some distinguishing factors that make the FAW more damaging is the fact that it spreads quickly and covers large geographic areas. The moth can travel over 500 km (300 miles) before oviposition (Rose *et al*. 1975). Similarly, the moths can move much longer distances: for example, a flight of 1,600 km from the southern U.S. state of Mississippi to southern Canada in 30 hours has been recorded (Rose *et al*. 1975). Secondly the larva is polyphagous making it one of the most damaging crop pests.

The fall armyworm movement each year usually generates sporadic difficulties across several crops, including cotton, *Gossypium hirsutum* (L.) (Hardke *et al*., 2015). Fall armyworm out-breaks and consequent harm can be volatile. When epidemics do happen, the severity of the problem is compounded by the ability of fall armyworm to attack a range of crops causing overwhelming crop losses (Hardke *et al*., 2015) The timing of this happening matches the recurrent northward movement of warmer temperatures and maize planting that follows the winter season, besides air transport systems advantageous to northward long-distance flight (Westbrook *et al.*, 2016). Estimates from a migration model based on these factors precisely forecast fall armyworm migration patterns as confirmed by genomic haplotype studies (Westbrook *et al.*, 2016). Nevertheless, because climate farming practices, and wind patterns are considerably diverse from North America, fall armyworm migrant conduct in Africa is indeterminate, a constraint to the development of regional and area-wide strategies for sustainable pest management (Nagoshi *et al.*, 2018).

The ostensibly swift spread of the pest in Africa advocates a robust migrant movement that would be consistent with fall armyworm conduct in North America. Swarms extend as far north as Canada, the result of year long-distance migrations from wintering areas limited in North America to the southern portions of Florida, Texas, the Caribbean, Mexico and Africa (Mitchell *et al.*, 1991; Pair *et al.*, 1991; Nagoshi *et al.*, 2012).

### 2.3 Population dynamics of *s. frugiperda*

Nagoshi and Meagher (2004) reported that population surveys in southern Florida corn fields typically shows a rise in the overall fall armyworm population in the spring, followed by a rapid and prolonged decline during the summer months that presumably reflects the northward annual migration of the pest. After the summer decline in the south, fall armyworm populations begin increasing in the fall and winter in agricultural areas, coincident with the late-year corn growing season (Nagoshi and Meagher 2004). The timing of this increase was shown to correlate with weather and wind conditions conducive to southward migration, leading to the suggestion of a north-to-south return movement before the winter freeze (Pair *et al*., 1986; Mitchell *et al*., 1991). Seasonal monitoring of FAW using sex pheromones for two years at eight locations from French Guiana northward to Canada showed a seasonal progression of movement by fall armyworm from the southernmost locations in the United States into Canada (Mitchell *et al*., 1991).

Area-wide management programs designed to cause changes in fall armyworm population dynamics in the overwintering areas can significantly alter the magnitude of the northward migration (Knipling 1980; Mitchell *et al*., 1991; Nagoshi and Meagher 2004). In addition to long-distance migration, understanding movement of FAW between crop fields is also important to develop an appropriate management strategy (Sparks, 1979,1986; Barfield *et al*.,1980). Martinelli *et al*. (2006, 2007) observed a considerable gene flow between FAW populations collected from cotton and cornfields in Brazil. This movement of FAW between different fields and host plants needs stewardship of crop protection methods for managing FAW to reduce the incidence of pesticide resistance due to the spatial and temporal overlapping of maize and cotton crops in some regions (Martinelli *et al*., 2007). Similarly, Nagoshi *et al*., (2006, 2007) found that the FAW infesting cotton in Mississippi comes from corn and suggested that cornfields provide an important refuge for the FAW strain infesting cotton and that late-season populations in the Mississippi delta may be migrants from more northern corn areas. The species overwinters in southern Florida and southern Texas, which serve as sources of the springtime populations that migrate northward into the central and eastern United States and Canada (Barfield *et al*., 1980; Johson,1987).

This capacity for a long-distance movement, up to 480 km/generation (Sparks, 1986), has contributed to the widespread distribution of the FAW in the Western Hemisphere (Nagoshi *et al*., 2007). This seasonal migration of FAW could occur in response to seasonal changes in rainfall, temperature, and planting of host plants (Westbrook *et al*., 2016). Moreover, prevailing winds and frontal systems with their converging air masses during the spring are thought to largely determine the extent and direction of FAW adult migration (Pair *et al*., 1986).

### 2.4 Geographic distribution of *s. frugiperda*

Studies on annual migration of fall armyworm in North America can be made by comparing chemical or viral susceptibility of fall armyworm populations from different locations (Fuxa, 1987; Pitre, 1988; Nagoshi *et al*., 2008), monitoring adult moths by pheromone trapping and radar (Rose *et al*., 1975; Pair *et al*., 1987), and correlating trap collections with wind and weather patterns (Luginbill, 1928; Pair *et al*., 1986; Westbrook and Sparks, 1986). However, the resolution of these detection methods is very low and more accurate and efficient molecular techniques should be employed which can identify strain-specific migration (Nagoshi *et al*., 2008).

Haplotype analysis to study migration of FAW corn strain populations in Louisiana, Mississippi, and Alabama were statistically indistinguishable from populations sampled in central and southern Texas suggesting the fall armyworm overwintering in Texas migrate north and eastward through Louisiana, Mississippi, and into Alabama, whereas Florida populations move northward into Georgia (Nagoshi *et al*., 2008). Brazilian FAW populations collected from corn and rice and found that the sex-linked tandem repeat element called FR, which was previously shown to have a strain-biased distribution in North American populations, suggested the presence of gene flow between the Brazilian and North American FAW populations (Machado *et al*., 2008).

In January 2016 major outbreaks of fall armyworm were reported in south-west Nigeria, and Ghana, and shortly after in Benin, Sao Tome and Togo (Goergen *et al*., 2016; Cock *et al*., 2017). It was initially confused with the native armyworm but morphological and molecular analysis by IITA found that the armyworms were *S. frugiperda* and not the native armyworm *S. exigua* or *S. exempta* (Goergen *et al*., 2016). As at September 28, 2017, 28 sub-Saharan African countries had confirmed the presence of fall armyworm with nine more countries suspecting or awaiting confirmation of the species' presence, within these countries is still the spreading of the fall armyworm (Njeru, 2017). The pest has spread across Sub-Sahara Africa except in Djibouti and Lesotho (FAO, 2018). Caterpillars of *S. frugiperda* appear to be much more damaging to maize in the west and central Africa than most other African *Spodoptera* species (Cock *et al*., 2017; Goergen *et al*., 2016). This is causing immense concern among agricultural experts, due to the potentially huge amount of damage this invasive species will do to African food crops if allowed to spread. According to the coordinator of the fall armyworm task force, USAID Bureau for food security, the pest is here to stay in Africa (Tamakloe, 2018).

In Ghana the caterpillar of fall armyworm was first reported on maize in the Yolo Krobo municipality of the eastern region of Ghana by a plant doctor in April 2016, Figure 2.1 but now present in all the ten regions and within these regions is still the spread of the fall armyworm (Abraham *et al*., 2017). In 2016, a team from Plant Protection and Regulatory Service Directorate (PPRSD) went around to collect samples of different stages of the caterpillars across the country. The samples were sent to the CABI diagnostic laboratory in the United Kingdom for molecular diagnosis. It was identified as *Spodoptera frugiperda* (J. E. Smith). Initially, farmers taught it was a new type of stem borers. However, when it was not responding to the initial control, they started reporting to agricultural extension agents. The fall armyworm has a wide range of hosts in Ghana, but the main host is maize but also severely affect cowpea and sugarcane. It is difficult to control because it hides in the whorl of the maize plant.

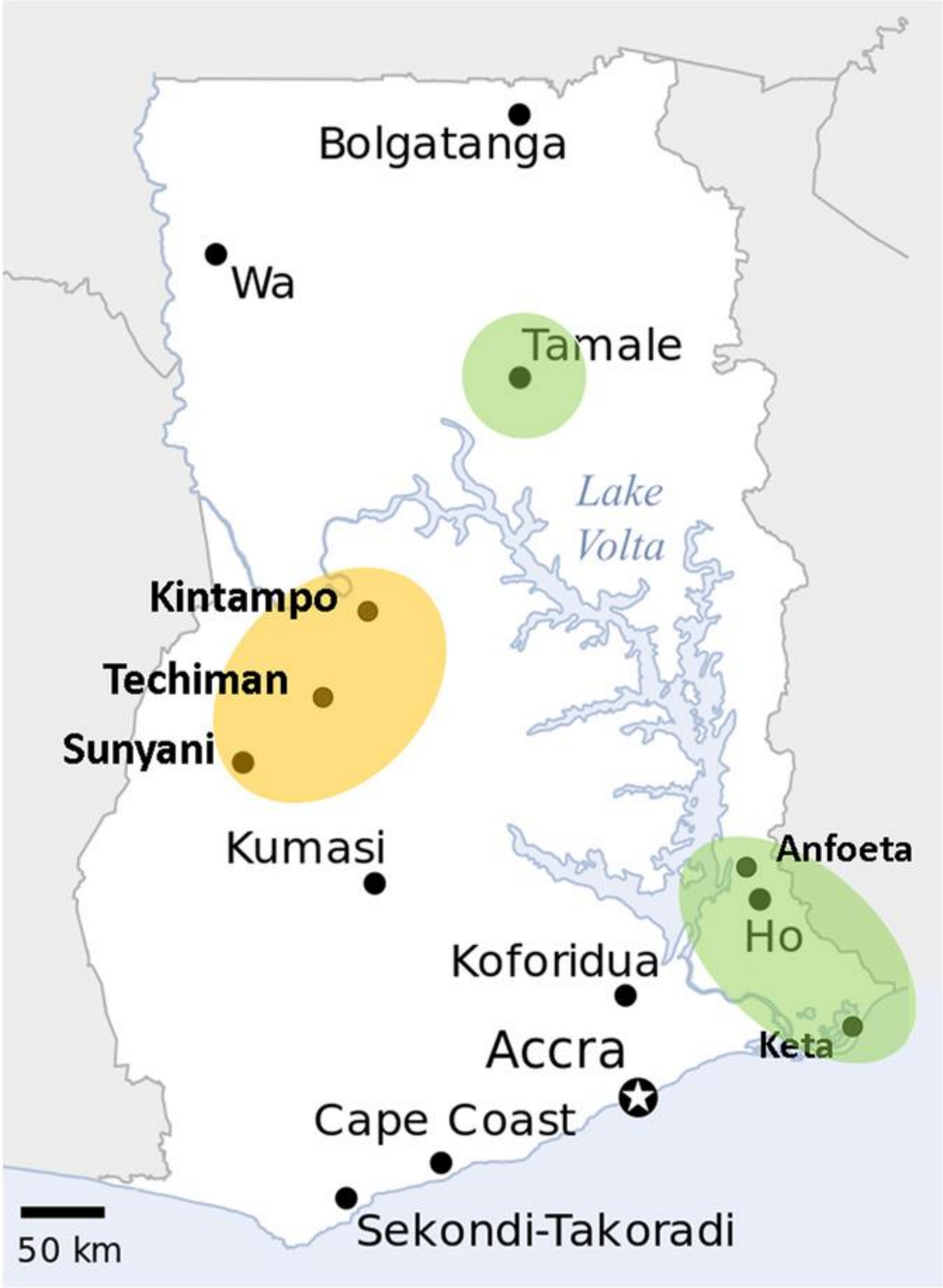

**Figure 2.1 Fall Armyworm Distribution in Ghana in 2016**

### 2.5 Host plant range of fall armyworm

The FAW has a very wide host range, with over 80 plants recorded. There is some evidence that fall armyworm strains exist, based primarily on their host plant preference. One strain feed principally on corn, but also on sorghum, cotton and a few other hosts if they are found growing near the primary hosts.

The other strain feeds principally on rice, Bermuda grass, and Johnson grass. As a polyphagous pest, the FAW shows a definite preference for the Poaceae. However, host of fall armyworm ranges over 80 plant species classified as

- Primary (main),
- Secondary (other) and
- Wild hosts. Despite, the most commonly recorded from wild and cultivated grasses, from maize, rice, sorghum, and sugarcane. (Table 2.1)

**Table 2.1: Some examples of plants attacked by FAW.**

| **Plant Name** | **Family** | **Context Type** |
|---|---|---|
| *Zea mays* (maize) | Poaceae | Main |
| *Spinacia oleracea* (spinach) | Chenopodiaceae | Main |
| *Solanum tuberosum* (potato) | Solanaceae | Main |
| *Musa* (banana) | Musaceae | Main |
| *Ipomoea batatas* (sweet potato) | Convolvulaceae | Main |
| *Zea mays* sub sp Mexicana (teosinte) | Poaceae | Other |
| *Capsicum* (peppers) | Solanaceae | Other |
| *Vitis* (grape) | Vitaceae | Other |
| *Vigna unguiculata* (cowpea) | Fabaceae | Other |
| *Malus domestica* (apple) | Rosaceae | Other |
| *Ipomoea purpurea* (tall morning glory) | Convolvulaceae | Wild host |
| *Solanum* (nightshade) | Solanaceae | Wild host |
| *Andropogon virginicus* (broomsedge) | Poaceae | Wild host |
| *Cenchrusincertus* (Spiny burrgrass) | Poaceae | Wild host |
| *Chenopodium album* (fat hen) | Chenopodiaceae | Wild host |

## 2.6 Fall armyworm description and life cycle

### 2.6.1 Description

Eggs are laid at night on the leaves of the host, stuck to the lower surface of the lower leaves, in tight clusters of 100-300 and sometimes in two layers, usually covered with a protective layer of abdominal bristles (Day *et al.,* 2017).

