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UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

EFFECTS OF DIFFERENT CONTROL STRATEGIES ON MAIZE PLANT RECOVERY AND YIELD AFTER FALL ARMYWORM INFESTATION

BY

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DECLARATION

I, hereby declare that except for references from other peoples' work which have been duly acknowledged, this thesis is my work towards the award of Master of Philosophy in Entomology carried out at the African Regional Postgraduate Programme in Insect Science (ARPPIS) University of Ghana, Legon, this work has not been submitted in whole or in part for any degree in this or any other university.

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DEDICATION

I dedicate this work to the Almighty God for His love, care, and mercies which protected me through my academic journey.

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ABBREVIATIONS

BT	: *Bacillus thuringiensis*
CABI	: Centre for Agriculture and Biosciences International
FAW	: Fall Army Worm
ICIPE	: International Centre of Insect Physiology and Ecology
MoFA	: Ministry of Food and Agriculture
PHL	: Post-harvest losses
LD	: Levels of destruction

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ABSTRACT

The larvae of Fall Armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith), (Lepidoptera: Noctuidae), can cause significant damage to crops such as maize if not well managed. The purpose of this study was to determine the levels of natural infestation of FAW along the phenology of maize under field conditions, investigate the critical stages for FAW control along maize phenology, and to ascertain the effect of different treatments on maize recovery and yield after FAW infestation. This was a descriptive cohort study in which 270 plants (150 for screen house and 120 for natural field) were infested with FAW at the various growth stages and followed to assess the level of damage using a scale developed by Davis and colleagues. The field plants were also treated with three different pesticides (Neem extract, *Bacillus. thuringiensis*, and Emamectin benzoate) to assess their effects on FAW and maize recovery and yield. Findings from this study reveal that, the most critical stages for controlling the FAW along the maize phenology are the seedling and vegetative growth stages. These stages are most susceptible to damage by FAW. Yield of maize was significantly higher on the plot with *B. thuringiensis* insecticide treatment (133.33 ± 4.76)kg/h followed by Emamectin benzoate (125.43 ± 1.383) kg/h and Neem extract (10.96 ± 1.64) kg/h , $P < 0.01$. Concerning recovery, in the screen house experiments, all the plants infested at the seedling and vegetative stages died before they could reach the tasseling stage. Meawhile, no death occurred when plants were infested at the tasseling and fruiting stages. On the natural field, no plant death was recorded (100.0% survival) on the treatment plots (Neem, *Bt*. and Emamectin benzoate) along the growth stages, while 4/30 (13.3%) of the plants died at the vegetative growth stage on the control plots. The insecticides used in the study had varied effects on FAW damage at different growth stages of the maize plant.Ths implies that each growth stage of the maize plant may require different insecticide treatment for effective control of FAW population especially at the seedling and vegetative stages where maize plants are most susceptible

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to FAW infestation. Interventions and policies aimed at controlling FAW on maize plants should therefore concentrate on the seedling and vegetative stages.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Maize is widely distributed all over the world and it is considered as 'Queen of all cereals'. The crop is grown in the temperate zones, sub-tropical zone, and tropical zones and can be grown in several environments (Ranum *et al.*, 2014). Globally, about 116 million tons of maize is consumed per year with 30% consumption in Africa alone. Sub-Saharan Africa (SSA) account for 21% of global consumption. The highest consumption, 174 kg per year, has been reported in Lesotho (IITA, 2018).

Maize is widely eaten in different parts of the world and serves as livelihood support especially for the rural poor. Africa depends on it for survival, because it is relatively less expensive than other cereals. This makes it an important food security crop (CABI, 2017; Prasanna, *et al.*, 2018).

About 85% of harvested maize is used as food by Eastern and Southern Africans, while entire Africa uses 95%, compared to other continents like America that use most of their maize as animal feed (IITA, 2018). Maize production has been the main activity for many farmers. In Africa, the top countries reported to account for about 95% of the total production of maize include Nigeria, Tanzania, Zambia, Kenya, Ghana, Uganda, South Africa, Mozambique, Ethiopia, Malawi, Mali, Cameroun, Angola, Benin, Burkina Faso, Democratic Republic of Congo (DRC), Togo, Zimbabwe, and Cote d" Ivoire (Adejumo *et al.*, 2007; Dutton,2009; De Groote & Kimenju, 2012; Ranum *et al.*, 2014; Vega Lizama & Cucina, 2014).

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The most important cereal crop eaten by most Ghanaians is maize and it is widely recognized. The majority of rural households grow maize in all parts of the country mainly for consumption and economic purposes. In a national survey on maize consumption, it was reported that about 94% of all households had consumed maize during an arbitrarily selected two-week period (Alderman and Higgins, 1992). Boateng *et al., (*1992) have also reported that maize and maize-based foods accounted for 10.8% of household food expenditures by the poor, and 10.3% of food expenditures by all income groups. Although the yield of maize and it's consumption in Ghana has been increasing over the years, from 1.5mt/ha in 2005/07 to 1.7mt/ha in 2008/10, and 42.5 kg per capita in 2000 to 43.8 kg per capita in 2005, respectively this yield is still less than a third of the achievable yield of 6.0 mt/ha [Ministry of Food and Agriculture (MoFA), 2016]. The low productivity has been associated with total reliance on rainfall for cultivation and low utilization of improved seed varieties, fertilizers, herbicides, mechanization, and pesticides (MoFA, 2016). The increase in yield has also been undermined by post-harvest losses (Cornelius *et al.,* 2008).

Considering the relative importance of maize in ensuring food security in Africa, its production needs to be given much attention. On the face of global climate change, coupled with on-farm challenges such as insect pests and crop disease emergence and resurgence, the production of major cereals including maize could decline by as large as 20% by mid-century (Vucetic 2011; Zeng *et al.,* 2018). Several factors have been identified to affect maize production. These include droughts, heat, poor soil fertility, inadequate input including fertilizer supply to farmers, lack of the market for farm produces, unreliable climate conditions such as erratic rainfall, lack of capital for farmers, and pest and disease problems.

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Annually, 54% of maize yield loss is caused by diseases, 20% by an insect pest, and 16% by animals (Shiferaw, 2011). One of the recent pests introduced and causing serious damage and reduction in yield in maize in Africa is the Fall armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera Noctuidae). The FAW has been a nuisance to food crops in Africa since its presence was reported in the continent in 2016 (Wossen *et al.*, 2017). Its presence has been reported in over 30 Sub-Saharan African countries where it has caused extensive damage to crops especially maize fields. The fall armyworm is believed to have originated from America, which occurred as far as from Canada to Argentina. In Ghana, the FAW was first detected in the Yilo Krobo district of the Eastern region in April 2016 (FAO, 2018). Since their introduction, they have become very serious pests to maize and other important cereals and staple crops.

The FAW possesses characteristics that make it unique and more devastating than other crop attacking insects (Prasanna *et al.*, 2018). These include its ability to feed on more than 80 different crops and the capability of spreading very quickly across large geographical areas. It can persist throughout the year meaning it does not only affect crops planted during the rainy season but also the irrigated crops as well and it can lay over 1500 eggs which becomes FAW moths within a space of 28 days (Prasanna *et al.*, 2018).

The impacts of Fall Armyworm have been felt at the national, continent, and household levels mostly in maize producing countries such as Ghana. According to Day *et al.*, (2017), the potential impact of FAW on the continent's maize yield lies between 8.3 and 20.6 million tonnes per annum of total expected production of 39 million tonnes per annum and with losses lying between $2,481 and $6,187 per annum of the total expected value of $11,590.5 per annum. A recent household socio-economic survey in Ghana has reported an estimated national mean loss of maize due to

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FAW to be 45% (Day *et al.*, 2017). This high economic lost call for strategies in controlling this debilitating pest.

1.2 Justification

In Ghana, maize is grown in all agroecological zones and is an important staple food accounting for more than 50% of total cereal production (Akramov and Malek, 2012). The bulk of maize produced goes into food consumption and it is arguably the most important food security crop with a per capita consumption of 43.8kg/head in 2005 (SRID-MoFA, 2011). However, the productivity of maize in Ghana is lower (1.7 t/ha) than the expected yield of 6.0 t/ha (SRID-MoFA, 2011). A combination of factors has been attributed to the low yield including drought, low soil nutrients, inappropriate planting time, inadequate control of weeds, limited use of agricultural inputs (especially fertilizer and improved seeds), diseases, and field pests infestations (SRID-MoFA, 2011).