Hatching requires 2-10 days usually 3-5 (Day *et al.*, 2017). The young larvae feed deep in the whorl; the first two instars feed gregariously on the underside of the young leaves causing a characteristic skeletonizing or 'windowing' effect (Day *et al.*, 2017). Larger larvae become cannibalistic and thus one or two larvae per whorl are usual. The rate of larval development through the six instars is controlled by a combination of diet and temperature conditions, and usually takes 14-21 days. (Day *et al.*, 2017). Larger larvae are nocturnal unless they enter the adult phase when they swarm and disperse, seeking other food sources. Pupation takes place inside a loose cocoon in an earthen cell, or rarely between leaves on the host plant, and 9-13 days are required for development (Day *et al.*, 2017). Adults emerge at night, and they typically use their natural pre-oviposition period to fly for many kilometers before they settle to oviposit, sometimes migrating for long distances. On average, adults live for 12-14 days (Day *et al.*, 2017).

FAW is a tropical species adapted to the warmer parts of the New World; the optimum temperature for larval development is reported to be 28°C, but it is lower for both oviposition and pupation. In the tropics, breeding can be continuous with four to six generations per year, but in northern regions only one or two generations develop. At lower temperatures, activity and development cease, and when freezing occurs all stages are usually killed. In the USA, FAW usually overwinters only in southern Texas and Florida. In mild winters, pupae survive in more northerly locations (Ramirez *et al.*, 1987).

### 2.6.2 Life cycle of fall armyworm

The life cycle is completed in about 30 days during the summer, but 60 days in the spring and autumn, and 80 to 90 days during the winter. The number of generations occurring in an area varies with the appearance of the dispersing adults. The ability to diapauses is not present in this species. In Minnesota and New York, where fall armyworm moths do not appear until August, there may be but a single generation.

The number of generations is reported to be one to two in Kansas, three in South Carolina, and four in Louisiana (John and Capinera, 2017). Figure 1 illustrates the lifestyle of the moth.

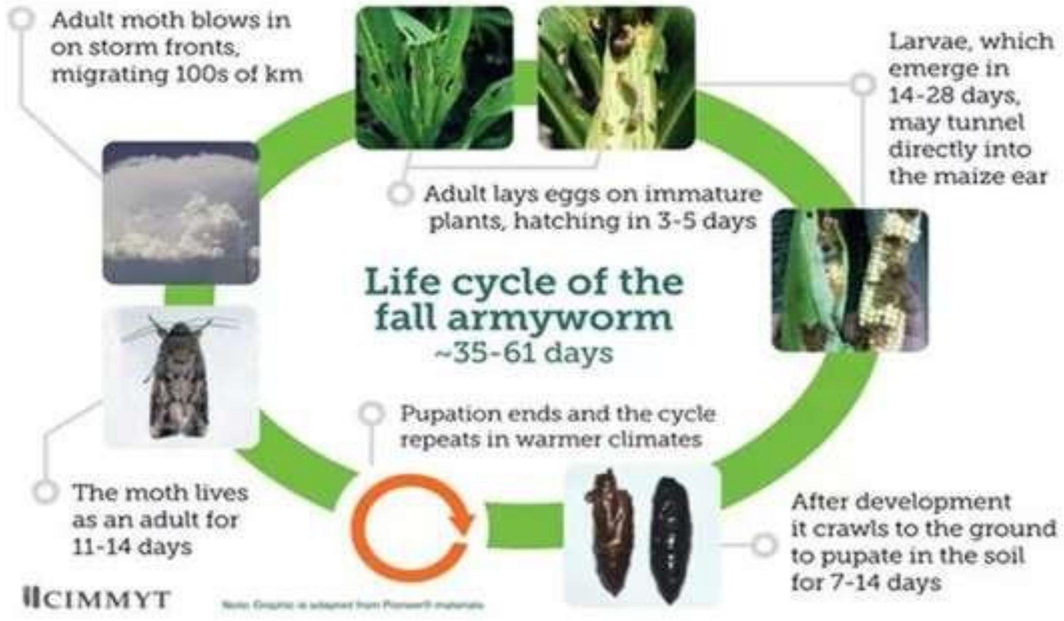

**Figure 2.2: Generalized life cycle of *Spodoptera frugiperda***

#### 2.6.2.1 The egg of fall armyworm

The egg is dome shaped, flattened base and curved upward to a broadly rounded point at the apex. The egg measures about 0.47 mm in diameter and 0.39 mm in height (Luginbill, 1928). The number of eggs per mass varies considerably but is often 100 to 200, and total egg production per female averages about 1500 with a maximum of over 2000. (Nagoshi *e tal*., 2010; Luginbill, 1928; Sparks, 1979). Eggs are generally laid on the abaxial (underside) surface of leaves shown in Figure 2. However, when oviposition frequency in a cotton field is high, females will oviposit eggs on all plant structures. The most preferred location for oviposition is on leaves emerging directly from the main stem in the middle to lower portion of the plant canopy (Ali, 1989). Eggs are usually hatched within 4 days under optimal conditions. Approximately 12 hours after deposition, eggs appear brown and become nearly black just prior to larval eclosion (Luginbill, 1928). Duration of the egg stage is only two to three days during the summer months (Johnson, 1987).

**Figure 2.3: Egg stage of fall armyworm.**

Source: Photo by Castner, University of Florida.

### 2.6.2.2 The larva of fall armyworm

There usually are six instars in fall armyworm. Head capsule widths are about 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm, respectively, for instars 1-6. Larvae attain lengths of about 1.7, 3.5, 6.4, 10.0, 17.2, and 34.2 mm, respectively, during these instars. Young larvae are greenish with a black head shown in Figure 3. The head turn orangish in the second instars. In the second, but particularly the third instars, the dorsal surface of the body becomes brownish, and lateral white lines begin to form. In the fourth to the sixth instars, the head is reddish brown, mottled with white, and the brownish body bears white sub dorsal and lateral lines as described in Table 2. Elevated spots occur dorsally on the body; they are usually dark in color, and bear spines. The face of the mature larva is also marked with a white inverted "Y" and the epidermis of the larva is rough or granular in texture when examined closely (Figure 4). The head capsule is traditionally dark in color, ranging from brown to black. Later in stars (L4– L6) lack primary setae and are generally smooth (Oliver and Chapin, 1981). Older larvae may range from light green to brown or even black in color. Markings on the larvae can include a non-continuous white line in the mid-dorsal area, as well as yellow and red “flecking” on the venter (abdomen). In addition to the typical brownish form of the fall armyworm larva, the larva may be mostly green dorsally. In the green form, the dorsal elevated spots are pale rather than dark Figure 3. Larvae tend to conceal themselves during the brightest time of the day. Duration of the larval stage tends to be about 14 days during the summer and 30 days during cool weather. Mean development time was determined to be 3.3, 1.7, 1.5, 1.5, 2.0, and 3.7 days for instars 1 to 6, respectively, when larvae were reared at 25ºC (Pitre and Hogg, 1983)

**Figure 2.4: Newly hatched larva**

Fall armyworm characteristic marks. © Visser ARC-VOP Roodeplaat

**Figure 2.5: Head capsule has inverted "Y" and four dot spot marks**

**Table 2.2: Different FAW larval stages**

| **Instar #** | **Body Length (Mm)** | **Coloring** | **Markings** |
|---|---|---|---|
| 1&2 | 1.5–3.5 | Green with a black head | None |
| 3&4 | 6–10 | Dorsal area tan color, ventral area green. Lateral white/beige stripes visible | Four dark pinnacular or raised spots arranged in a square on the 8th abdominal segment and in a trapezoid on the 9th |
| 5&6 | 15–40 | Light tan, green, black | Four dark pinnacular or raised spots arranged in a square on the 8th abdominal segment and a trapezoid on the 9th |

Source: (CABI, 2017b)

### 2.6.2.3 The pupa

Pupation of FAW normally takes place in the soil at a depth of 2 to 8 cm. The larva constructs a loose cocoon, oval and 20 to 30 mm in length, by tying together particles of soil with silk. In situations where the soil is too hard, larvae may web together leaf debris and other materials to form a cocoon on the soil surface (Sisay *et al*., 2018). The pupa is 14 to 18 mm long and 4.5 mm wide in size, and reddish-brown in color (Figure 2.5). During summer, the pupal period lasts for eight to nine days. In winter, it can take up to 20 to 30 days (Capinera, 2002) and may be long as 55 days (Vickery, 1929). In FAW pupation experiment it was observed that with specimens of both sexes pupating at the same time the females emerged a day or so earlier than the males (Vickery, 1929). The pupal phase of FAW can't withstand extended times of cold winter, for instance, Pitre and Hogg (1983) considered winter survival of the pupal stage in Florida and discovered 51 per cent survival in southern Florida, however just 27.5 per cent survival in central Florida and 11.6 per cent survival in northern Florida.

**Figure 2.6: Pupae of *Spodoptera frugiperda***

### 2.6.2.4 The adult

Fall armyworm adults (moths) have a wingspan of about 32 to 40 mm. The upper portion of the forewings of the male FAW is mottled dark grey, with a distinctive white spot near the dorsal tip, or apex, of the wing, while the lower portion of the forewings is a light grey to brown color shown in Figure 2.6 (Oliver and Chapin 1981).

The forewings of females are less distinctly marked, ranging from a uniform grayish brown to a fine mottling of gray and brown shown in Figure 2.7. The hind wings appear light grey to white. Male adults are often confused with yellow-striped armyworms, *Spodoptera ornithogalli* (Guene´e). Yellow striped armyworm adults have crescent-shaped markings on the forewings resulting in more contrast in color shades compared to fall armyworm male forewings. Fall armyworm female adults also may be confused with beet armyworms, *Spodoptera exigua* (Hu¨bner). Beet armyworm adult forewings have a paler ground color with a pale round orbicular spot, while female fall armyworm adult forewings have an oval dark- centered orbicular spot (Todd and Poole, 1980) Figure 2.7. Fall armyworm moths have filiform (threadlike) antennae common in Noctuid's. These moths are generally most active at night (Oliver and Chapin, 1981). After a pre-oviposition period of three to four days, the female normally deposits most of her eggs during the first four to five days of life, but some oviposition occurs for up to three weeks. Duration of adult life is estimated to average about 10 days, with a range of about seven to 21 days (Johnson, 1987).

**Figure 2.7: Typical adult male fall armyworm**

**Figure 2.8: Typical adult female fall armyworm**

## 2.7 Damage and economic importance of fall armyworm

Fall armyworm generally feeds on foliage, but during heavy infestations, larvae will also feed on corn ears. Foliar damage to corn is usually characterized by ragged feeding, and moist sawdust-like frass near the whorl and upper leaves of the plant. Early feeding can appear to be like European corn borer damage; however European corn borer larvae bore into the stalk whereas fall armyworm larvae continue to feed on the foliage making larger more ragged holes. Ear damage is like the damage caused by the corn earworm, chewed kernels and visible frass, except that fall armyworm tends to burrow through the husk instead of feeding down through the silks.

According to Rose *et al.*, (2000), several factors suggest that *S. frugiperda* is likely to become more damaging to maize than other species of the same genus occurring in Africa. Whereas congeneric afro tropical armyworms first build up dense populations on wild grasses before older larvae move onto cultivated gramineous crops, adult females of *S. frugiperda* directly oviposit on maize. Unlike in most other Spodoptera species in Africa, the mandibles of caterpillars of the fall armyworm have comparatively stronger, serrated cutting edges, which ease the feeding on plants with high silica content (Brown and Dewhurst, 1975; Pogue, 2002). Older larvae become cannibalistic and can dominate interspecific competitors and reduce intraspecific rivals (Chapman *et al*., 2000). As shown in several countries in the tropical Americas, where climatic conditions allow a constant reproduction of the pest, the damage inflicted to maize is particularly severe. Thus, *S. frugiperda* is considered the most important pest of maize in Brazil (Sarmento *et al*., 2002), the third largest maize producer in the world after the USA and China. For this country alone, costs to control the fall armyworm on maize exceed 600 million dollars annually (Ferreira *et al*., 2010).

Yield reductions in maize due to the feeding of the fall armyworm have been reported as high as 34% (Carvalho, 1970; Cruz and Turpin, 1982; Williams and Davis, 1990). Reported losses vary according to the stage of the plant attacked. However, the relationship between stages of attack and yield is complex. Also, loss relationships may vary from area to area, crop variety to crop variety and even between adjacent fields with different agronomic practices. Thus, determination of damage caused to different maize cultivars is an important first step in determining the economic threshold for fall armyworm on maize (Cruz *et al*., 1999).

The presence of this new pest in West and Central Africa adds to the threat already caused by native lepidopteran maize stalk/stem- or ear-borers of economic importance, in particular the *Noctuidae Busseola fusca* (Fuller), *Sesamia calamistis* Hampson, and the *Pyralidae Eldana saccharina* Walker and *Mussidia nigrivenella* (Ragonot) (Atkinson, 1980; Harris, 1962). The economic consequences of the establishment of *S. frugiperda* on the African continent may not be limited to its direct effects on agricultural production but also has the potential to adversely affect access to foreign markets. In recent years, the rates of quarantine interceptions of fall armyworm caterpillars on fresh vegetables and living plants at European entry points have significantly increased (Goergen *et al*, 2016). As a result, the status of *S. frugiperda* was reassessed in 2015 and ranked as A1 quarantine pest on the list of the European and Mediterranean Plant Protection Organization (EPPO, 2015). With its new range extension, it is anticipated that the fall armyworm will soon be included in the list of quarantine pests of other regional plant protection organizations (Goergen *et al*., 2016).

Damage on maize may be observed on all plant parts depending on the development stage. Larger caterpillars act as cutworms by entirely sectioning the stem base of maize plantlets. During the maize vegetative phase, constant feeding results in skeletonized leaves and heavily windowed whorls loaded with larval frass. On grown maize plants, larvae also attack reproductive organs feeding on tassels or boring into the ears. Following hatching, neonate larvae usually bore into the host plant and develop under protected conditions. Hence control with contact insecticides is often ineffective though it remains until today the most widely practiced management measure. Its frequent overuse has led to the emergence of regional populations resistant to several classes of pesticides (Adamczyk *et al*., 1999) and favored the use of transgenic Bt-maize (Goergen *et al*., 2016).

Fall armyworm movement each year generally creates sporadic problems across multiple crops, including cotton, Gossypium hirsutum (L.). Fall armyworm outbreaks and subsequent damage can be unpredictable. When outbreaks do occur, the severity of the problem is compounded by the ability of fall armyworm to damage a range of vegetative to reproductive plant structures, creating the opportunity to cause devastating crop losses (Hardke *et al*., 2015).

Early instars stages first to third are found in the lower-to-mid levels of the plant canopy, where they feed on foliage (Cook,*et al* 2004). Larvae in the first few instars “skeletonize” or partially feed on leaves near the egg mass from which they eclose. Early in the cotton- growing season, later instars have the potential to destroy terminals on cotton seedlings (Leigh *et al*. 1996). Older instars (L4–

L6 stages) are usually present within the lower regions of the plant canopy, feeding on fruiting structures (Cook *et al*., 2004).

Older larvae typically injure bracts, large squares (flower buds), and young bolls in a manner like the bollworm (Luginbill, 1928). Heavy infestations have the potential to injure all fruiting forms (Leigh *et al* 1996). Larger larvae feed internally in fruiting structures making successful chemical control more difficult. This problem is exacerbated due to increased tolerance to insecticides during the later larval instars (Cook *et al*., 2004). Cotton bolls at any age are susceptible to fall armyworm damage with significant damage observed regardless of boll age (Adamczyk, 1998; Emfinger *et al.*, 2007). The majority of fall armyworm feeding on cotton occurs during the last three instars and accounts for 98% of the foliage or fruit consumed during their life cycle (Sparks, 1979). As much as 80% of the food is consumed during the final instar (Luginbill, 1928).

## 2.8 Fall armyworm response so far

The invasion of FAW into Africa brought several challenges regarding control measures to adopt. The Plant Protection and Regulatory Services Directorate (PPRSD), in collaboration with the Centre for Agriculture Biosciences International (CABI) and other stakeholders, in April 2017, developed a short to medium- and long-term plan for managing the pest in the country. Training of workers on early detection and management of FAW for staff drawn from each district through the country has also been carried out. MOFA, in collaboration with the United States Agency for International Development, (USAID) procured 1,000 knapsacks for the three northern regions and has also provided training for their usage.

A special task force of 16 members was constituted by MOFA on May 10, 2017, comprising experts from MOFA, other Ministries, and as well as development partners and other stakeholders to work in collaboration towards the eradication of the fall armyworm. The task force since its inauguration has completed several tasks towards the management of the worm, including the identification of many chemical (biological and synthetic) based on their mode of action that can kill the FAW. The task force was assigned to co-ordinate sensitization and awareness of farmers on the detection of FAW to enable to them report to MOFA. Other duties include surveillance and monitoring, implementation of prevention and control measures against FAW, research for long-term measures to combat the pest by using biological control and sourcing for resources for short and long-term strategies to combat the pest.

Prasanna *et al*., (2018) stated that, though it was difficult to recognize and distinguish the incidence of the worm in Africa, the absence of corroborated approaches to successfully manage the ravaging worm was also absent. Any effort to suppress and control the pest was on the use of synthetic insecticides. Application of these insecticides was indiscriminate and higher doses used which have the potential damage to human, animal, and the environment will probably persist as an important agricultural pest across much of Sub Saharan Africa for a predictable future.

Through the USAID feed the future programme, collaboration is going on with various governments and communities to tackle the pest attack. USAID, through the feed the future initiative is leading the US government's efforts to combat the fall armyworm with a broad coalition of partners including the private sector, universities, donors, research institutions and country governments (Tamakloe, 2018). Other measures being undertaken by MOFA to curb the menace are the distribution of pesticides to all district offices in the country where farmers can access in FAW infestations, the formation and training of 'Nnoboa' Spraying Teams in farming communities and intensification of public awareness creation for farmers and the general public. Ghana had commenced scouting of natural enemies of the FAW, which once identified, will be reared to help reduce the population of the pests.

### 2.9 Management strategies for fall armyworm

Management of FAW in maize fields begins with prevention. Planting early in the season. Avoid late planting and avoid staggered planting as this would continue to provide the favored food of FAW locally. This is one of the most important recommendations for smallholders. In line with this, in January 2018 some FFS farmers in Kenya reported significant yield losses to FAW on late-planted maize plots, compared to adjacent plots which were planted earlier.

Good soil health and adequate moisture are critical: they are essential to grow healthy plants, which can better withstand pest infestation and damage. Also, unbalanced inorganic fertilization of maize especially excessive nitrogen use can increase oviposition by female FAW. The efficacy of managing crop residues to break the life cycle of FAW generations is not well established by research.

A very important management option for smallholder farmers in Africa, based on the experience of smallholders in the Americas, is to visit their fields regularly, and crush egg masses and young larvae “use your fingers.

Some smallholder farmers in the Americas report using ash, sand, sawdust or dirt into whorls to control FAW larvae. Ash, sand and sawdust may desiccate young larvae. Dirt may contain entomopathogenic nematodes, Nucleopolyhedrosis Virus (NPV), or bacteria (such as Bacillus sp.) that can kill FAW larvae. Smallholder maize farmers in Central America and FFS farmers in Africa also report using lime, salt, oil and soaps as control tactics. Lime and ash are very alkaline.

### 2.9.1 Monitoring and surveillance

In the context of insect pest resistance management, monitoring is an ongoing and repeated measurement of an insect pest’s susceptibility to a toxin. Together, monitoring can be done using pheromone traps established in the fields to trap adult male moths. FAW numbers in the traps are counted, recorded, and used to inform appropriate action. The information from the traps are reported for management recommendations and decision making (Prasanna *et al*., 2018).

Surveillance means the informal, passive finding of pest issues as they arise. In other words, the method does not vigorously search for a specific pest; it only notes when a problem occurs.

#### 2.9.1.1 Trap selection

According to Prasanna *et al*., (2018) a pheromone trap is a kind of insect trap that uses pheromones to attract (usually) male insects. A pheromone is a chemical secreted by (usually) a female insect to attract males for mating. Pheromones can travel by air very long distances and hence are very useful for monitoring insect presence. Sex pheromones and aggregation pheromones are the most common types of pheromones in use. Currently, there are several different pheromone lures being assessed as well as a variety of trap types. All of these may work, but some pheromone lures also attract a limited number of non-FAW moths, which may cause some confusion. Based on currently available information, the following traps are recommended. (Figure 2.8 and 2.9)

- Universal Bucket Trap for use in smallholder farms

**Figure 2.9: Universal bucket trap**

- The Heliothis-style Pheromone for regional monitoring

**Figure 2.10: Heliothis-Style Pheromone**

#### 2.9.1.2. Trap placement and setup

i. The pheromone trap should be erected one month before planting.

ii. The trap is placed in or next to the maize field so that the scent of the pheromone is carried across the tops of the plants by the wind. iii. The trap is hanged in an erect position from a long pole (3-4 meters) so that the trap is approximately 1.25 meters off the ground.

iv. When traps are hanged, they should be oriented in the most vertical, straight-up and-down position possible, to prevent water from getting in from the side (Prasanna *et al*., 2018).

#### 2.9.1.3 Trap monitoring

i. The trap is emptied weekly. This is done by detaching the “moth-trap” from the frame of the pheromone trap. The moth-trap is turned upside down for live FAW moths to crawl up the sides of the trap.

ii. The thorax of the moths is pinch between your thumb and forefinger to freeze the wing muscles and help identify the FAW moths.

iii. There may be several moths other than the FAW in the trap. Sort out and count the FAW moths (wings with a white patch near the apex of wing; hind wing veins light-colored) and any African Armyworm (AAW) moths (hind wing veins brown colored) separately.

iv. As the maize plants grow taller, the trap is moved up the pole so that the bottom of the trap is always about 30 cm above the plants (Prasanna *et al*., 2018).

### 2.9.2 Field scouting and action threshold

#### 2.9.2.1 Field Scouting for FAW

The implementation of an effective Integrated Pest Management (IPM) program requires activities such as monitoring, surveillance and scouting (Ausher, 1997). Forecasting at what time a pest will be present and then measuring the level and severity of an invasion allows timely mitigation of the problem using the fewest and safest interventions to effectively and economically guard against yield loss while preserving needed ecosystem services and minimizing harm to the environment (Prasanna *et al*., 2018). Scouting involves an activity that is conducted according to a protocol by a trained individual – naturally by a farmer, trained at the farmer field school or extension level, observing his or her own fields for the pest.

According to Prasanna *et al* (2018), scouting is best done when you have information of the pest and the crop agro ecosystem. Scouting permits the grower to exactly measure pest pressure (e.g., the intensity of FAW infestation) and crop performance in the field (Prasanna *et al*., 2018). Scouting is done in order to estimate both the economic risk of pest influx and the probable effectiveness of pest control interventions within the immediate field context.

#### 2.9.2.2 Scouting protocols

The activity of scouting should not only be done with the aim of early detection but for also easy control of pest as the smaller the insect the easier to control. Preferably, scouting ought to begin shortly after seedling emergence (VE; Early Whorl). FAW completes its life cycle in 30-40 days and the first generation of FAW larvae generally attacks the seedlings, so fields should be rechecked weekly at the seedling and Early Whorl stages (Prasanna *et al*., 2018). Farmers should visit fields twice a week during vegetative stage, especially in periods of heavy oviposition by FAW, and once a week or every 15 days in later stages. FAW egg masses take 2-3 days to hatch in most African temperatures. So, during periods of heavy infestation, by visiting fields at least twice a week, you can crush egg masses between your fingers before they hatch. This is easier and less costly than dealing with hundreds of bigger larvae a few days later. Field observation also helps farmers to check the overall state of crop development, soil moisture, presence of other pests and diseases. In general, scouts should look for signs of FAW egg-hatch and feeding by early instar larvae, rather than looking for the small FAW larvae themselves. As described below, such signs include characteristics such as leaf damage, holes in the ear, and frass. Neonate (freshly hatched) and first-instar larvae are quite small on the order of 1 mm and can be difficult to find. However, with a little practice, farmers can become quite adept at spotting even the small pinhole signs of FAW feeding. By the time FAW larvae are big enough to identify without a hand lens, they are difficult to control (Prasanna *et al*., 2018). Percent infestation can be assessed by sampling 20 plants in five locations, or 10 plants in 10 locations (Capinera, 2002). Van Huis (1981) recommended that resource scarce farmers should count the number of injured whorls in 20 consecutive plants at 5 randomly selected sites. Similarly, Andrews (1988) recommended sampling 20 plants per site from 5 sites and use of a 40% infestation of maize as a threshold in Honduras. To determine larval density in a field, large sample size is needed, especially when larval densities are low, or larvae are young. In pasture lands sampling is done by walking from four sides following the diagonals of sampling area using a square foot metal quadrant. If larval density per square foot is 3 or more, the threshold is reached to apply treatments (Nagoshi and Meagher 2008).

### 2.9.2.3 Scouting patterns

The activity of Scouting a field involves correctly measuring the level of FAW infestation, generally uttered as a fraction of infested plants. If possible, random sampling should be done. Practically implementing randomization on the field for scouting can be difficult. There are several approaches to easily scout a field. A commonly used approach is the “W” pattern shown in Figure 2.10. This pattern is particularly easy to follow well up into the Tasseling Stage of the maize crop (Prasanna *et al*., 2018).