One of the recent pests introduced and causing serious damage and reduction in yield in maize in many African countries including Ghana is the Fall armyworm (FAW). The introduction of the FAW in 2016 has affected over 18,000 hectares (ha) of farmlands, causing the country to lose about $64 million (FAO, 2018). A recent household socio-economic survey in Ghana has reported an estimated national mean loss of maize due to FAW to be 45% (Day *et al.*, 2017). The FAW causes damage by feeding on both vegetative and reproductive structures. Two major concerns have dominated discussions since the outbreak of the Fall Armyworm. Reports of control failure with recommended pesticides. The reasons for control failure: are under-dosing, ineffective active ingredients, and resistance in the FAW population (Prasanna *et al.*, 2018). Notwithstanding, there have been arguments that there is a critical period beyond which treatment may not be effective.

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This implies that with adequate control at the critical stage yield should not be affected. The questions are what are these critical stages? And how do the different recommended control measures save the situation when applied at these critical stages? This study therefore aimed at providing answers to some of these pertinent questions.

1.3 Main objective

This study aimed at determining the critical stages along the maize phenology where FAW infestation is most severe and determine the effect of different treatments on maize recovery and yield.

1.3.1 Specific objectives

1. To determine the levels of natural infestation along the phenology of maize under field conditions.
2. To establish the critical stage for fall armyworm control along the maize phenology in a screen house.
3. To determine the effect of different treatments on maize recovery and yield after fall armyworm infestation

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CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Maize production in Ghana

Maize (*Zea mays* L.) after its introduction in the late 16th century, got established as an essential indispensable crop mainly in the southern part of Ghana. It is the most widely distributed crop of the world as it is cultivated in the tropics, sub-tropics, and temperate regions and thus serves as a universal crop (Ramirez-Cabral *et al.*, 2017).

In Ghana, maize is the most widely produced and consumed cereal crop accounting for more than 50% of local cereal production (Amanor- Boadu, 2012). The crop serves as a major source of calories for the majority of Ghanaians. It is widely eaten because it is often cheaper than rice and wheat, two of the other most consumed cereals. In northern Ghana, the report indicates that it has nearly substituted pearl millet and sorghum as traditional staple crops (Annan, *et al.,* 2005). The grains are also used in making com starch and industrial alcohol, local grain balls "kenkey" eaten with fried fish and pepper and other local foods (Jespersen *et al.,* 1994; Halm *et al.,* 1996; Sanni *et al.,* 2002).

Since 1965, the trend of maize production has been increasing among poorly resourced smallholder farmers (SARI, 1996). The average yearly maize production in Ghana has been reported to be 1.5 million MT between 2007 and 2010 (Rondon and Ashitey, 2011) with an annual yield reported to be growing around 1.1% (McGuire, 2014). In Ghana, the agro-ecological zones for maize cultivation can be mainly grouped into four; Forest zone, Guinea savannah zone, Coastal savannah, and Transitional zone (FAO, 2018).

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In general, the production of maize occurs in almost every part of the country, but more than 70% of the maize output is from three of the agroecological zones (Guinea Savanna, Forest Savanna, and Transitional Zones). The five major maize growing areas are in the Brong- Ahafo, Ashanti, Northern, Central, and Eastern Regions (Oguntunde & van de Giesen, 2004).

The use of maize in homes is more common in Ghana than industrial processing. It can be fermented and used in various forms for meals and also boiled or roasted for food in most homes especially among rural households. Some examples of fermented maize meals in Ghana are "Koko" (porridge), "banku", "tuo zaafi", "akple", "kenkey," etc. The major industrial processing of maize is used mainly as poultry and livestock feeds.

The maize plant like any other living organism has developmental stages. As the plant grows, canopy density increases and makes the plant easily accessible to insects for infestation (Ahmadabadi *et al* 2007). The growth or developmental stages of maize are divided into Vegetative (V), Tasseling (VT), and Reproductive (R) (Fig 2. 1). The V stage of maize is defined as the number of maize leaves displaying a leaf collar and not the total number of leaves on the plant (Prasanna *et al.*, 2018).

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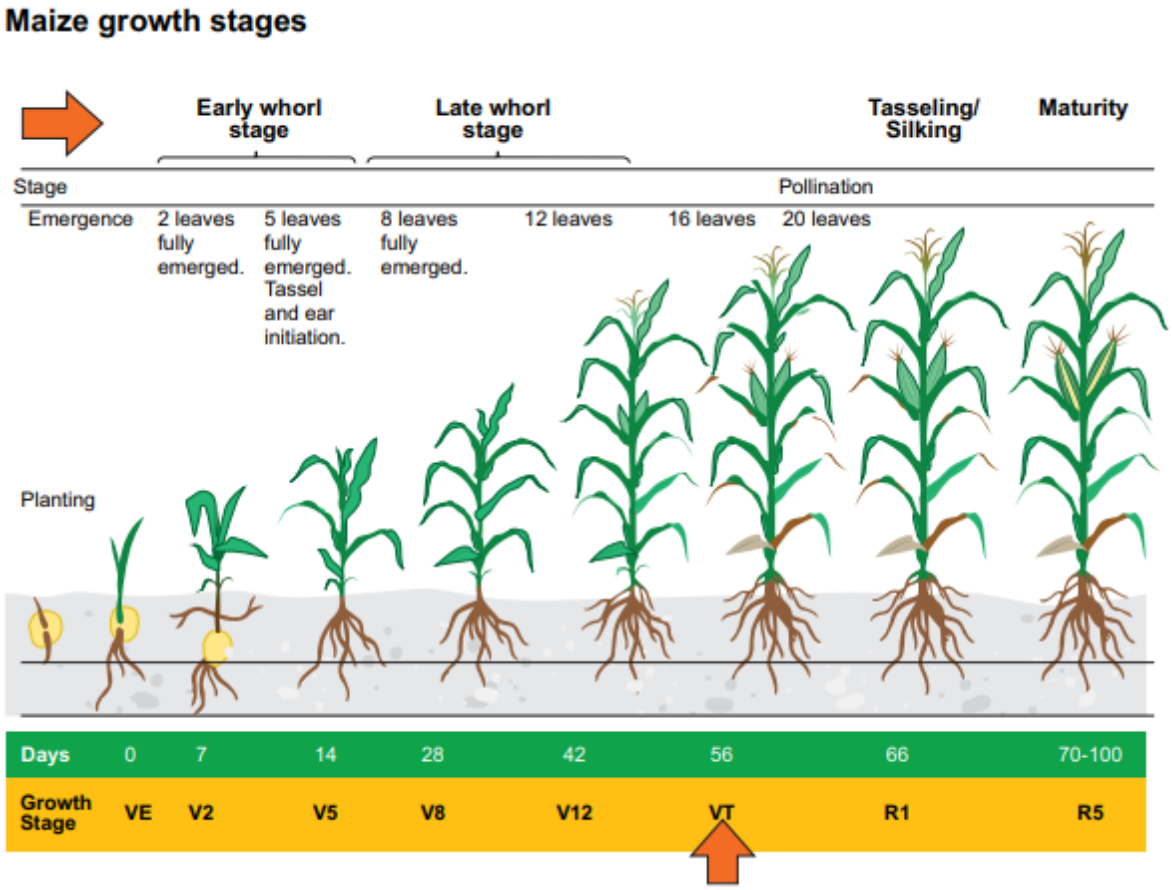

Fig. 2.1: Maize growth stages: "VE to V5 stages" "Early Whorl," the V8 to VT stages "Late Whorl," and "the R1 to R3 stages" "Tasseling & Silking."

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

2.2 Challenges to maize production in Ghana

Even though, the average yield of maize in Ghana has been rising; from 1.5 mt/ha in 2005/07 to 1.7 mt/ha in 2008/10, this yield is less than a third of the achievable yield target of 6.0 mt/ha set by the Ministry of Food and Agriculture (MoFA). Some of the constraints include a combination of factors such as drought, heat, poor soil fertility and water-logging/excess moisture, inadequate transport system, inadequate input and subside for farmers, lack of market for farm produce, lack of storage facilities, unreliable climate conditions such as erratic rainfall, lack of capital for farmers and pest and disease problem. It is estimated that about 54% of the achievable yield of maize is

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lost annually to rodents and insects (20%), weeds (18%), and diseases (16%) in Africa. Similar losses have been reported in Central and South America and Asia (Shiferaw *et al.,* 2011).

2.3 The fall armyworm (FAW)

The order Lepidoptera is one of the largest insect orders in the world and contains butterflies and moths. Butterflies and moths are characterized by scales on their wings that come off when they are handled. Many species in the order Lepidoptera are economically important pests feeding on plants, stored grains, or fabrics. Insects that belong to the order Lepidoptera undergo complete metamorphosis passing through the egg, larva, pupa, and adult stages (Ni *et al.,* 2014; Wossen *et al.,* 2017).