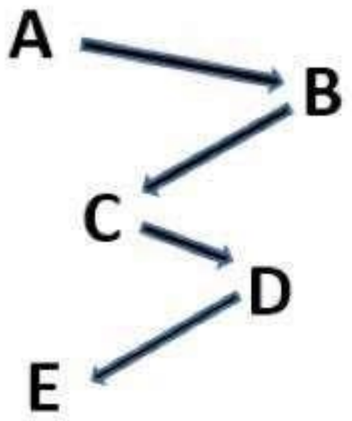

**Figure 2.11: “W” Pattern for scouting a field; Source: (Prasanna *et al.*, 2018)**

The farmer paces into the field about 5 meters evading the edge rows of the field to avoid the edge effects. The farmer then moves in a zigzag’s manner across the field, ending at 5 different locations. At each of these places, the farmer measures 10-20 plants looking for signs of FAW feeding. The percentage of damaged plants is recorded, and the farmer moves to the next checkpoint. After evaluating 5 locations in the field, the farmer determines the percentage of damaged plants for the field and then refers to Table 2.3 for guidance to determine if mitigation is warranted. These Action Thresholds are used in place of Economic Thresholds when the latter is not available. If the village has Economic Threshold data, they should be used as they are a better guide to mitigation. In lieu of an Economic Threshold, the Action Thresholds, based on the expert opinions of FAW researchers in Africa and the Americas, should serve as accurate guides (Prasanna *et al*., 2018).

There is nothing prescriptive about the “W” scouting pattern. The scouting pattern might need to be improvised based on the maize growth stage or field shape. For example, densely planted maize at the Tassel Stage or beyond may be difficult to traverse using the "W" pattern. An alternative is to use the "Ladder" pattern shown in Figure 2.11. In this method, rows A-E are used as alleys to more easily traverse the field in a semi-systematic manner (Prasanna *et al.*, 2018).

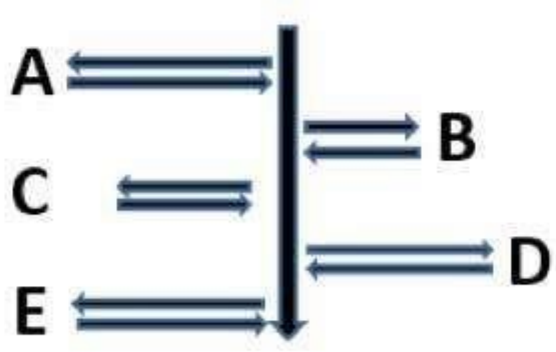

**Figure 2.12: Ladder pattern for scouting fields; Source: (Prasanna *et al.*, 2018)**

### 2.9.2.4 Action thresholds

An action threshold is a value for a parameter that when reached should trigger a response (See Table 2.3). In FAW management the parameter is usually the percentage of maize plants showing fresh damage, but there is no consensus on what this value should be for smallholder maize farmers in Africa. Action thresholds vary with context, including the value of expected yield, the relationship between damage and yield loss which is not yet well documented in Africa and the stage of the crop. Because maize has the capacity to recover from some damage, appropriate action thresholds may be higher than might be expected (Rwomushana *et al.*, 2018).

The decisions to spray an insecticide are founded on the calculated Economic Threshold and Economic Injury Level. Figure 2.12.

Decision point:

- At early whorl stage (knee high), act if >20% of plants are damaged.
- At late whorl stage (shoulder high), act if >40% of whorls are freshly damaged.
- At tassel and silk stage, do not spray pesticides.

**Table 2.3: Summary of FAW Action Thresholds.**

| **Maize Crop Stage** | **V Stage** | **Action Threshold for Smallholder Farmer** | **Action Threshold for Village-Level Progressive Farmer** |
|---|---|---|---|
| Early Whorl Stage | VE-V6 | 20% (10-30%) | 20% (10-30% |
| Late Whorl Stage | V7-VT | 40% (30-50% | 40% (30-50%) |
| Tassel and Silk Stage | R1-R3 | NO SPRAY<br>Unless low-toxicity and supportive of conservation biological control | 20% (10-30%) |

Source: (Prasanna *et al*., 2018)

#### 2.9.2.5 Interpreting the action thresholds

- The Commendations are presented as the midpoint of the range, e.g., 20% (range of 10-30%). Figure 2.12. These are presented as Action Thresholds based on expert opinion, including practitioners in Africa and the Americas. These approximations will be reviewed as Economic Thresholds as and when data turn out to be available.

Farmers generally are advised to consult host country extension advisors whenever possible to provide real-time advice on the use of Table 2.3 (Prasanna *et al*., 2018).

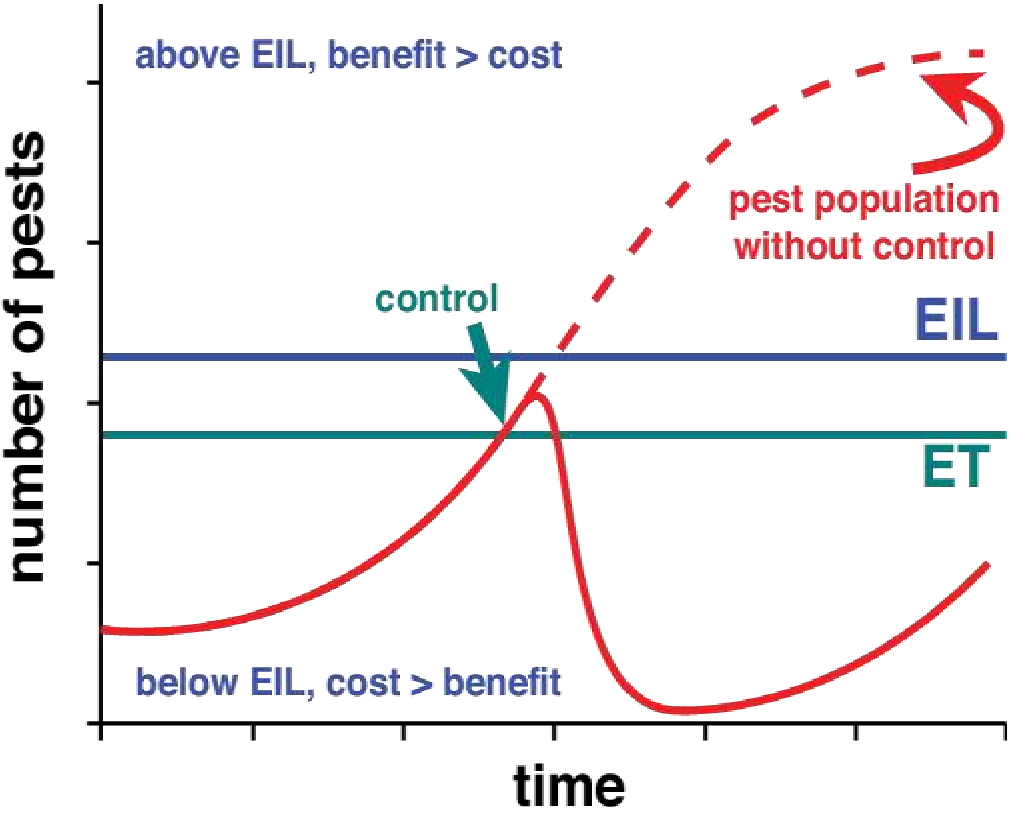

**Figure 2.13: The economic threshold (ET) and the economic injury level (EIL). Source: Barbercheck and Zaborski (2015).**

- In some cases, experts will choose the lower (10%) Action Threshold for treating maize at the Early Whorl Stage. Other experts may select a higher Action Thresholds founded on their expertise and the local situation (Prasanna *et al*., 2018).
- To eliminate the cases where farmer will spray over head at the VT or reproductive stages and avoid spillage of the chemical used. The farmer will decide to treat early and at a lower Action Threshold because smallholder farmers lack Personal

Protective Equipment (PPE), and knowledge on the safe use of pesticides.

### 2.9.3 Host plant resistance

Host plant resistance is a key tool in developing a strategy to control fall armyworm. Significant information exists for resistance traits of corn to fall armyworm, but very little data exists for cotton. For corn, Antibiosis and non-preference have been the key mechanisms of host plant resistance and fall armyworm- resistant hybrids have successfully produced greater yields compared to susceptible hybrids at similar infestation levels (Sparks, 1986; Wiseman and Davis, 1990; Wiseman *et al.*, 1983; Wiseman *et al.*, 1981).

Partial host plant resistance and natural enemies often act synergistically to suppress pest insects (Van Emden, 1999). Price, (1986) pointed out the need to understand the biology of each trophic level before the complex interactions between host plant resistance and natural enemies can be understood.

This can be a useful technology for sustainable FAW management, particularly in the African context, where many of the farmers are smallholders with limited access to safe and affordable FAW control options. Recent advances have been made in identifying FAW-resistant maize populations, developed using diverse sources of resistance. The International Maize and Wheat Improvement Centre (CIMMYT) is working on the rapid conversion of the preferred but FAW-susceptible lines into resistant versions. Ten promising CIMMYT maize inbreeds have been identified and validated in Kenya with leaf damage ratings between 2.0 and 6.0, and ear damage ratings below 3.0, while the susceptible check ratings were 7.0 or above. Key will be how fast first-generation FAW-tolerant maize varieties can be scaled up and deployed as an immediate relief to the farming communities.

So far, five materials look promising and may be available within 2-3 years. This will need to be coupled with accelerated breeding for improved Africa-adapted varieties with FAW resistance and other farmer-preferred traits, leading to the release and deployment of second-generation FAW-tolerant maize hybrids/OPVs in the coming years. Critical to this technology will be the systematic analysis of compatibility and possible synergies between host plant resistances with other IPM approaches (e.g. biological control) (Rwomushana *et al*., 2018).

Additionally, AATF has been working on drought-tolerant (DT; Drought Gard® or CspB from *Bacillus subtilis*) and insect-resistant (Bt from *Bacillus thuringiensis*) transgenes or traits donated royalty-free, to develop white maize varieties under the trademark TELA®. Preliminary results from confined field trials carried out in

Kenya, Mozambique and Uganda with TELA® varieties stacked with both DT and Bt traits showed partial but significant control of the FAW. Six TELA® varieties with only Bt insect-resistant trait have already been commercialized in South Africa, the only country in the continent where planting genetically modified maize is currently permitted. Trials of GMO crops are in progress in another seven African countries (Cameroon, Egypt, Ghana, Kenya, Malawi, Nigeria, and Uganda) (Rwomushana *et al*., 2018).

According to Rwomushana *et al*., (2018) there is much debate around the suitability of genetically modified crops for smallholder farmers in Africa. Much of this is not about safety, but around socio-economic issues and the capacity of regulators, even where appropriate legislation is in place. If introduced, effective regulation is required to reduce the risk of resistance developing. Most Bt maize hybrids lost their ability to control fall armyworm within 3 years of introduction in Brazil

(Fatoretto *et al*., 2017).

### 2.9.4 Biological control

Biological control principally put emphasis on restoring natural control (Prasanna *et al*., 2018). According to Ehler, 1998, a biological control involves living organisms such as parasites, predators, or pathogens. Parasitoids are biological agents for which at least one of their life stages is intimately associated with specific life stages of the pest and with greater levels of specificity (e.g., parasitoid species belonging to *Trichogramma* and *Telenomu*s parasitizing eggs of insects including FAW). The larvae of parasitoids always kill their host as the outcome of their development. Predators, on the other hand, are never intimately associated with the insect pest, and the pest serves as prey for the predator often with less specificity.Eamples include insects such as ladybird beetles, earwigs, and sapsucking insects such as *Orius* and *Podisus* that prey on various life stages of FAW. *Entomopathogens* include bacteria, fungi, protozoans, nematodes, or viruses that infects and causes diseases in insects (e.g., fungi such as *Metarhizium anisopliae* and *Beauveria bassiana*; viruses such as *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV); and bacteria such as Bacillus thuringiensis (Bt), and others that are known to infect FAW).

There are 53 species of parasites, representing 43 genera and 10 families that attack fall armyworm globally (Ashley, 1979; Sparks, 1986). Entomogenous pathogens can suppress fall armyworm populations in at least three ways: 1) optimization of naturally occurring diseases, 2) introduction and colonization of pathogens into insect populations as natural regulatory agents, and 3) repeated applications of pathogens as microbial insecticides (Gardner and Fuxa, 1980). Several microbial pathogens have been studied in hopes of utilizing them to control fall armyworm populations. Viruses demonstrate limited efficacy against fall armyworm, but are not temporally effective, allowing for significant damage prior to insect mortality (Sparks, 1986). Inconsistent results have been documented in field studies evaluating the use of entomogenous pathogens to suppress fall armyworm on corn and cabbage. Fall armyworm specific Bt isolates have not been developed for commercial spray formulations (Sparks, 1986), but the Cry1F Bt protein is generally considered to be more toxic to fall armyworm than other Cry proteins (Tindall *et al.*, 2006). Current literature does not describe predators that attack fall armyworm. Many predators attack fall armyworm eggs and larvae, but there is no summary available to describe these species (Lewis and Nordlund, 1980; Sparks, 1986). While predators influence fall armyworm survival and development, their role is largely undermined by parasitoids, which are more efficient in affecting fall armyworm populations. Previous attempts to utilize fall armyworm parasitoids generally have been unsuccessful (Gross and Pair, 1986; Sparks, 1986).

Complex habitat structure such as the field edge not only provides a broad range of resources to biological control agents, such as protective cover from environmental extremes, (Langellotto and Denno, 2004), wild flowers nectar, grass pollen (Marino and Landis, 1996) which are nutrients used by the genus

Euplectrus , but it also can serve to reduce encounter rates with con- specifics, thus favoring coexistence (Hayroe *et al.*, 2016).

Although several pathogens have been shown experimentally to reduce the abundance of fall armyworm larvae in corn, only Bacillus thuringiensis presently is feasible, and success depends on having the product on the foliage when the larvae first appear. Natural strains of Bacillus thuringiensis tend not to be very potent, and genetically modified strains improve performance (All *et al*., 1996).

### 2.9.5 Cultural control

Cultural control is an important component of pest management strategies including FAW. In many great cases, damage to field crops by fall armyworm could be practically eliminated if the crops were kept free from grass. Cumulatively plant health, can be improved through soil management and crop nutrition, can ensure that plants develop well before pest damage significantly affects yield-defining components (e.g., leaf area). Healthy plants can also invest more in defense (Chapin, 1991), thereby increasing the likelihood of escaping serious damage. In other words, if clean culture strategies were utilized inflexibly by the farmers, damage could be limited. This insect is basically grass-feeding animal species and breeds in grasses wherever conceivable. In the case of *S. frugiperda*, several studies have indicated that low or no till agriculture and polycultures are less attacked by the pest compared to monoculture cropping systems planted using conventional cultivation (Andrews, 1988). In Cuba, intercropping of maize with sunflower resulted in lower infestation by FAW and higher yield compared to the maize monocrop (Ryder, 1968). Survey conducted in Ethiopia and Kenya showed that 14% and 39% of the farmers practiced cultural methods (such as handpicking) for FAW managements (Teshome *et al*., 2018).

The benefits of cultural approaches often arise from the interplay of ecological factors across a range of spatial scales – from plot to field to farm to landscape – that disrupt and control the pest at multiple stages throughout its life cycle (Veres *et al*., 2013; Martin *et al*., 2016). For example, cultural practices such as intercropping, companion cropping, conservation agriculture, and agroforestry may simultaneously improve the health of the crop, provide shelter and alternative food sources for natural enemies, and reduce the ability of FAW larvae to move between host plants. Van Huis (1981) also found that in Nicaragua infestation of maize by FAW was 20-30% lower when interplanted with beans compared to planting maize alone. The mixed cropping systems are likely to support more predators, disrupt egg laying by FAW female moths and hinders the plant to plant migration of FAW larvae after hatching. Leaving few strips of weeds between rows of maize also can help to reduce maize infestation by serving as unsuitable host for the larvae that move between maize plants. Flooding rice fields until the plants are nearly covered is a common practice in Venezuela in order to drown larvae (Labrador, 1967).

Intercropping or crop rotations with crops that are not preferred by the pest can help repel FAW. Some intercrops, particularly those producing natural insecticides (e.g., Tephrosia) or repugnant semiochemicals (e.g., Desmodium), repel the adult female moths; reducing the number of eggs lay on host plants.

Conversely, creation of sustainable ecosystems (e.g., through surface crop residue retention) that attract and conserve natural enemies of FAW, including generalist predators (e.g., spiders, ants, or birds) and parasitoids, can contribute to enhanced pest predation and parasitism that controls FAW populations. Increasing habitat diversity at the landscape scale e.g., through the preservation or cultivation of patches of natural vegetation, tree cover, or hedgerows can increase the abundance of insectivorous birds and bats. The effect of these voracious and highly mobile pest predators depends on the availability of suitable habitat within the field (e.g., suitable perches or roost sites) and across the broader landscape (Cock *et al.*, 2017).

In one recent study conducted across East Africa, farmers who fully implemented the Push-Pull approach reduced FAW infestation and crop damage by up to 86%, with a 2.7-fold increase in yield relative to neighboring fields that did not implement the approach (Midega *et al.*, 2018). Though implementing Push-Pull requires initial financial costs to establish the companion plants, costs gradually reduce in subsequent seasons. Furthermore, beyond controlling FAW and other stem borer pests, Push-Pull has also been reported to reduce *Striga* infestation, increase nitrogen and soil humidity, and most importantly, provides a suitable environment for the proliferation of predators and parasitoids of FAW (Khan *et al.*, 2010).

The field should at a point be lightly disked ploughed promptly to kill the larvae and pupae. Shallow cultivation of crops as the larvae have gone down to pupate is exceptionally suggested. Such cultivation kills quantities of pupae and uncovered others which are killed by the hot sun in a short time. It has been discovered that pupae are killed by less than one-half hours exposure to the sun when the soil temperature is more than 100°F. The most essential cultural remedy in rice field is flooding. Flooding suffocates the greater part of the larvae, provided the water is left on the fields for not less than two days.

Fall armyworm does not possess a diapause mechanism, so cultural control strategies that suppress overwintering populations are ineffective in an annual cropping system. However, cultural practices do have the ability to influence fall armyworm populations during the production season. Host plant resistance is a key tool in developing a strategy to control the fall armyworm. Significant information exists for resistance traits of corn to fall armyworm, but very little data exists for cotton. For corn, antibiosis and non-preference have been the key mechanisms of host plant resistance and fall armyworm-resistant hybrids have successfully produced greater yields compared to susceptible hybrids at similar infestation levels (Sparks, 1986; Wiseman and Davis, 1990; Wiseman *et al*., 1981).

The most important cultural practice, employed widely in southern states, is early planting and/or early maturing varieties. Early harvest allows many corn ears to escape the higher armyworm densities that develop later in the season (Mitchell, 1978). Reduced tillage seems to have little effect on fall armyworm populations (All, 1988), although delayed invasion by moths of fields with extensive crop residue has been observed, thus delaying and reducing the need for chemical suppression (Roberts and All, 1993). Cultural practices also employed insect parasites such as wasps and flies, ground beetles, and other predators can help suppress armyworm numbers (Flanders *et al.*, 2007)

According to Abate *et al.,* (2000), most subsistence farmers in Africa do not apply pesticides to maize to control pests; nevertheless, they do practice cultural control methods which deter or kill pests, such as maize intercropping with common beans, handpicking and killing of caterpillars, application of tobacco extracts, wood ashes and soils to leaf whorls.

### 2.9.6 Use of pheromones

Pheromone is a substance produced and released into the environment by an animal, affecting the behavior or physiology of others of its species. Mating disruption, mass trapping, attract-and-kill, and push-pull are some direct pest control strategies that depend on the use of pheromones. Pheromone lures are a critical tool for detecting and managing insect pest populations. These pheromones are used in conjunction with sticky cards and other traps that are available separately. Pheromone traps are effective, but remember they are attracting the insect and does not kill them. Use of sex pheromone traps can also reduce the male moths and their multiplication. The females produced sex pheromone of fall armyworm is commercially available in most part of the world. Pheromones have been a useful tool for monitoring male populations (Mitchell *et al*., 1985: 1989; Adams *et al*., 1989; Pair *et al*., 1989; Malo *et al*., 2004; Batista-Pereira *et al*., 2006). Monitoring with pheromone traps is useful because pest pressure varies from farm to farm and over time. Knowledge of when and where adult pests are active and abundant provides a sensitive early warning system to enable field sampling and/or control measures to be initiated at the appropriate time.

Commercially available FAW sex pheromones have been used in the USA and have been shown to be a useful tool for monitoring FAW males (Adams *et al*., 1989; Mitchell *et al*., 1989). A kit containing synthetic pheromone plus a trap is marketed in various countries in South America, including Brazil. According to one manufacturer the trap should be placed in the center of the planting area and used at a density of one trap for every five hectares of crop (Biocontrol). One lure lasts a month, so several lures are required for one trap per season. Since most pheromones degrade rapidly if exposed to bright light or high temperature, lures should be stored in tightly sealed glass containers or foil pouches and preferably kept in a freezer or refrigerator to ensure their longevity. Because volatility and degradation rates vary among pheromone components for various insect species, and release characteristics are different for various dispensers, no generalization can be made about the life of lures (Knodel *et al*., 1995). Backlight traps and pheromone-baited cylindrical electric grid traps were used to monitor seasonal population dynamics of fall armyworm in Louisiana and Florida respectively. Disposable sticky traps baited with pheromone, (Z)-9-dodecen-1-ol acetate, also have been used extensively in surveys for the adult fall armyworm in Georgina and Florida. These traps are relatively inexpensive, easy to transport and assemble, and they can be deployed in situations where electric power is unavailable.

The traps and the trapping procedures for monitoring fall armyworm are dependent on the attractant and the nature of the area. The selected site should be inside or on the edge of maize field, or in an open area nearby. The traps should be hung from a suspended pole or branch about 1.5 m above the ground. One trap should be used for every 0.5 – 2 ha. The traps should be checked two times per week by counting the number of fall armyworm moths inside. The pheromone lure usually needs to be replaced every 3 – 6 weeks to achieve optimum results (FAO, 2017). Sticky traps are generally most effective in capturing fall armyworm males when positioned 1 m above the ground in and around host crops.

Sparks (1986) explained that, about 25 years ago, sex pheromones were envisioned by entomologists as tools with great potential to eliminate the entire male population of a species. The female-produced pheromone could supposedly be used to trap out all males, mixed with insecticides to lure males to their death, or dispersed over vast areas to disrupt communication between sexes, thereby eliminating mating and the species. Sparks (1986) reviewed the potential of the FAW pheromone for monitoring and managing populations at that time. Since that time, Mitchell *et al.*, (1985) have identified three additional components in addition to the two identified by (Sekui and Sparks, 1967). Although the female produces a five-component pheromone, a mixture of two components only is required to effectively lure males into traps. Entomologists have yet to correlate trap catch of males with actual populations of FAW in the vicinity of traps. However, pheromone traps remain the tool of choice to determine the relative abundance of FAW populations in each area (Sparks, 1986)

Pheromones are actively being developed to mass-trap males and are effective when used at large scale (Godwin *et al.*, 2017). As well as using synthetic sex pheromones for monitoring FAW, research is in progress to see if they can be used for control. There are two approaches; trapping and mating disruption. In trapping, the aim is to reduce the male population to such an extent that females are unable to mate (Rwomushana *et al*, 2018). Gilson *et al.*, (2018) report tests using traps made from plastic drinks bottles with a pheromone lure, but there is no evidence yet that enough males can be caught in an area to reduce FAW damage.

According to Rwomushana *et al.*, (2018), mating disruption involves releasing so much pheromone into the environment that males become confused and cannot find the females whose own pheromone emissions are lost in the cloud of synthetic pheromone. Often this approach is impractical as pheromones are expensive to produce. However, a company in the US (Provivi) has developed a new method of synthesizing such molecules which should reduce the cost by up to 90%. Trials are therefore being conducted in East Africa to test the mating disruption approach, although as with trapping, it is likely to be most effective when implemented over a large area.

Card´e and Haynes, (2004) explained that the most common type of behavioral reproductive isolation in moths is through sexual communication. Females attract males from a distance by emitting a species-specific sex pheromone, usually consisting of two or more volatile compounds that are released from the sex pheromone gland in the scot phase. So far, the sex pheromones of about 1600 moth species have been identified (El-Sayed, 2009). The sex pheromone of *S. frugiperda* was identified in 1986 (Tumlinson *et al*., 1986) and field experiments have been conducted in several regions (Mitchell *et al*., 1985; Tumlinson *et al*., 1986; Andrade *et al*., 2000).

### 2.9.7 Use of bio-pesticides

Given the dangers of chemical pesticides, the development of lower-risk approaches using biological pesticides for FAW is high (Abrahams *et al*., 2017).

According to Rwomushana *et al*., (2018), biopesticides are products based on pathogens of the pest, but may also be taken to include other biologically based products such as plant extracts (botanicals), biochemicals with various modes of action, and even predators and parasites (microbial).

A recent study assessing biopesticides (broad sense) potentially useful for FAW management (Rwomushana *et al*., 2018) reviewed products registered in 30 countries, 11 in FAW's native range and 19 in Africa. 50 biopesticide active ingredients were identified. Twelve of these are already reported as being effective against FAW outside Africa, most of these being already registered in at least some African countries for other pests. However, there are safety concerns regarding four of these, which need to be assessed in a local context. The remaining eight active ingredients were recommended for immediate field testing in Africa, and some such tests are in progress. One of the microbial biopesticides identified as a priority by Bateman *et al*., (2018) was baculoviruses, which highly host specific, non-pathogenic to beneficial insects and other non-target organisms, and are attractive candidates for integrated pest management. Littovir (RAVAGEX), a Spodoptera sp. baculovirus-based product, initially developed for control of the African cotton leafworm, has been tested and registered against FAW in Cameroon by Andermatt Biocontrol (pers communication). Trials are in progress in 6 countries in Africa to test the efficacy of a product (Fawligen, manufactured by AgBiTech) based on a multiple nucleopolyhedrovirus isolate, but so far, no naturally occurring viruses of FAW have been detected in Africa. African Armyworm is attacked by a virus but attempts to commercialize production of the virus in Tanzania failed (Rwomushana *et al*., 2018).

*Bacillus thuringiensis* (Bt)-based products are relatively widely available in Africa, and as reported above, were widely used in Ghana in the most recent season. However, different subspecies/strains of Bt are effective against different pests, so not all Bt products in the market may be suitable for FAW. Trials are required to confirm which strains/products are most effective in Africa, and such work is ongoing at ICIPE (Rwomushana *et al*., 2018).