The genus *Spodoptera* belongs to the family Noctuidae where the moths are nocturnal. Noctuidae larvae are smooth and dull-coloured having 5 pairs of prolegs; most of them feed on the foliage of the plant and few on fruits (Martinelli *et al.,* 2007; Kakumani *et al.,* 2015). The genus *Spodoptera* consists of several species that are important crop pests including *S. litura* (Fabricius) (the tobacco caterpillar), *S. exempta* (Walker) (the African armyworm), *S. exigua* (Hübner) (the beet armyworm), *S. ornithogalli* (Guenée) (Yellow striped armyworm), *S. littoralis* (Boisduval) (the Egyptian cotton leafworm) and *S. frugiperda* (J.E. Smith) (the fall armyworm) (Barrera *et al.,* 2015).

The fall armyworm *S. frugiperda* is native to the tropical regions of the western hemisphere from the United States to Argentina. *Spodoptera frugiperda* is an important pest of maize and many other crops throughout the Americas, remaining one of the most common lepidopteran pests in the United States (Clark *et al.,* 2007). It causes significant damages to the cultivated grasses of

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economic importance such as maize, sorghum, sugarcane but also other legumes and cotton. *Spodoptera frugiperda* was reported for the first time in 2016 in several African countries including Ghana, causing significant damages to maize (CABI, 2017).

The larvae of the African armyworm are major pests of cereals and rangeland in many Sub-Saharan African countries. During outbreaks, the species population size and invasion areas can be vast. The fall armyworm presents sympatric speciation that has been studied and described and it appears to be diverging into two strains, the corn and rice strains. However, it is a polyphagous pest that attacks over 80 plant species (Ashley *et al.*, 1989). It commonly feeds on field corn, sweet corn, sorghum, Bermuda grass, rice, and grass weeds such as crabgrass and *Digitaria spp*. Other field crops such as millet, oat, soybean, sugar beet, buckwheat, peanut, are susceptible to damage by the FAW (CABI, 2017).

The young larvae start to feed on the leaf tissue from one side, leaving the opposite epidermal layer intact. By the second or third instar, larvae begin to make holes in leaves and feed on the edge of the leaves inward. Feeding in the whorl of corn often produces a characteristic row of perforations in the leaves. Older larvae cause wide defoliation, often leaving only the ribs and stalks of maize plants, or a ragged, torn appearance (Capinera, 2014).

Studies in the past have shown that infestation by FAW on sweet corn causes more injury at the late whorl stage compared to early and mid-whorl stages. Larvae of FAW burrow into the growing point of plants (buds, whorls, etc.) and destroy the growth potential of plants, or clip the leaves (Marenco *et al.*, 1992). In corn, they also burrow into the ear and feed on kernels like that of corn earworm, *Helicoverpa zea* (Boddie). But, unlike corn earworm, fall armyworm feed by burrowing through the husk on the side of the ear. Leaf damage by FAW and stem borer is also confusing. However, it is possible to determine which species is responsible for the damage through close

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examination as the holes formed by FAW have smooth edges whereas holes cut by maize stem borer larvae have ragged edges (Abel *et al.,* 2000; CABI, 2017).

The corn strain of FAW prefers corn or maize and other large grasses and the rice strain prefers the rice and other small grasses (Martinelli *et al.,* 2007; Kakumani *et al.,* 2014). Maize is however the most attacked crop by the fall armyworm whose populations increase importantly with migration from one region to another. Its densities vary tremendously from year to year and place to place due to the increase of acreage of maize production in traditional agricultural regions (Farias *et al.,* 2008; Ray *et al.,* 2015).

2.3.1 Biology and ecology of FAW

The complete life cycle of the FAW takes about 30 days during the summer but is prolonged (60 days) in the spring and autumn, and 80 to 90 days during the winter. The adult FAW can measure from 32 to 40 mm. Males are brown and grey. In the female, however, they exhibit sexual dimorphism (Prasanna *et al.,* 2018).

The adult insect-pest lays eggs on the upper surface of leaves but occasionally they may lay on other parts of the host plants. The egg is dome-shaped with a flattened base that measures about 0.4 mm in diameter and 0.3 mm in height. A single adult female can lay on average 1500 to 2000 eggs during its lifetime (Rodhain,2015; De La Rosa-Cancino *et al.,* 2016). The FAW has six instars. Young larvae are greenish with a blackhead. During the second instar, the head turns orange. At the third instar, lateral white lines begin to form and the dorsal surface of the body becomes brownish. A reddish-brown head appears in the fourth to the sixth instars mottled with white, and the brownish body bears white subdorsal and lateral lines. Elevated spots occur dorsally on the body which is usually dark in colour and bear spines (CABI, 2017).

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Newly hatched larvae are gregarious and feed on the leaves of the host plant on which the eggs were deposited, but when they grow larger they will disperse to other plants (Capinera, 2014). The first and second instars feed on one side of the leaf and skeletonizing it, but as they grow they eat and make a hole through the leaf. 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 (Capinera, 2014; Rodhain, 2015).

The average duration of the larval stage tends to be about 14 days during the summer and 30 days during cool weather and the pupation normally takes place in the soil, at a depth of 2 to 8 cm (Capinera, 2014). The duration of the pupal stage is about 8-9 days during the summer but can reach 20 to 30 days during the winter (Capinera, 2014).

The colour of the adult moths of FAW varies and their wingspan can reach 32 to 40 mm. Male moths have a shaded grey and brown forewing with triangular white spots at the tip and near the centre of the wing. The forewings of females are less distinctly marked, ranging from a uniform greyish brown to a fine mottling of grey and brown. The hind wing of both sexes is shining silver-white with a narrow dark border (Capinera, 2014; CABI, 2017).

2.3.2 Life cycle of the FAW

2.3.2.1 Egg

One female can lay up to 2000 eggs grouped in masses of 100 to 200 eggs in layers. The female also deposits a layer of greyish scales between the eggs and over the egg mass imparting a furry or mouldy appearance (Fig 2.2). The egg stage duration is only 2-3 days in the warmth period. FAW eggs hatch approximately at the same time in two to five days after oviposition (Capinera, 2005; Nagoshi & Meagher, 2008).

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Fig. 2.2: Egg mass of FAW deposited on the stem (left) and leave (right) at the early stage of the maize plant.

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

2.3.2.2 Larva

The fall armyworm larvae have five to six different instars; each instar varies slightly in physical appearance (Fig 2.3) and processes from 12 to 18 days in tropical natural conditions. The last instar of the FAW caterpillar is about 38 to 51mm in length (Omoto *et al.,* 2016). Widths of the head capsule are about 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm for instars one to six, respectively (Capinera, 2005). Young larvae are greenish with a blackhead that turn to orangish in the second instar. The dorsal surface of the body appears brownish in the second instar and third instar and lateral white lines start to form. A reddish-brown head appears in the 4th and 6th instar and the brownish body bears white subdorsal and lateral lines (Capinera, 2014).

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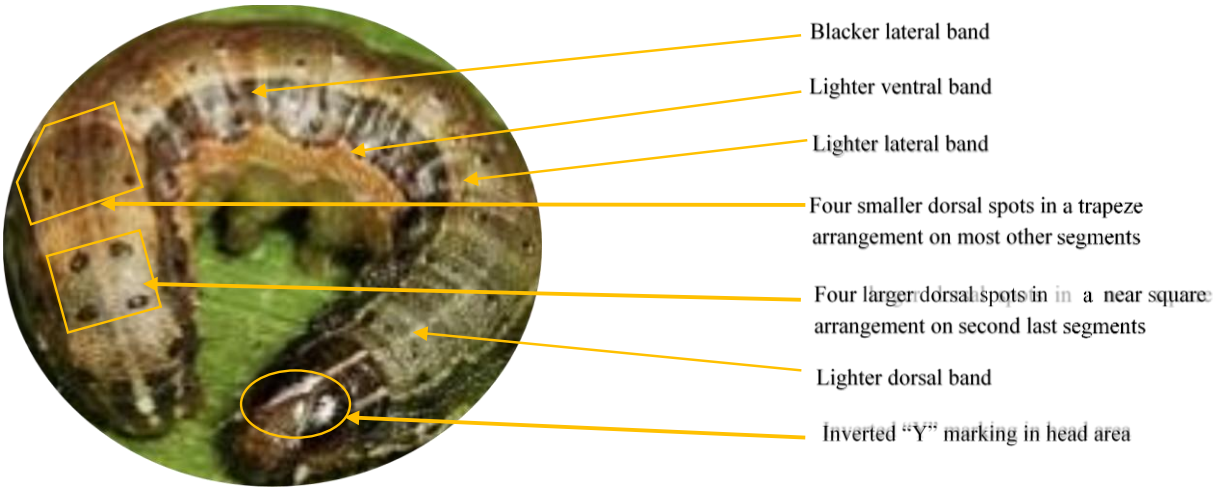

Fig. 2.3: Larval stage of FAW.
Source (Prasanna *et al*., 2018).