*Beauveria bassiana* is reported as effective against FAW in the laboratory in the Americas and *Metarhizium anisopliae* is effective against related pests, so products based on these fungi are also worth testing, although preliminary trials at ICIPE were not immediately promising. Work on entomopathogenic nematodes of FAW is in progress at University of Neuchatel, where novel methods of formulation have been developed that can enhance efficacy (Rwomushana *et al*., 2018).

*Spinetoram* and *spinosad*, bacterial fermentation products, are reported effective against FAW, but present some risks that need mitigation. *Methoxyfenozide* and silicon dioxide are also reported effective against FAW in its native range and should be trailed in Africa (Rwomushana *et al*., 2018).

Given that biopesticides such as microbial and microbial extracts, microbials and semi chemicals are generally considered to be lower risk options for pest management, they are a promising avenue for exploration. When used in conjunction with good crop management, they can help to keep pest levels under control, reducing the need to apply other pesticides. This study provided a basis for designing interventions to make biopesticides more widely available for FAW control in Africa (Bateman *et al*., 2018). Given the concerns posed by pesticides, the development of low-risk management approaches using biopesticides for FAW based on biochemical, microbial or microbial pest management products is high on the list of near- term activities identified in action plans for affected countries in Africa, at both national and regional level. For example, the national FAW response plan of Ghana has four components, and Component 3, covering “Control, Management and Research,” includes the identification, testing and deployment of lower- risk options such as biopesticides. At the continental level, the Food and Agriculture Organization of the United Nations (FAO) has developed a Framework for Partnership (FAO, 2018).

In Ghana, a major change from 2017 is the increased use of biopesticides. This reflects a national policy to recommend and subsidize its use. The most common active ingredient used was *Bacillus thuringiensis* (Bt); over half the users had received it for free. Very few farmers use biopesticides in Zambia. A few farmers reported using very highly toxic pesticides, which is a serious concern (Rwomushana *et al*., 2018).

### 2.9.8 Use of botanicals

Botanicals are pesticides derived from plants. They degrade rapidly and therefore are considered safer to the environment than the common synthetic chemicals. However, as with any pesticide, botanicals must be used properly

Botanical extracts have long been proposed as attractive alternatives to synthetic insecticides for pest management. Botanical extracts are eco-friendly, economical, usually target-specific, and biodegradable. The greatest strength of botanical extracts is their specificity, as most are essentially nontoxic and non-pathogenic to animals and humans Botanicals degrade rapidly in sunlight, air and moisture and by detoxification enzymes. Rapid breakdown means less persistence and reduced risk to non-target organisms. However precise timing and/or more frequent applications may be necessary. Botanical insecticides are fast acting. Although death may not occur for several hours or days, insect may be immediately paralyzed or stop feeding. Most botanicals have low to moderate mammalian toxicity. Some botanicals quickly breakdown or are metabolized by enzymes inside bodies of their target pests. Breakdown may occur rapidly, so that the insecticide only temporarily stuns the insect but does not kill it (Rice, 1983). The potency of some botanicals may vary from one source or batch to the next. Tolerance for residues of some botanicals on food crops has not been established. Botanical insecticides include nicotine from tobacco, pyrethrum from chrysanthemums, derris from cabbage, rotenone from beans, sabadilla from lilies, ryania from ryania shrub, limonene from citrus peel, and neem from the tropical neem tree. Most, other than nicotine have low levels of toxicity in mammals and birds and create few adverse environmental effects (Prakash and Rao, 1997). Various plant species have shown insecticidal properties against FAW, for example extracts of neem, Azadirachta indica, Argemone ochroleuca Sweet (Papaveraceae), Boldo, Peumus boldus Molina (Monimiaceae), jabuticabeira, Myrciaria cauliflora [Mart.] O. Berg (Myrtaceae). (Sisay *et al.*, 2019)

Botanicals are cheap, readily available, and affordable, which are important qualities of pest control products for smallholder farmers in Africa (Stevenson *et al.*, 2017). Rwomushana *et al.*, (2018) stated that a large diversity of plants has insecticidal properties. The active ingredients of some of these, or their synthesized equivalents, are the basis for formulated products, while various local concoctions use such plants Azadirachtin (neem) is effective against FAW in the Americas, and in Ghana, for example, three products based on azadirachtin are already registered for use against FAW. Oxymatrine and matrine (found in *Sophora* spp) are reported effective against FAW in the field and laboratory bioassays respectively in the Americas. So are worth trailing in Africa where they are already registered in some countries for other pests. Garlic oil, orange oil and maltodextrin are reported effective against related pests so could also be tested against FAW. Pyrethrins (from *Chrysanthemum cinerariaefolium*, formerly Pyrethrum) are effective against FAW and registered in Africa but have nontarget risks that require mitigation.

In Mexico, recent studies have shown that extracts of *Couroupita guianensis* and *Myrtillocactus geometrizans* could be good candidates for the control of *Spodoptera* due to their larvicidal activity. Also, extracts from *Synedrella nodiflora* and *Lupinus stipulatus* have shown to have biological effects on mature insects of the genus (Ayilgutiérrez *et al*., 2018). And researchers from Brazil have also demonstrated that the application of a 5% extract concentration of pequi fruit decreased the amount of damage caused by the FAW caterpillars (Souza *et al* 2018), although a higher concentration was phytotoxic. While botanicals are generally thought to be “natural” and therefore “safe”, this is not always the case, some have negative impacts. For instance, although azadirachtin does not meet any of the criteria for highly hazardous pesticides, and is generally considered safe to beneficial insect species, some adverse effects on hymenopteran parasitoids (wasps) have been reported. It can also cause an allergic skin reaction in humans in some cases (Rwomushana *et al*., 2018).

Anjarwalla *et al* (2016) stated that the demand for botanicals is set to grow due to increases in organic farming, consumers demanding safe food and environmentalists lobbying for eco-friendly pesticides. Unfortunately, pesticidal plant products are not always readily available in the right forms for small scale farmers nor are there any ready-to-use products. This challenge is an opportunity for small scale farmers to increase access and raise the profile of plant pesticides by engaging in low-cost processing and marketing of such products. Thus, as the demand for organic products grows the potential for marketing and trading in plant pesticide products will also grow (Anjarwalla *et al*., 2016).

However, selling most pesticidal plant products is currently beset with some challenges which include: lack of data on efficacy, safety, toxicity, persistence, shelf life and safety, inconsistent performance of crude extracts and inherent differences in plant chemistries, unreliable and or unknown raw material supply, as well as lack of standardization and documented application protocols (Sola *et al*., 2014; Anjarwalla *et al*., 2016). Legislation in all countries requires that all pesticides including botanicals must be registered; a process that requires detailed data. This remains a major constraint to promotion and marketing. However, successes in some countries like India, Kenya and Tanzania where specific procedures have been developed for biopesticide registration has led to remarkable successes in this regard (Sola *et al*., 2014).

Nevertheless, there are already several pesticidal plants that have been adequately researched (neem, pyrethrum, tephrosia) presenting opportunities for marketing and upscaling. For this to happen there is need to invest in local production and distribution; development of low-cost technologies and value chain development where small-scale farmers can play a critical role (Sola *et al*., 2014; Anjarwalla *et al*., 2016).They also use local botanicals neem, hot pepper, local plants and some farmers report success. Other farmers recycle the naturally occurring entomopathogens, by collecting the larvae killed by virus or fungi, grinding them, straining the body parts out leaving just the fungal spores or viroid particles, mixing this filtrate with water and spraying it back into the whorls of infested plants.

### 2.9.9 Use of synthetic insecticides

An insecticide is a pesticide formulated to kill insects. Chemical insecticides of manmade or synthetic products continue to be the main method of battling insect pests of crops. These insecticides are usually registered by the environmental protection agency (EPA) that are considered to pose minimal risk to the user and the environment when used as directed. Insecticide applications can be effective for specific pests if used carefully. Rwomushana *et al*., (2018) stated that numerous synthetic pesticides can kill FAW and manufacturers and distributors have been pursuing registration for many different active ingredients.

Rwomushana *et al*., (2018) again stated that the 2017 Evidence Note identified seed treatment as possible use of pesticides for FAW control, and a product (Fortenza Duo) based on cyantraniliprole and thiamethoxam is being promoted by Syngenta and the African Development Bank. Results from trials of seed treatment in Zambia suggest that the product offers protection of seedlings for up to 4 weeks and potentially saves the farmer 1- 3 foliar insecticide sprays in commercial farms. Seed treatments may be more useful when they complement insect resistant seed traits, as the treatment will not protect the crop from the larvae that migrate from the whorl and feed on the ears during later crop stages. The efficacy of the seed treatment may also be affected by soil type, as seed sown in sandy soils emerges faster and benefits from longer protection than seed sown in loamy or clay soils. Whether seed treatment will be cost-effective for smallholders remains to be seen.

Chemical synthetic insecticides are still considered the mainstay of agricultural pest control. Although the development of resistance against insecticides is a common phenomenon, recent advances in research and technology have renewed interest in this subject and resistance risk assessments have been developed for many species using different assay methods (Durmuşoğlu *et al*, 2015).

## 2.10 Insecticide resistance

Insecticides are usually applied to sweet corn in the southeastern states to protect against damage by fall armyworm, sometimes as frequently as daily during the silking stage. In Florida, fall armyworm is the most important pest of corn. It is often necessary to protect both the early vegetative stages and reproductive stage of corn. Because larvae feed deep in the whorl of young corn plants, a high volume of liquid insecticide may be required to obtain adequate penetration. Insecticides may be applied in the irrigation water if it is applied from overhead sprinklers. Granular insecticides are also applied over the young plants because the particles fall deep into the whorl. Some resistance to insecticides has been noted, with resistance varying regionally. Foster

(1989) reported that keeping the plants free of larvae during the vegetative period reduced the number of sprays needed during the silking period. The grower practice of concentrating the sprays at the beginning of the silking period instead of spacing the sprays evenly provided little benefit.

Insecticide applications are the main control measure against fall armyworm, but several applications are required to be effective (Hruska and Gladstone, 1988; Bokonon *et al*.,2003) and development of resistance to selected insecticides has been reported (Pitre, 1986). According to review of CABI, (2017) many of the cheapest and most widely used pesticides is not known whether the FAW populations in Africa were already resistant on arrival, but strategies should be devised and implemented to reduce the likelihood of pesticide resistance developing. Pests develop resistance to pesticides through repeated exposure of successive generations to chemicals with the same mode of action if and only if strategic application way is applied based on principles of manufacture. (Pitre, 1986).

The insect is known for building-up resistance to insecticides very quickly. It is therefore essential that farmers rotate insecticides with different modes of action to avoid resistance build-up. Rotating between different active ingredients is not enough. Consecutive generations of fall armyworm must be treated with insecticides with different modes of action. Insecticides belonging to the diamide chemical class must be used with care. Please consult the labels of these insecticides with regards to application cycles and the number of applications per season.

Application according to Crop Life South Africa should be done when 5-10% of the plants have been infected. Effective control can only be obtained if the larvae are sprayed during the early development stages. Control of adult larvae is very difficult. Spray the larvae when they are visible, e.g. when they are feeding on exposed leaf surfaces or the outside of the cobs. As soon as they penetrate the whorl or are inside the cobs, nothing will effectively control them. Therefore, early detection is essential as the small larvae are easier to control, effectively. The application equipment must be in a good working condition and be calibrated before any application is done. Do not spray between the maize rows as the target sites will be missed and control will be inadequate. Aim the application at the insects in the plant row. Adhere to guidelines for the safe application of the insecticide, such as wearing protective clothing and using face masks

# CHAPTER THREE

## 3.0 MATERIAL AND METHODS

### 3.1 Laboratory efficacy studies

### 3.1.1 Study area

The laboratory insecticide bioassay experiment was conducted at the Entomology laboratory, Faculty of Agriculture (FOA), University for Development Studies (UDS), Nyankpala in the northern region of Ghana between May and August 2018.

### 3.1.2 Test insecticides

The insecticides tested represented various classes and mixtures that are marketed by different chemical companies and recommended for use in the control of fall armyworm in Ghana. Each insecticide was a combination of two active ingredients, with varied modes of action and chemical groups. Table 3.1 shows a list of the test insecticides.