2.3.2.3 Pupa

The pupa is the less active stage of the fall armyworm. To avoid external attacks and the impact of environmental factors, the last larval instar gets in the soil where pupation normally takes place at a depth of 2 to 8 cm (Barros *et al.*, 2010). The last larval instar constructs a loose cocoon by tying together particles of soil with silk. The pupa is reddish-brown (Fig. 2.4) and measures 14 to 18 mm in length and about 4.5 mm in width (Santos *et al.*, 2003). The duration of the pupal stage is about 7 to 9 days under laboratory conditions. The pupal stage of the fall armyworm cannot withstand protracted periods of cold weather (Santos *et al.*, 2003).

Fig. 2.4: The pupa stage of FAW.
Source (FAO, 2018).

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2.3.2.4 Adult

The triangular white spots are observed at the tip and near the centre of the forewings of the male moth, while the female has forewings less distinctly marked, ranging from a uniform greyish brown to a fine mottling of grey and brown. The hind wing is iridescent silver-white with a narrow dark border in both sexes (Fig. 2.4). The duration of adult life is estimated at an average of 10 days, with a range of about 7 to 21 days (Capinera, 2005).

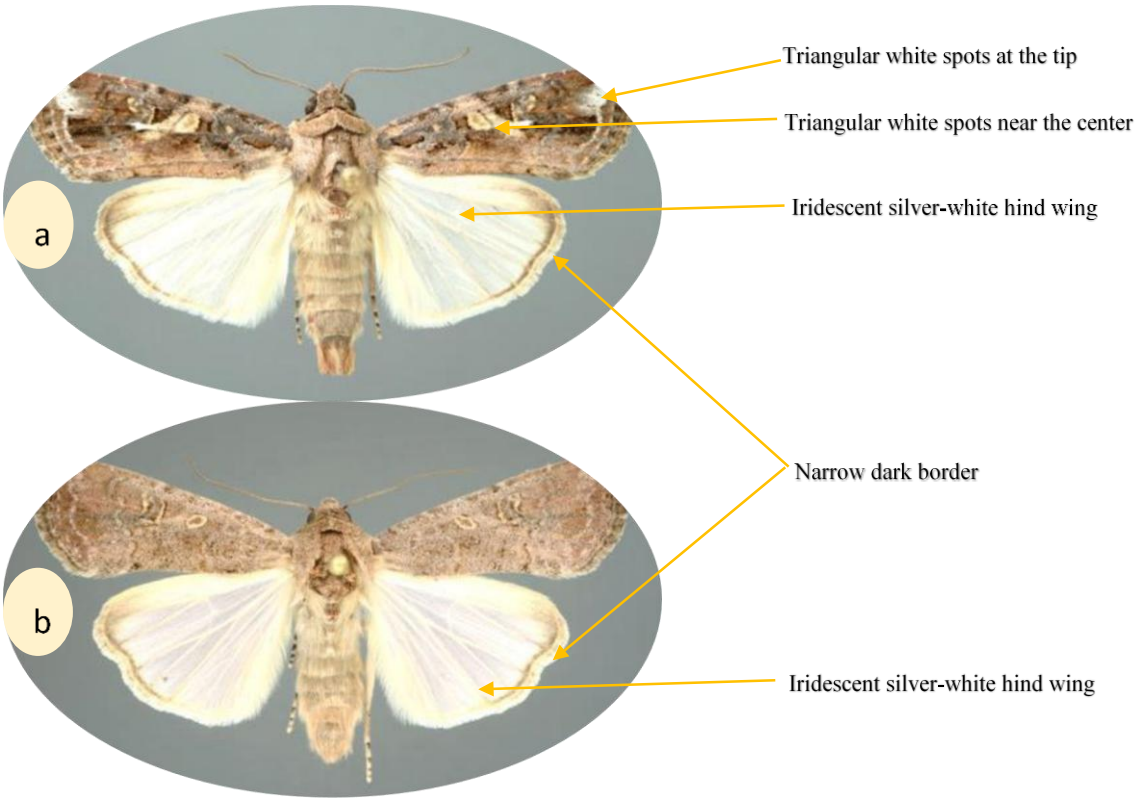

Fig. 2.5: The adult stage of FAW. a. (male), b.(female)

Source (FAO, 2018)

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2.3.3 Damage and impact of the fall armyworm

The larvae of FAW feed on young leaf whorls, ears, and tassels causing significant damage to maize, resulting in an estimated 20% yield loss. Larger larvae can act as cutworms by entirely sectioning the stem base of maize seedlings (Midega *et al.,* 2018). Some factors have been identified to contribute to the extent of damage the FAW cause to maize. These include geographical location, time of planting, the cultivar planted, and cultural practices inherent in and around the field (Day *et al.,* 2017). According to a recent study, maize yield loss due to FAW can range from 8.3 million tonnes to 20.6 million tonnes per year in the absence of management practices (Day *et al.,* 2017).

Accurate assessment of the presence of FAW infestation at the early stage of the plant is known as scouting. The level of destruction caused by the worm is visible (Fig. 2.5) and samples of the affected part of the plant can be taken for thorough examination (Singh *et al.,* 2014). Ideally, sampling is done randomly, but scouting a field in a purely random manner is quite difficult and probably unnecessary. What can be done easily is to scout a field in a semi-systematic manner? This pattern is particularly easy to follow well up to the Tasseling Stage of the maize crop (Prasanna *et al.,* 2018). The scout usually walks in a along a "W" transet in the field, stopping at 5 different locations. Signs of FAW infestation are assessed for 10-20 plants at each location and the level of damage is recorded (Prasanna *et al.,* 2018).

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Fig. 2.6: damage caused by FAW on cob and leaf.
Source (Prasanna *et al*., 2018).

2.3.4 Management of the fall armyworm

The recent economic damage caused by FAW on maize farms particularly in SSA countries is highly significant. This calls for efficient collaboration in a way that can help control the debilitating pest in the continent. One of the ways is an Integrated Pest Management (IPM) approach which provides a useful framework to control such pest (FAO, 2017). Presented below are some of the key management methods adopted and practised so far in some African countries including Ghana.

2.3.4.1 Natural control

The female adult FAW prefers to lay eggs on maize. The food and agriculture organization (FAO) recommends maize farmers to practice plant diversity (FAO, 2018). This will reduce FAW infestation and support natural enemies to control the pest. Thus, the practice of intercropping

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systems and the use of multiple varieties, can reduce the rate of oviposition, therefore helping reduce the level of infestation (FAO, 2018). Hence the practice of monoculture of maize by farmers should be discouraged. In Central America, farmers have noticed that when maize is planted with other crops such as beans and squash, they experience fewer pest attacks of FAW populations (FAO, 2018). The practice of polycrops have been recommended by agronomist to control FAW infestation for four main reasons:

1. Plant diversity in the same field confuses the FAW making it difficult to find its preferred maize host plant, eating less or laying fewer eggs.
2. The emission of chemicals by certain plants prevent attack by the female FAW moth. They are attracted (pulled) to certain plants. This "push-pull" effect in the maize field is an important step in preventing FAW infestation. A recent study has reported observation of this recommendation. FAW population was observed to be more than 80% lower in plots where this "pull-push" phenomenon was observed with associated increased yield compared to monocrop plots (Midega, *et al.*, 2018).
3. The practice of poly-cropping may provide natural enemies (parasitoids and predators) to control the FAW.
4. Intercropping increases soil organic matter, e.g. leguminous crops like groundnut increase nitrogen content thereby increasing or improving plant health to compensate for FAW damage (FAO, 2018).

The use of cultural methods to scare or deter pests is a common practice among African farmers. Maize intercropping, handpicking, and killing of caterpillars, application of wood ashes, and soils to leaf whorls are among the common practice (Day *et al.*, 2017).

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2.3.4.2 Biological control

One of the most important and alternative methods of controlling FAW populations is biological control. It is the method of using other organisms to control the FAW populations. It is safe and provides sustainable plant protection (Samia *et al*., 2016; Burtet *et al.*, 2017).

Many biological organisms, vertebrates, and invertebrates can help control FAW. While some occur naturally in the form of predators, parasitoids (wasps and flies), and entomopathogens, others need to be introduced. Common predators include birds, bats, beetles, earwigs, and other insects. In the Americas, and probably in Africa, these natural enemies can be active during all development phases of FAW, egg, larval, pupal, and adult stage (FAO, 2018). Natural enemies have the potential to significantly reduce the FAW populations and hence the damage caused by FAW. However, several factors influence their impact. These include the diversity of organisms being active, their life-style, local presence, numerical and timely abundance, host specificity, agronomic practices, pest management methods (FAO, 2018). The larva's main defence against enemies is their ability to reach large numbers and migrate before seasonal conditions are suitable for predators. Direct predation has been shown to significantly reduce their population and increases the yield of maize (Burtet *et al.*, 2017).

Their behaviour of migrating away from over-seasoning and reproduction sites makes the natural enemies less efficient (Corcos *et al.*, 2018; Leach & Isaacs, 2018). Studies have reported recovery of FAW larvae from different species of hymenopteran parasitoids and dipteran parasitoids. These studies concluded that natural enemies can substantially control FAW populations (Quispe *et al.*, 2017; Corcos *et al.*, 2018). The majority and most common larval and pupal parasitoid species belong to the ingress-and-sting guild (Ndemah *et al.*, 2001).

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FAW is susceptible to a lot of entomopathogens including viruses, fungi, protozoa, nematodes, and bacteria (Gassmann *et al.,* 2009; Petzold-Maxwell *et al.*,2013; Hoffmann *et al.*, 2014; Sanjuan *et al.,* 2014; Zothansanga *et al.,* 2016).

Fungal pathogens such as *M. anisopliae* and *B. bassiana* can cause a common disease in FAW larvae. Many of them occur naturally in FAW population. Some cause natural epizootics to FAW larvae (Toledo *et al.,* 2010).

Pheromone lures are an important tool for detecting and managing insect pest populations (Thomas 2003; Haberkern & Raffa, 2003). Lepidopteran pheromones have been successfully used for insect monitoring, mass trapping, and mating disruption for diverse groups of insect pests (Tumlinson, Mitchell *et al.,* 1986). Commercially available FAW sex pheromones have been used and shown to be a useful tool for monitoring FAW males. Populations of adult male FAW are monitored in agricultural systems with a multicomponent sex pheromone as a lure in traps (Fleischer *et al.,* 2005; Unbehend *et al.,* 2014; Miller *et al.,* 2015)

The FAW is a major pest of the maize plant and over the years, the larva has developed resistance to many insecticide-engineered crops (FAO, 2018). Biological control measures of FAW have been helpful. *B. thuringiensis* (*Bt*) are valuable options for managing FAW and Bt-engineered maize is used in many countries for FAW control (Burtet *et al.,* 2017).

Many actions can be taken by farmers to protect and favour populations of natural enemies in their fields (this is called "conservation biological control"). Measures include avoiding overuse of synthetic insecticides that can have harmful effects on natural enemies; ensuring diverse boundaries around fields including open flowers and shrubs as habitat or food for natural enemies; trees or bird perches in or near fields. If pesticides are considered necessary, selecting products

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that are compatible with biological control such as *Bt* and botanicals based formulations are essential (FAO, 2018; Harrison *et al.,* 2019).

Recent studies have shown that neem extracts are efficacious on some dipterans. In such a study, the neem seed extract (MiteStop(R)) diluted with tap water of 1:33 dilution factor killed both larvae and adult mites, ticks, and blood-sucking or biting insects (Walldorf *et al.,* 2012).

B. thuringiensis (Bt) is a soil bacterium that forms spores containing crystals containing one or more Cry or Cyt proteins that have potential and specific insecticidal activity. Different strains of Bt produce different types of toxins, affecting a narrow taxonomic group of insects. Therefore, it is used in non-chemical pest management, including inherent pest resistance through GM crops (Bacon *et al.,* 2001; Dashora *et al.,* 2017; Rojas *et al.,* 2018).

2.3.4.3 Chemical control

In many insect pest species, insecticides are important management options in the control of crop pests. The fall armyworm, *S. frugiperda* is an economically important pest of small grain crops that occurs in all maize growing regions of the Americas.

In China, the FAW population is mainly controlled by the use of chemical insecticides. This has led to resistance to many of the insecticides used including Emamectin benzoate. Fall armyworm mortality on treated diets with Emamectin benzoate was observed to be (90.6 to 100%) (Zuo *et al.,* 2018). A substantial volume of the insecticide is needed to penetrate and kill the larvae feeding deep in the whorl of the maize plants. In situations where overhead sprinklers are used for irrigation, insecticides can also be applied in the irrigation water and it must be monitored well (CABI, 2017).

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The recent invasion of FAW has alarmed governments of different African countries to deploy a massive pesticide spray programme as emergency response in FAW affected areas mainly in maize fields to protect crop damage and prevent further expansion of the pest. In recent surveys conducted in Ethiopia and Kenya, it was noted that farmers were applying different types of un-registered insecticides. This response by farmers might be due to the invasive nature of the pest that needs a rapid response and get a lengthy pesticide registration process remains a setback (CABI, 2017; FAO, 2018). The misuse of insecticides led to resistance developments (CABI, 2017). Resistance to some organophosphorus insecticides has been observed which ranged from 12 to 271-fold; the highest resistance level observed was with methyl parathion (Carvalho *et al.*, 2013). Resistance to carbamates with the highest resistance level being observed with carbaryl has also been reported (FAO, 2018; Carvalho *et al.*, 2013).

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CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study areas

The study was carried out at the Biotechnology and Nuclear Agriculture Research Institute (BNARI) research farm (5°40'25"N, 0°12'59"W) of the Ghana Atomic Energy Commission (GAEC), located in the Ga East Municipality of the Greater Accra Region of Ghana. The experiments were undertaken from July 2018 to July 2019. An area that has not been under cultivation for at least three years was used as the experimental field with the assumption that three years is enough time for the soil ecosystem to regenerate and maintain some level of equilibrium. The area was ploughed and harrowed. The soils of the study area belong to the savannah Ochrosols subgroup with the physical characteristics described in Table 3.1 below (Frimpong *et al.*, 2018).

Table 3.1: Physical characteristics of soil in the study area

Month	TMR	Temperatur7e		Average RH
		Max.	Min.	
January	56.01	32.57	24.48	27.62
February	94.88	32.83	24.34	27.73
March	153.53	32.69	24.34	27.91
April	118.65	32.37	24.39	42.88
May	133.73	_	_	_
June	183.97	_	_	_
July	82.37	23.06	23.27	54.63
August	21.06	27.26	22.77	43.17
September	171.31	29.26	23.18	46.60
October	79.46	30.93	24.03	36.33
November	27.74	32.17	23.64	48.60
December	_	32.89	23.80	44.86

TMR is total monthly rainfall, RH is relative humidity and dash represents no data. Adopted from (Frimpong *et al.*,2018).

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3.2 Colonization and rearing of fall armyworm

The FAW colony was established from unsprayed infested farms from the University of Ghana Legon farms and farms around the Ghana Atomic Energy Commission and were brought to the insectary of the Radiation Entomology and Pest Management Centre at Ghana Atomic Energy Commission for rearing. The eggs were obtained together with the leaves with scissors and put into a lined Petri dish. These eggs were put under standard insectary conditions of temperature, 28^0 C for 2-3 days which hatched into young larvae (1st instar larvae).

The 1st instar larvae were transferred into clean containers that were lined with white tissue paper. Fresh maize leaves were cut into small sizes and put into the containers with well tight covers for the larvae to feed on. Holes were created on the top of the lid of the containers and covered with mesh and sealed with glue for easy respiration. The larvae were fed every three days with the fresh maize leaves. The old leaves were changed, and the containers were cleaned before the new feed was given.

From 2nd to 6th instars, 10 larvae were put into a container with enough feed to avoid cannibalism. Larvae took 14-30 days before reaching the adult stage. The pupae were put into an oviposition cage made up of mesh and plastic. Maize seedlings planted in small plastic pots filled with soil were placed in the cage for the adult moth to lay eggs on. Cotton soaked with a 10% solution containing sugar was placed in a petri dish inside the cage as a source of food for the emerging adults.

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3.3 Natural infestation and impact of the fall armyworm along the phenology of the maize plant

3.3.1 Field establishment and maintenance

The project made use of two environments; screen house and natural field for growing the maize plants. In obtaining the natural field environment, the soil for the natural field was ploughed together with the weeds. The ploughed land was left for 7 days and then harrowed and the fieldset out in a randomized complete block design layout (RCBD) with 3 replications. A distance of 1 m belt was created between plots to separate a plot of land from each other. Each plot occupied a land size of 20.25m2 (4.5m length by 4.5m wide). A planting distance of 70 cm between rows and 40 cm between plants within a row was utilized.

Two seeds were planted per hill. All the planting was done early in the morning on the same day to provide growth parity for all the plants. Ten days later, the seedling of maize was tinned to remain one seedling per hill. Fertilizers were applied to the plants to boost their growth and yield. N.P.K. was applied at the seedling stage to boost their growth, at the rate of 50kg per acre where one (1) teaspoonful per plant was applied. Ammonia was also applied at the tasseling stage to increase the yield at the rate of 50kg per acre where one (1) teaspoonful per plant was applied as recommended by the manufacturer. Farm hygiene was also observed to allow the optimum growth of the plants. The Obatanpa maize when planted matures in 110 days and has four (4) growth stages namely; the seedling, vegetative stage, the tasseling stage, and the fruiting/ maturity (cob formation) stage with their respective growth stage intervals of 21 days, 28 days, 26 days and 35 days. Data was collected weekly based on the growth stages.