**Table 3.1: Insecticides used in the study**

| Trade Name | Active Ingredients | Chemical Groups | Manufacturing Company | Application Rate |
|---|---|---|---|---|
| ATTACK | Emamectin Benzoate 1.9% (Wv) Ec + Nonhazardous Ingredient 98.1% | Avermectins, Milbemycins | Iprochem | 300 ml/ha |
| NORMAX | Teflebenzuron 75g/L + Alphacypermethrin 75 g/L | Benzoylureas | BASF Agri production | 300 ml/ha |
| GALIL | Imidacloprid 250g/L + Bifenthrin 50g/L | Neonicotinoids | Adama Makhteshim | 65 ml/ha |
| ADEPA | Ethyl Palmitateethyl Oleate, 9-Methyl-Z-10-Tetradecen-1-Olacetate.Elcosen-1-Ol, Cis-9-Trans Squalene | Organophosphates | Kwadustsa and Joam Co Ltd | 1 /ha |
| EMASTAR | Emamectin Benzoate 12g/L + Acetamiprid 64g/L | Avermectins, Milbemycins | Adama Makhteshim | 250 ml/ha |

| | | | | |
|---|---|---|---|---|
| DEAN | Emamectin Benzoate 12g/L + Imidacloprid 50g/L | Avermectins, Milbemycins | Eastsun Chemical | 1 /ha |
| K-OPTIMAL | Lambda-Cyhalothrin 15g/L + Acetamiprid 20g/L EC | Pyrethroids | Eastsun Chemical | 1 /ha |
| PYRINEX QUICK | Chloropyrifos 400g/L + Deltamethrin 24g/LEC | Organophosphates | Adama Makhteshim | 500 ml/ha |
| NEEMAZAL | Azadirachtin | Botanical | Locally produced | 600 ml/ha |

### 3.1.3 Collection of fall armyworm larva

Samples of fall armyworms (FAW) larva at different instar stages were collected from the leaf whorl-stage on field maize near Nyankpala. This field maize was untreated at the time of the larval collection. The larva sampling was done using a pair of forceps and a glass jar lined with moist tissue with a net cover. The presence of frass, windowpanes and cut whorl on the plants made location of the larvae easy. When a larva was identified, a small brush was used to brush it into the glass jar. The larvae were collected from a thorough search of several maize plants from different locations of maize on the field. These were carefully transported from the field to the laboratory for bioassay.

### 3.1.4 Preparation of serial dilutions of insecticides

Nine synthetic insecticides obtained from an agro input dealer shop were used. Table 3.1 shows the list of insecticides. Each Synthetic insecticide was thoroughly mixed with water following the manufacturers 'recommended dose rate to create a stock solution. This was done by taking the required dosage of each insecticide using syringes. The dosage pulled was transferred into a plastic vial. Proportional quantity of water desired was then added into the plastic vial containing measured insecticide formulation and then agitated thoroughly to obtain a homogenous solution. The procedure was repeated for all the nine insecticide treatments. Serial dilutions of desired concentrations were standardized for each insecticide.

### 3.1.5 Experimental design and bioassay procedure

The experiment was laid out in a Completely Randomized Design (CRD). Each of the insecticide treatments were replicated four (4) times. The leaf-dip method was adapted for this experiment. This method is fairly like field exposure conditions and has been used to monitor insecticide resistance in many lepidopteran pests. The leaf dip procedure also allows the product to be distributed uniformly on leaf surface and makes it possible to check whether doses are effective for pest control (Paramasivam and Selvi, 2017). Maize was planted in an insect proof screen house devoid of the adult FAW. At 5 weeks after planting, fresh leaves were collected from the un-infested plants for the bioassay. The leaves were dipped individually into the prepared insecticide solution for 10 seconds with gentle agitation. These were air dried for 2 hr at room temperature. A total of Forty (40) leaves were dipped per treatment. For the control treatment, the leaves were dipped in clean water and air dried as was done for the insecticide. The treated leaves were placed in labeled petri dishes, suitable for holding the leaf material in good condition for up to the number of days required for the experiment.

One larva was put in each petri dish. There were 10 petri dishes for each treatment in a replication. In all there were 40 petri dishes for a treatment. Single larva was put per petri dish to check cannibalism. The Petri dish was stored in a chamber where not exposed to direct sunlight and extreme temperature. The incubation chamber was equipped with a humidifier to ensure the leaves stay fresh for the 96 hours observation period.

### 3.1.6 Data collection and analysis

Observations for instar mortalities were made at an interval of 12 hr, 24 hr, 48 hr and 72 hr after treatment. Final observation was made at 96 hours at which time some of the larvae in the control containers had molted.

Larvae were considered dead when touched with a fine camel brush and no coordinated movement seen. Also, larva was exposed to sunlight to confirm their death if not responding to the heat.

The data obtained on average mortality was converted to percent mortality of fall armyworm for each treatment at each time checked and corrected for control mortality using Abbott's formula as follows

Corrected % Mortality = $\frac{\text{\% mortality in treatment} - \text{\%mortality in control}}{100 - \text{\% mortality in control}}$ x 100 (Abbott, 1925).

The data were then subjected to analysis by using Analysis of Variance (ANOVA) and means were separated by using Least Significant Difference (LSD) test at 5% significance level. The statistical analysis was performed using GENSTAT 12th edition. A correlation analysis was performed to determine the relationship between mortality and the various insecticide treatments.

## 3.2.0 Field efficacy studies

### 3.2.1 Study area

The field efficacy experiment was conducted on a farmer's field at Sung in the Karaga District (latitude 9° 55'30" N and longitude 0° 25'47" W of the equator), of the northern region of Ghana, during the 2018 cropping season.

### 3.2.2 Land preparation and planting

The experimental field was cleared of all bushes, herbage and shrubs, disc ploughed and disc-harrowed to fine soil tilt during the last week of June 2018. Each plot was then lined pegged and labeled before planting. An improved high yielding maize variety (Ahondzin), obtained from a seed grower in Tamale was used. Sowing was done the 24/6/2018. A maximum of 3 seeds were sown per hill and later thinned to 2 plants per stand two weeks after emergence. A pre-emergent Pendimethalin (Activus 500 EC) and post emergent Nicosulfron 230 g/kg + Mesoterion 570 g/kg (Super-Nicogan 800 WG) weedicide was used to control weeds.

### 3.2.3 Experimental design and treatments

The field was laid out in a randomized complete block design (RCBD). A total of 30 plots, each measuring 4m by 4m with inter row and intra row spacing of 0.8 m and 0.4 m respectively was used. A 1-meter distance was allowed between plots and 2 meters between blocks to avoid spray drift to adjacent plots. A total plot size of 16m$^2$ was therefore covered.

The test insecticides used were like those of the laboratory experiment described earlier.

### 3.2.4 Application of treatments

The insecticides used (Table 3.1) were obtained from an agro input shop in Tamale market. Each of the ten treatments was applied in three replications at 3 weeks after germination. The spraying was done with a previously calibrated hand - operated knapsack sprayer of 15-liter capacity fitted with a hollow cone nozzle. The control plots were sprayed with clean water only. All agronomic practices were kept even on all plots throughout the experiment.

Twenty plants from each plot were selected, at random for recording the pest population and damage. Action for Control was needed when egg masses were present on 5% of the plants or when 25% of the plants showed damage symptoms and live larvae were present. On each spraying occasion, all experimental units were treated on the same day. Plants in each plot were sprayed until complete coverage or wetting was achieved. Treatment was repeated if the spraying was followed by a significant rainfall within 6 hours. (Passerini and Hill, 1993). The population of fall armyworm was recorded a day before and 3, 5 and 7 days after treatment. Per cent population mortality was corrected for control mortality and calculated by using modified Abbot's formula (Fleming and Retnakaran, 1985) as below:

% corrected mortality

$$=1-\left(\frac{\text{Post−spray population in treatment x pre−spray population in control}}{\text{Pre−spray population in treatment x post−spray population in control}}\right) \text{ x } 100$$

### 3.2.5 Data collection and analysis

A total of 20 plants selected from each treatment were carefully examined for mortality at

3, 5, and 7 days after treatment (DAT). Dead larvae were collected, counted and recorded.

Larvae were considered dead if they could not make coordinated movement away from a gentle stimulation with a paint brush or when exposed to the heat of the sun.

The data obtained were analyzed by using analysis of variance (ANOVA) and means were compared by using least significant difference (LSD) test at $p < 0.05$. Correlation analyses was performed to determine the relationship between mortality at 3, 5 and 7 days after treatment against the different insecticide.

# CHAPTER FOUR

## 4.0 RESULTS

### 4.1 Toxicity of insecticide in the laboratory bioassay

The results on the toxicity of the insecticides against the FAW larvae from the laboratory studies are presented in Table 4.1. All the insecticides proved toxic to the larvae. After 12 hours of inoculation, Dean and Ema star recorded 100% larval mortality while no mortalities were recorded for the control treatment. The 100% mortality recorded for Dean and Ema star at 12 hours was not significantly different from the 96.67% recorded for Attack. They were however significantly different from the 50% mortality recorded for Pyrinex quick. The least mortality at this period were recorded in Neemazal, Galil. Adepa, Normax and K-Optimal that were not significantly different from that of the water control at 12 hours. A similar trend was observed at 24 hours after exposure although there was a general increase in mortality across all the treatments except Neemazal.

In 48 hours however, the mortalities recorded for K-optimal, Normax and Neemazal had increased and were not significantly different from each other but were significantly greater than the water control (Table 4.1). The mortality caused by Pyrinex was like those in Dean, Attack and Ema star, that recorded the highest mortality after 48 hours after exposure.

The results generally showed Fall armyworm mortality increased with time.

**Table 4.1: Effects of insecticide treatment on fall armyworm mortality in the lab.**

| INSECTICIDE TREATMENT | Mean Larvae mortality (%) after hours of exposure | | | | |
|---|---|---|---|---|---|
| | 12 hr. | 24 hr. | 48 hr. | 72 hr. | 96 hr. |
| ADEPA | 16.67a | 20.00a | 40.00b | 50.00ab | 66.67ab |
| ATTACK | 96.67c | 100.00c | 100.00c | 100.00d | 100.00c |
| DEAN | 100.00c | 100.00c | 100.00c | 100.00d | 100.00c |
| EMA STAR | 100.00c | 100.00c | 100.00c | 100.00d | 100.00c |
| GALIL | 10.00a | 20.00a | 26.67ab | 50.00ab | 60.00ab |
| K-OPTIMAL | 13.33a | 30.00a | 50.00b | 70.00bc | 80.00bc |
| NEEMAZAL | 10.00a | 10.00a | 46.67b | 60.00b | 63.33ab |
| NORMAX | 13.33a | 26.67a | 43.33b | 63.33b | 76.67abc |
| PYRINEX QUICK | 50.00b | 70.00b | 76.67c | 93.33cd | 93.33c |
| WATER | 0.00a | 6.67a | 10.00a | 33.33a | 53.33a |
| LSD | 24.29 | 26.20 | 23.68 | 24.68 | 26.20 |
| Cv | 34.80 | 31.80 | 23.40 | 20.10 | 19.40 |
| p-value | <0.001 | <0.001 | <0.001 | <0.001 | 0.004 |

## 4.2 Correlation for larvae mortality after different time

There were significant correlations between larvae mortality for all the periods under observation. Correlation between 12 hr and 24 hr was close to unity (r = 0.97, $p < 0.000$). It was observed that co-coefficient of the relationship between any two consecutive incubation period was close to unity (Table 4.2).

**Table 4.2: Correlation of larval mortality after different exposure time**

| | 12 hr | 24 hr | 48 hr | 72 hr | 96 hr |
|---|---|---|---|---|---|
| 12 hr | - | | | | |
| 24 hr | 0.97** | - | | | |
| 48 hr | 0.92 ** | 0.925** | - | | |
| 72 hr | 0.82 ** | 0.875** | 0.95** | - | |
| 96 hr | 0.75 ** | 0.765** | 0.86** | 0.92** | - |

## 4.3 Efficacy of insecticide in the field trial

### 4.3.1 General observations

The major insect pest encountered in the field was the fall armyworm. The outbreak of FAW occurred during the third week after plant emergence. The FAW larvae were found in the whorl, on the leaves and around the stems behind feeding holes and frass on leaves and on developing shoots. Infestation by various instar larval stages caused damage to plants and suppressed growth and subsequent yield of the maize. The larvae of the FAW bore into the whorl, leaves and subsequently damaging cobs.

Important natural enemies of the pests such as parasitic wasps, ants and lady bird beetle predators were present in the field. Moreover, it was also observed that maize plants treated with the k-optimal suffered phytotoxic leaves. All other treatments did not show any abnormal colour changes in their leaves. It was observed that ema star persisted for control than Dean as was noted with their differential mortality in the 5th and 7th DAT. Pyrinex quick appeared to have quick knockdown effect and less persistent.

### 4.3.2 Insecticide efficacy

There were significant differences among the treatments for the number of dead fall armyworm larvae collected on 3, 5 and 7 days after the insecticide spraying (Table 4.3). On the third day after application, means of 7.0 dead worms were recorded for Dean treated plots while no dead worm was collected from the water treated field. Similarly, Ema star and Pyrinex quick were significantly different from the control. However, there was no significant difference between Dean, Ema star, and Pyrinex quick. Mortality of Attack, Adepa, Galil, K-Optimal, Neemazal, and Normax were not significantly different from the control.

On the fifth day (5 DAT), a mean of 4 dead larvae were counted for Ema star treated plots while no dead worms were recovered from plots treated with Attack, Galil and water.