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3.4 Effects of fall armyworm infestation on maize artificially infested at specific growth stages

3.4.1 Establishment of potted maize in a screen house

For the screen house experiment, top black loamy soil mixed with compost at a ratio of 2:1 was collected and put into 150 sacks made from woven PVC fibre. Pots containing the soil were adequately watered to make it moist and were left for three days before planting. The pots were arranged in the screen house with a floor area of 5m x 5m. 10 pots were arranged in a row and were replicated 3 times at each growth stage with a control. At each growth stage, 30 pots were provided. To prevent the FAW from moving from the treatment pots to the control pots, a grease was used to create a boundary between the treatment pots and the control pots in the screen house.

The variety of maize used was the "Obatanpa". Before planting, cutlass was used to provide planting holes in each of the pots in the screen house. After providing the planting holes (with the depth of 1.75 inches), 2 of the seeds were put in each hole in a pot at the screen house. All the planting was done early in the morning on the same day to provide growth parity for all the plants. Ten days later, seedlings of maize were tinned to remain one seedling per pot. Watering was done regularly, every three (3) days from the seedling stage through the vegetative stage. Fertilizer was applied at a rate similar to the that used in the open field experiment.

3.4.2 Infestation of maize with fall armyworm

An infestation of the plants with FAW was done at the various growth stages of the maize plant in the screen house. The first infestation was done at the seedling growth stage followed by the vegetative growth stage, the tasseling growth stage, and the fourth was done at the fruiting or cob formation stage. Three of the second instar two-weeks old larvae were infested per maize plant and after a week of infestation, data were collected.

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3.4.3 Data collection

The data was collected weekly after each infestation on each plant from the seedling growth stage until the plant matured or died. In all, 150 plants were examined with 120 treatments and 30 control. The whorl, the leaves, the tassel, and the cob were assessed. Damage was evaluated using the Davis scale (Davis *et al.*, 1992).

3.5 Effects of different fall armyworm management practices on maize recovery and yield

3.5.1 Study design and field layout

Three different treatments arranged in a randomized complete block design (RCBD) were used for this experiment. The treatments included the application of a conventional insecticide Ema-star 112 EC (Emamectin Benzoate 48g/l + Acetamiprid 64g/l), Adama West Africa, Accra:- bio-pesticide, Agoo WP (*B. thurengensis 55%* + Monocultap 45%) Abbott Laboratories, North Chicago, USA and a neem-based product, Ozoneem (100% neem oil), Ozone Biotech, Haryana, India. Each treatment plot and control plot had three replications which were summed up to nine (12) plots in total.

3.5.2 Chemical treatment of infested plants

Scouting was done every other day, starting on the fourth day after germination to determine the presence of FAW. Treatment applications started when 10% of sampled plants showed signs of FAW infestation. The application was done every three (3) weeks at the manufacturer's recommended doses. For Ozoneem, the recommended rate was 45ml/15L, for Ema-star, the recommended rate was 30ml/15L and Agoo, the recommended rate was 50g/15L. These rate were maintained for each application and a separate knapsack sprayer was used for each insecticides. The first application was done at the seeding stage when the maize plant was two weeks old

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(14days after planting). The second application was done when the maize plant reached its vegetative growth stage, and the third was done at the tasseling stage. At maturity, the maize was harvested, threshed and the seeds were weighed. The dry weight and the moisture contents were determined and calculated for each treatment plot and the values were compared to the control plots. The damage was evaluated on the leaves, the whorl, the tassel, and the cob until the maize matured.

3.5.3 Data collection and analysis

Data was collected weekly on each treatment plot from the seedlings stage, through vegetative growth to maturity. Data were collected in the middle of each plot in "W" transet route excluding two border rows and two columns. The plants were randomly selected by counting, 1, 2, and 3. Each third plant was selected and followed up to maturity. A total of ninety (90) plants were selected and examined from the treatment plots. Thirty (30) from each treatment and ten (10) from each plot. For the control, which was the natural field, thirty (30) plants were examined and ten (10) plants from each plot. Davis *et al.*, (1992) visual scale was used to determine damage severity.

3.5.4.1 Fall armyworm sampling

Infestation by FAW was determined at all the growth stages (seedling, vegetative, tasseling, and fruiting/maturity) using the centre row of each plot, by visually examining the whorl, the leaves, the tassels, and the cob, for FAW larvae, feeding damage or frass.

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3.5.4.2 Damage estimation

The level of damage was evaluated on the leaves, the whorl, the tassel, and the cob at each developmental stage until the maize matured. The level of damage was assessed on all 270 plants including the screen house and the natural fields using the Davis visual scale (Davis *et al.*, 1992) with slight modifications as shown in Table 3.2. and Table 3.3.

Table 3.2: Damage rating scale

Level of damage/injury to plants by FAW	Rating
No injury or few pin-holes on 1 to 2 leaves	1
Few short holes/shot holes on more than 5 leaves	2
Short holes on more than 5 leaves	3
Several leaves with short holes and a 2 to 3 long lesions	4
More than 5 holes with long lesions	5
More than 5 leaves with lesions about 2.5cm	6
Long lesions common on one-half of the leaves	7
Long lesions common on one-half to two-thirds of the leaves	8
More than 5 leaves with long lesions and complete defoliation were observed	9
Death	15

Visual injury to plant assessment adopted from (Davis *et al*., 1992).

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Table 3.3: David's scale Analysis

Explanations	Definitions	Rating
Extensive whorl damage	severe	8-9
Minimal visible leaves damage	mild	0-4
Marginal tassel damage	moderate	5-7
Minimal cob damage visible cob damage	mild	0-4
Marginal leaves damage	moderate	5-7
Kernels damage	mild	0-4
Ear damage	mild	0-4
Whorl damage	moderate	5-7
Extensive leaves damage	severe	8-9

Analysis of the Severity of damage determined from the Davis scale (Davis *et al.*, 1992). Thus, 0 - 4 (Mild), 5 - 7 (moderate), and 8 - 9 (Severe) on whorl, leaves, tassel, cob, kernels, and ear.

3.5.4.3 Yield estimation

The maize which survived the FAW infestation matured in 110 days and was left to further dry on the plants for 10 days before harvesting. The harvesting was done by hand-picking and was separated plot by plot to obtain the harvested grains into their various experimental sacks hence, 12 different harvest sacks (3 control sacks for natural field and 9 treatment sacks for natural field) were obtained. In the screen house, the control plants, cobs developed alright but seeds were not developed on the cobs for it to be evaluated. Harvesting, dehusking, and shelling were also done to get grains into their respective sacks. For each sack, the unmarketable grains were separated from the marketable ones for subsequent evaluation. Aerial winnowing was done to remove the chaffs from the grains. The winnowed grains were weighed on a Sartorius scale in a pre-weighed

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can. The actual weight of the maize was obtained by subtracting the weight of the can from the weight of the maize plus can and the values for air-dried maize were recorded in grams. The yield was analyzed by comparing the weight of maize obtained from the control plots and the insecticide-treated plots. Grain loss was determined based on the treatments.

3.5.4.4 Data analyses

The raw data collected were entered into an excel spreadsheet and imported into the Statistical Package for Social Scientist (SPSS) for analysis. At the screen house and the natural field, growth stages of maize plants were summarized in means and standard errors. Field trials were arranged in a randomized complete block design. An independent t-test was used to compare the mean number of fall armyworm and the severity of damage along the various growth stages of the maize plant for both treated and untreated plots. One-way analysis of variance (ANOVA) using a generalized linear model was done to compare the mean number of fall armyworms and severity of damage among the control and treated plots in the field. Where there were significant differences, post hoc (Tukey's) test was done for mean separation. Also, correlation was done at the natural field to determine the association between levels of fall armyworm and the severity of damage to the maize plant. The severity of damage was determined from the Davis scale (Davis *et al.*, 1992). Thus, 0 - 4 (Mild), 5 - 7 (moderate) and 8 - 9 (Severe). All analyses were considered significant at $P < 0.05$.

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CHAPTER FOUR

4.0 RESULTS

4.1. Natural infestation and impact of the fall armyworm along the phenology of the maize plant under field conditions

The level of FAW infestation on the natural field (treatment and control) for the four growth stages in this experiment was determined by visually examining the whorl for FAW larvae, feeding damage, or frass. Presented in Table 4.1 is the average number of FAW along the phenology of the maize plant under field conditions. The average number of FAW recorded for both the control and treatment groups for three of the growth stages (seedling, vegetative, tasseling) was approximately 1.0. At the fruiting/maturity stage, almost no FAW was recorded. It was observed that a higher number of FAW was present at the seedling and vegetative stage of the plant than the tassling and fruity/maturity stage. The mean number of FAW at the control and the treatment plots were significantly different from each other ($P < 0.01$, $F = 32.2$). At the seedling stage, significant higher number of FAW was recorded at the Bt + monosultap treatment plot (1.07 ± 0.07) than the control (1.07 ± 0.07) and the Neem oil (0.92 ± 0.04) ($P < 0.01$, $F = 32.2$). The least mean number of FAW was recorded at the maize plot treated with Emamectin benzoate + Acetamiprid (0.43 ± 0.06) at the seedling stage. At the vegetative stage, significantly higher number of FAW was recorded on the neem oil treatment plot (1.37 ± 0.06) and the least on the control plot (1.07 ± 0.07) ($P < 0.01$, $F = 4.94$). In Table 4.2. the mean number of FAW differed significantly ($P <0.01$) from each other for all the treatments at the different growth stages except the fruity/maturity stage ($P = 0.21$, $F = 0.61$).

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Table 4 .1: Average number of FAW on the plant at different growth stages for the control and treatment fields

Treatments	Growth stages			
	Seedling	vegetative	Tasseling	Fruiting/Maturity
Control	0.99 ± 0.05a	1.07 ± 0.07a	0.92 ± 0.04a	0.43 ± 0.05a
Neem oil	0.92 ± 0.04a	1.37 ± 0.06b	0.99 ± 0.01a	0.01 ± 0.01b
Bt + monosultap	1.07 ± 0.07a	1.22 ± 0.04b	1.00 ± 0.00a	0.02 ± 0.01b
Emamectin benzoate + Acetamiprid	0.43 ± 0.06b	1.11± 0.07a	0.56 ± 0.07b	0.04 ± 0.02b
DF =	3	3	3	3
F =	32.2	4.94	28.29	60.9
P <	0.01	0.01	0.01	0.01

Values are presented in means and standard error of the mean (SEM). Means in the same column with different superscripts are significantly different from each other (P < 0.05) using Tukey's test.

Table 4 .2: Average number of FAW on the plant at different growth stages for the treatment fields

Treatments	Growth stages			
	Seedling	vegetative	Tasseling	Fruiting/Maturity
Neem oil	0.92 ± 0.04a	1.37 ± 0.06a	0.99 ± 0.01a	0.01 ± 0.01b
Bt + monosultap	1.07 ± 0.07a	1.22 ± 0.04a	1.00 ± 0.00a	0.02 ± 0.01b
Emamectin benzoate +Acetamiprid	0.43 ± 0.06b	1.11± 0.07b	0.56 ± 0.07b	0.04 ± 0.02b
DF =	2	2	2	2
F =	41.4	4.94	40.05	1.61
P	<0.01	<0.01	<0.01	0.21

Values are presented in means and standard error of the mean (SEM). Means in the same column with different superscripts are significantly different from each other (P < 0.05) using Tukey's test.

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4. 2 Effects of insecticide treatments on damage and plant recovery

There was no significant difference in damage caused by FAW at the seedling stage (P =0.11, F = 2.03) and the tasseling stage (P =0.07, F = 2.43) for the control and treatment plots (P =0.11, F = 2.03). However, at the vegetative stage, there was significantly higher damage due to FAW at the control plot and the treatment plots (P < 0.01, F = 11.46). Higher damage was recorded for the plots treated with Neem oil (5.08 ± 0.33) followed by the control (4.23 ± 0.37) and the plots treated with Bt + *monosultap* (4.14 ± 0.32). Significant less damage was recorded for the Emamectin benzoate +Acetamiprid treatment at the vegetative stage (2.2 ± 0.40). This implies that at the vegetative stage, Emamectin benzoate +Acetamiprid could be effective for the control of FAW. At the tasseling and fruiting stage, less damage to the pest was observed. Details are presented in Table 4.3 below.

Table 4.3: Severity of damage (SD) along the growth stages at the natural and treatment field

Treatment	Severity of damage			
	Seedling	vegetative	Tasseling	Fruiting/Maturity
Control	1.22 ± 0.09a	4.23 ± 0.37b	1.12 ± 0.11a	0.60± 0.08a
Neem oil	1.50 ± 0.09a	5.08 ± 0.33b	1.07 ± 0.13a	0.09 ± 0.03b
Bt + monosultap	1.33 ± 0.09a	4.14 ± 0.32b	1.10 ± 0.16a	0.06 ± 0.03b
Emamectin benzoate +Acetamiprid	1.49 ± 0.54a	2.21 ± 0.40a	0.70 ± 0.11a	0.03 ± 0.02b
DF	3	3	3	3
F	2.03	11.46	2.43	33.10
P	0.11	<0.01	0.07	<0.01

Values are presented in means and standard error of the mean (SEM). Means in the same column with different superscripts are significantly different from each other (P < 0.05) using Tukey's test.

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4.3 Efficacy of the different insecticides used for the control of FAW

Severity of damage caused by FAW did not differ significantly for all the insecticides used at the seedling stage (P =0.38, F= 0.99), Tasseling stage (P = 0.07, F = 2.71) and fruity/maturity stage (P =0.43, F= 0.86) . However, a significant difference was observed at the vegetative stage with Neem oil insecticide treatment plot recording the highest damage (5.08 ± 0.33) and Emamectin benzoate +Acetamiprid recording the least damage (2.21 ± 0.40).

Table 4.4: Efficacy of the insecticides used for the control of FAW

Treatment	Severity of damage			
	Seedling	vegetative	Tasseling	Fruiting/Maturity
Neem oil	1.50 ± 0.09a	5.08 ± 0.33a	1.07 ± 0.13a	0.09 ± 0.03b
Bt + monosultap	1.33 ± 0.09a	4.14 ± 0.32a	1.10 ± 0.16a	0.06 ± 0.03b
Emamectin benzoate +Acetamiprid	1.49 ± 0.54a	2.21 ± 0.40b	0.70 ± 0.11a	0.03 ± 0.02b
DF	2	2	2	2
F	0.99	17.09	2.71	0.86
P	0.38	<0.01	0.07	0.43

*Values are presented in means and standard error of the mean (SEM). Means in the same column with different superscripts are significantly different from each other (*P *< 0.05) using Tukey's test.*

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4.4 Critical stage for fall armyworm control along the maize phenology in a screen house

Table 4.5 below presents the critical stage for fall armyworm control at the various growth stages examined. There was a significantly higher mean number of FAW at the seedling stage (1.09 ± 0.05) than the vegetative stage (1.0 ± 0.00) at the first infestation (seedling stage). However, at this stage, the severity of damage was significantly higher at the vegetative growth stage (7.90 ± 0.11) than the seedling (4.67 ± 0.21). At the second infestation (vegetative stage), the damage was severe which resulted in the death of the plant. A similar trend in terms of damage was observed at the 3rd infestation (Tassling stage).

Table 4.5: Mean number of FAW (± SE) recorded at the critical stage for fall armyworm control along the maize phenology

	1st INFESTATION (Seedling stage)		2nd INFESTATION (Vegetative stage)	3rd INFESTATION (Tasseling stage)		4th INFESTATION (Maturity Stage)
	Seedling	Vegetative	Vegetative	Tasseling	Early Fruiting	Fruiting/Maturity
FAW	1.09 ± 0.05a	1.0± 0.00b	1.0 ± 0.00	1.0 ± 0.02c	1.0 ± 0.04c	1.0 ± 0.10
SD	4.67 ±0.21a	7.90 ± 0.11c	7.90 ± 0.61	3.58 ± 0.25a	5.07 ± 0.32a	5.21 ± 0.89

Values are presented in means ± (SEM). In the same row of each of the infestation, values with different letters as superscript are significantly different from each other (P < 0.05).

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4.5 Effects of different treatments on maize recovery and yield after fall armyworm infestation.

4.5.1 Effects of insecticide treatments on yield

Table 4.5.1 revealed that the yield for Neem, Bt, and Emamectin + Acetamiprid were similar but significantly higher than the control or unsprayed plot. The control plot had the least marketable yield (107.04 g ± 1.05). The significant difference observed was between the marketable yield from the control treatment and the other three treatments (Neem, *Bt*. and Emamectin). Concerning the unmarketable yield, the control field recorded a significantly higher yield (40.88 g ± 4.05) compared to the other three treatments. Moisture content did not differ significantly from all the treatments ($P < 0.05$).

Table 4.5.1: Grain yield and moisture content of maize from natural (control) and treatment fields.

Treatment	Yield/g		Moisture content	
	marketable	unmarketable	Air dry weight	Oven dry weight
Control	107.04 ± 1.05c	40.88 ± 4.05b	105.99 ± 1.46	97.86 ± 1.07
Neem	221.89 ± 33.18a	22.18 ± 1.31a	102.45 ± 2.39	93.59 ± 2.16
Bt	266.44 ± 9.64a	15.72 ± 1.19a	100.90 ± 3.24	93.88 ± 2.09
Emamectin benzoate+Acetamiprid	254.53 ± 28.01a	14.99 ± 5.82a	106.25 ± 3.08	98.78 ± 2.08
P-value	0.003	0.004	0.440	0.198

Values are presented in means ± SEM. in the same column, values with different letters as superscript are significantly different from each other ($P < 0.05$).