Mortality was significantly highest in Ema star, but this was not higher than those in Dean Neemazal and Pyrinex quick

**Table 4.3: Effects of insecticide treatment on fall army worm mortality on the field.**

| INSECTICIDE TREATMENTS | Mean larval mortality (%) after exposure | | |
|---|---|---|---|
| | 3 DAT | 5 DAT | 7 DAT |
| ADEPA | 1.67 (1.35) | 1.33 (1.18) | 0.33 (0.88) |
| ATTACK | 0.33 (0.88) | 0.00 (0.71) | 0.33 (0.88) |
| DEAN | 7.00 (2.71) | 4.33 (2.20) | 3.33 (1.90) |
| EMA STAR | 5.33 (2.40) | 4.67 (2.26) | 5.67 (2.48) |
| GALIL | 2.33 (1.57) | 0.00 (0.71) | 1.00 (1.17) |
| K-OPTIMAL | 2.67 (1.61) | 0.33 (0.88) | 0.33 (0.88) |
| NEEMAZAL | 2.33 (1.66) | 2.67 (1.56) | 0.33 (0.88) |
| NORMAX | 2.67 (1.64) | 1.67 (1.44) | 1.67 (1.35) |
| PYRINEX QUICK | 6.67 (2.61) | 2.00 (1.32) | 1.33 (1.18) |
| WATER | 0.00 (0.71) | 0.00 (0.71) | 0.00 (0.71) |
| LSD (5%) | 3.78 (1.05) | 2.69 (0.79) | 2.08 (0.68) |
| CV (%) | 71.10 (35.70) | 92.20 (35.60) | 84.60 (32.00) |

DAT = Days after treatment; values in parenthesis are square root transformed values.

Similarly, Ema star recorded the highest (5.67) larvae mortality at 7 DAT. However, number was not significantly different from that of Dean (3.33). Generally, the number of dead fall armyworms larvae recovered from the plots was low. No mortality was recorded in water treated control throughout the periods of data collection.

### 4.4 Correlation between larval mortality and days after exposure

There were no significant relationships between the number of dead larvae counted on the 3, 5 and 7 days after application and grain yield. It was however observed that the number of dead larvae at 5 DAT was strongly correlated with number of dead larvae at 7 days after application (Table 4.4). Also, there were significant correlations between 3 and 7 days after application and a weak correlation observed 3 and 5 days after application.

**Table 4.4: Correlation between larvae mortality and grain yield**

| | DAT 3 | DAT 5 | DAT 7 |
|---|---|---|---|
| DAT 5 | 0.3372 ** | | |
| DAT 7 | 0.2817 ** | 0.5436 ** | |
| Yield (kg/ha) | 0.2487ns | 0.1986ns | 0.0227ns |

ns= not significant; ** = significant ($p < 0.001$)

### 4.5 Impact of insecticide treatment on maize yield

The yield of maize ranged from 930-2730 kg/ha when the various insecticide treatments were applied (Figure 4.13). The lowest yield was recorded for water treatment plots while the highest was from plots sprayed with Dean. There were significant yield differences among the insecticides applied. Generally, applying insecticides resulted in more than double the yield than water control. Neemazal was also significantly higher than control.

All the insecticides yielded significantly higher than the water control.

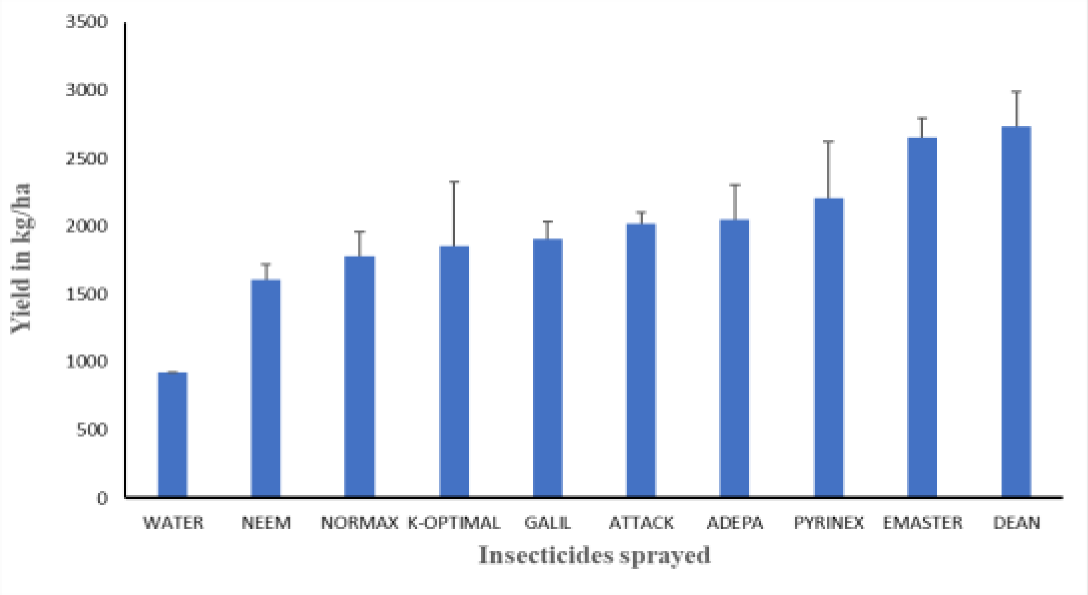

**Figure 4.1: Effect of insecticide treatment maize grain yield.**

# CHAPTER FIVE

# DISCUSSION

## 5.1 Effect of insecticides on fall armyworm mortality

In this study, all the synthetic insecticides tested were toxic to FAW larvae. They demonstrated high larval mortality in both laboratory and field trials. In laboratory bioassays, moderate to high larval mortality was achieved with Pyrinex Quick, Attack, Ema star and Dean. It was noted that in both the laboratory and field trials, the percent larval mortality increased over time after insecticides application, which may indicate residual toxicity of the insecticides to FAW.

The results obtained in the field study revealed that the highest dry weights were obtained from plants treated with synthetic insecticides compared to control plants. As is common with other insect pest species, synthetic insecticides are important management options in FAW control in the Americas (Andrews, 1988).

In Mexico, chemical control of FAW in maize is achieved by the application of methylparathion, chlorpyrifos, methamidophos, and phoxim, among other synthetic insecticides (Malo *et al*.,2004). Also, in the southern United States, synthetic insecticides are applied on sweetcorn against FAW, often 3–4 times weekly. In Florida, FAW is one of the most important sweetcorn pests, and synthetic insecticides are applied to protect both the vegetative stages and reproductive stage (Capinera, 2017). Several insecticide applications are required to kill larvae feeding deep in the whorl of plants. In situations in which overhead sprinklers are used for irrigation, synthetic insecticides can also be applied in the irrigation water. Keeping plants free of larvae during the vegetative period can help to reduce the number of sprayings needed at the silking stage (Foster,1989)

Some of the synthetic insecticides reported by those authors corroborate the findings of the present study. For example, there was a general increase in larvae mortality as the exposure time increased. This observation is like the findings of Birhanu *et al.* (2019) and they suggested that increasing mortality over incubation time may be due to residual toxicity of the insecticides. Although synthetic insecticides are effective to control FAW, in Africa the increased risk to human health due to a lack of appropriate safety precautions is a major concern about synthetic insecticide use (Abrahams *et al.*,2017).Furthermore, the pest has developed resistance to major classes of synthetic insecticides in its native region (Yu,

1991). This suggests the need for resistance management as a vital component of IPM. Resistance management is likely to be successful when combined with routine monitoring of pests, and the use of non-pesticidal methods such as biological and cultural control, field

sanitation, and host plant resistance. Thoughtful and appropriate use of synthetic insecticides is essential for the successful management of FAW and for the increased productivity of maize in Africa. The recent invasion of FAW has alarmed governments of numerous African countries and caused them to deploy a massive pesticide spraying program as an emergency response in FAW-affected areas, mainly to maize fields to protect against crop damage and prevent the expansion of the pest. In recent surveys conducted in Kenya and Ethiopia, it has been noted that farmers are applying different types of unregistered synthetic insecticides according to (Kumela *et al.*, 2018), possibly because of the invasive nature of the pest, which requires a rapid response and a lengthy pesticide registration process.

From this study, all the pesticides tested had lethal effects on the Fall armyworm larvae. The active ingredients in the insecticides were toxic to the FAW larvae. Although all the insecticides were toxic, some were more lethal than the others. Ema star, Dean and Attack showed 100% mortality within 12 hours after exposure in the laboratory. This may be due to the chemical group they belong. All three (Ema star, Attack and Dean) are avermectin and milbemycin's. The quick action from Ema star and Dean may also be due to their dual mode of action (systemic and systemic). Although Attack is labelled as a non-systemic botanical, it was able to elicit 96.67% mortality within 12 hours of inoculation. This may be due to its potency as a contact insecticide. The gradual increase in larval mortality over time suggests that the residual toxicity of the insecticides could deal with the overlapping generations of the Fall armyworm. Ema star especially ensure a clean field because of its persistent nature in control devoid of pinhole leaves and other damages of FAW when they are sprayed early. Application according to Crop Life South Africa should be done when 5-10% of the plants have been infested. Effective control can only be obtained if the larvae are sprayed during the early development stages. Control of adult larvae is very difficult and must not be allowed up to the later instar stage before controls measures are triggered.

From the field study, it was observed that the number of dead worms recovered after spraying the insecticides was generally low. This may be due to larvae feeding deep in the whorl that they could not be easily recovered even if they died. The low level of mortality may also be due to the uneven distribution of the pest on the field. Unlike in a screenhouse experiment conducted under controlled conditions and artificial infestation, where high mortalities are recorded, conditions on the field are highly variable and infestation is normally heterogenous.

### 5.2 Impact of insecticide treatments on maize yield

The fall armyworm feeds on the leaves of the maize plant during the vegetative phase and move to the cobs during the silking and grain filling stage FAO (2018). From this study, it was found that the application of all synthetic insecticides to control the Fall Armyworm resulted in yield increment over the water control plots. The use of pesticides has led to more than doubling the yields and without pesticides crop productivity will drop resulting in increase of food prices.

The yield recorded by spraying Ema star and Dean was almost thrice the yield recorded from the water control field. Neem oil which is readily available also showed a significant yield increment over the water control. All the insecticides showed increased grain yield which suggests that they are effective in fall armyworm control.

# CHAPTER SIX

## 6.0 CONCLUSION AND RECOMMENDATIONS

### 6.1 Conclusion

The study revealed that all the insecticides tested were toxic against the FAW. The swiftness to kill the larvae however varied among the insecticides. While Ema star and Dean caused 100% mortality within 12 hours, it took Attack 24 hours to cause 100% mortality. Only Ema star, Dean and Attack caused 100% larvae mortality in the lab experiment. This was followed by Pyrinex quick and K-optimal which caused 93.33% and 80% mortality respectively. Galil caused the lowest mortality from the leaf-dip experiment. In the field studies, not all dead larvae could be recovered after spraying hence the low number of mortalities recorded. However, the application of Ema star and Dean resulted in the highest mortality of the larvae with attack recording the lowest. Ema star was found to be persistent and last longer in the control of the larvae.

Moreover, Ema star and Dean give more than 250% increase in grain yield relative to the water control. Also, maize grain yield was highest in plots sprayed with Ema star or Dean and lowest in Neemazal**.** Generally, spraying of insecticides led to yield increment and reduced the severity of the FAW on the field.

## 6.2 Recommendations

Based on the conclusions from the findings of this study, the following recommendations could be made.

Farmers can achieve the most effective control of FAW and for maximum grain yield with the use of Ema star or Dean at their recommended doses.

Where Pyrinex quick, K-optimal, Normax, Adepa and Neemazal becomes the sole option, farmers may need to spray at higher dosages for effective control

Further work needs to be done to evaluate the residual life of these insecticide as well as the potential of pest to develop resistance to them.

It is also recommended that follow-up studies should be conducted to evaluate the effects of insecticides on yield under artificial infestation in a greenhouse and perform cost benefit analysis for the various insecticides

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# APPENDICES

APPENDIX 1: ANOVA table of number of dead larvae at 3 days after treatment

| Source | DF | sum of square | mean square | F value | pr(>F) |
|---|---|---|---|---|---|
| REPS | 2 | 7.8 | 3.9 | | |
| TRT | 9 | 161.367 | 17.9296 | 3.69 | 0.0089 |
| Error | 18 | 87.533 | 4.863 | | |
| Total | 29 | 256.7 | | | |

APPENDIX II: ANOVA table of number of dead larvae at 5 days after treatment

| Source | DF | sum of square | mean square | F value | pr(>F) |
|---|---|---|---|---|---|
| REPS | 2 | 25.8 | 12.9 | | |
| TRT | 9 | 82.3 | 9.1444 | 3.72 | 0.0085 |
| Error | 18 | 44.2 | 2.4556 | | |
| Total | 29 | 152.3 | | | |

APPENDIX III: ANOVA table of number of dead larvae at 7 days after treatment

| Source | DF | sum of square | mean square | F value | pr(>F) |
|---|---|---|---|---|---|
| REPS | 2 | 8.867 | 4.43333 | | |
| TRT | 9 | 86.033 | 9.55926 | 6.5 | 0.0004 |
| Error | 18 | 26.467 | 1.47037 | | |
| Total | 29 | 121.367 | | | |

APPENDIX IV: ANOVA table of grain yield

| Source | DF | sum of square | mean square | F value | pr(>F) |
|---|---|---|---|---|---|
| REPLICATION | 2 | 0.01 | 0.005 | 0.07 | 0.9288 |
| TREATMENT | 9 | 7.1429 | 0.7937 | 11.79 | 0 |
| Error | 18 | 1.2113 | 0.0673 | | |
| Total | 29 | 8.3642 | | | |