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4.5.2 Maize plant recovery at the screen house and natural field

At the seedling stage (first infestation), all the plants (100%) survived to the vegetative growth stage and all (100%) died before the tasseling growth stage. At the vegetative growth stage (2nd infestation), all the plants (30) survived up to the end but died before the tasseling growth stage. At the tasseling (3rd infestation) and fruiting/maturity (4th infestation) all (100%) the plants survived (Table 4.6).

Table 4.5.2: Number of live plants at the growth stages in the screen house.

Growth stages	Seedling stage (1st infestation)	Vegetative stage (2nd infestation)	Tasseling stage (3rd infestation)	Fruity/maturity stage (4th infestation)
Seedling	30 (100.0)	_	_	_
vegetative	30 (100.0)	30 (100.0)	_	_
Tasseling	_	0 (0.0)	30 (100.0)	30 (100.0)
Cob formation stage/maturity	_	0 (0.0)	30 (100.0)	30 (100.0)

Values are presented in n (%)

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4.6 Maize plant recovery at the natural field

Table 4.6 below shows the number of maize plants that survived along the growth stages. No death was recorded (100.0% survival) on the treatment fields (Neem, *Bt*. and Emamectin benzoate) along the growth stages. On the control field, 4/30 (13.3%) of the plants died at the vegetative growth stage.

Table 4.6: Number of live plants at the natural field

Treatments	Growth stages			
	Seedling	vegetative	Tasseling	Fruiting/Maturity
Control	30 (100.0%)	26 (86.7%)	26 (86.7%)	26 (86.7%)
Neem	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)
Bt	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)
Emamectin benzoate	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)

Values are presented in n (%).

4.7 Effect of fall armyworm on the severity of damage (SD)

A correlation between FAW infestation and the severity of damage among the control and the treatment plots was determined. Results indicate a significant positive correlation between FAW infestation and the control, (r = 0.397), *Bt*. (r = 0.540), Emamectin (r = 0.510) and Neem (r= 0.628) treatments. This implies as the number of FAW increases, the severity of damage of the plant increases. Details are presented in Figure (4.3 – 4.6).

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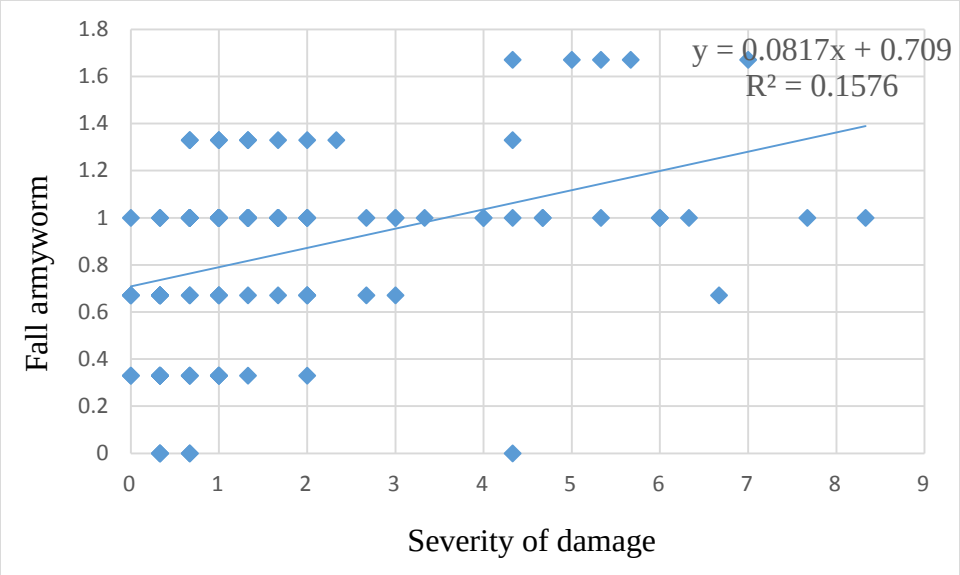

Fig. 4.1: Effect of FAW infestation on the severity of damage (control plot).

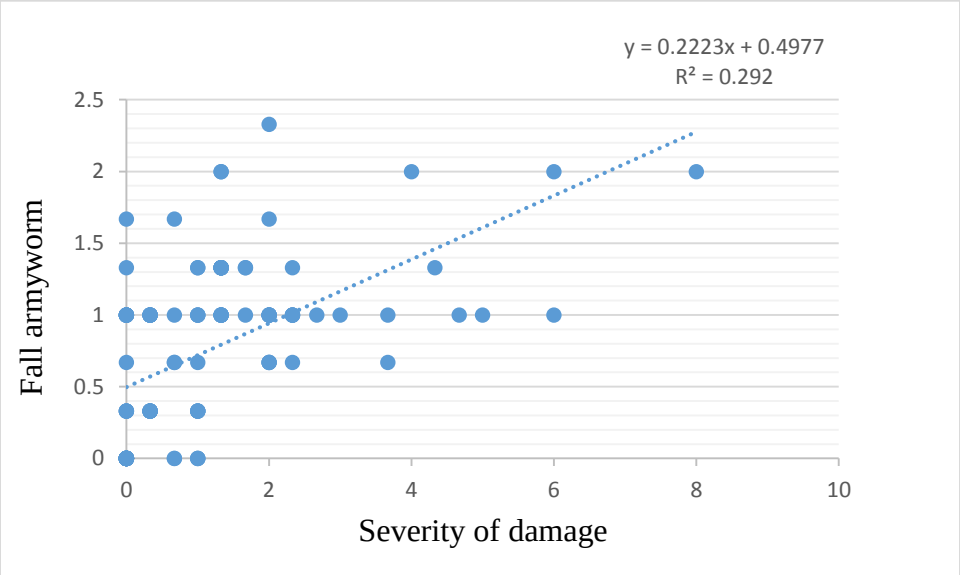

Fig. 4.2: Effect of FAW infestation on the severity of damage (Emamectin Benzoate + Acetamiprid treatment)

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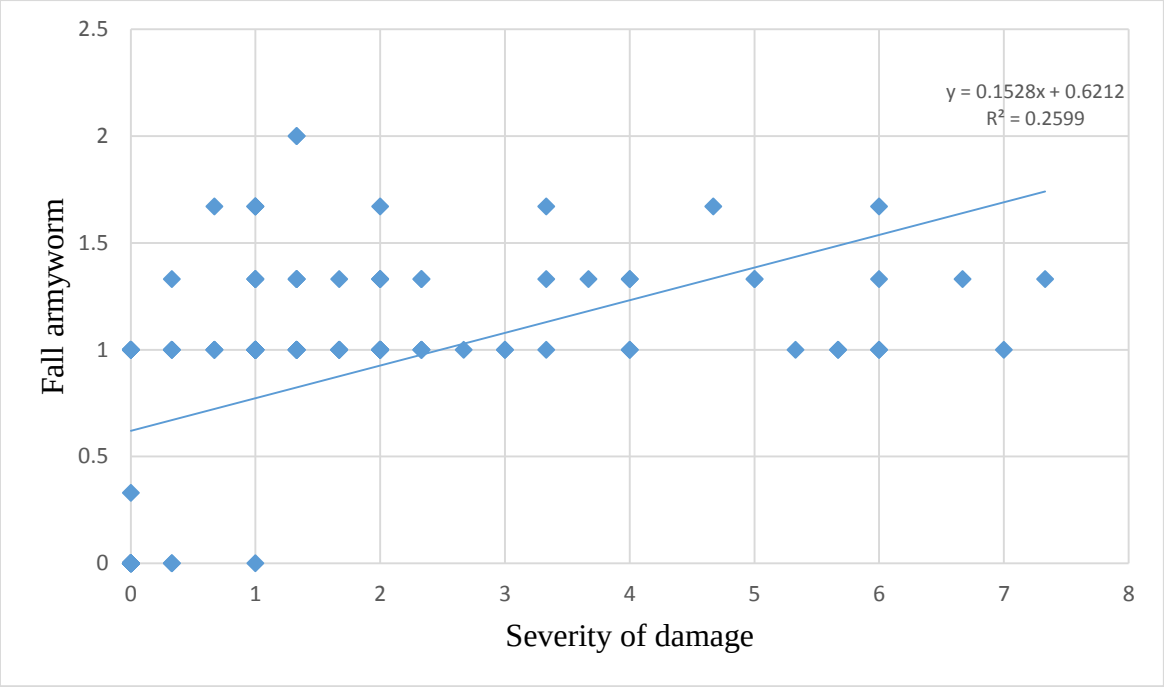

Fig. 4.3: Effect of FAW infestation on the severity of damage (Bt. treatment)

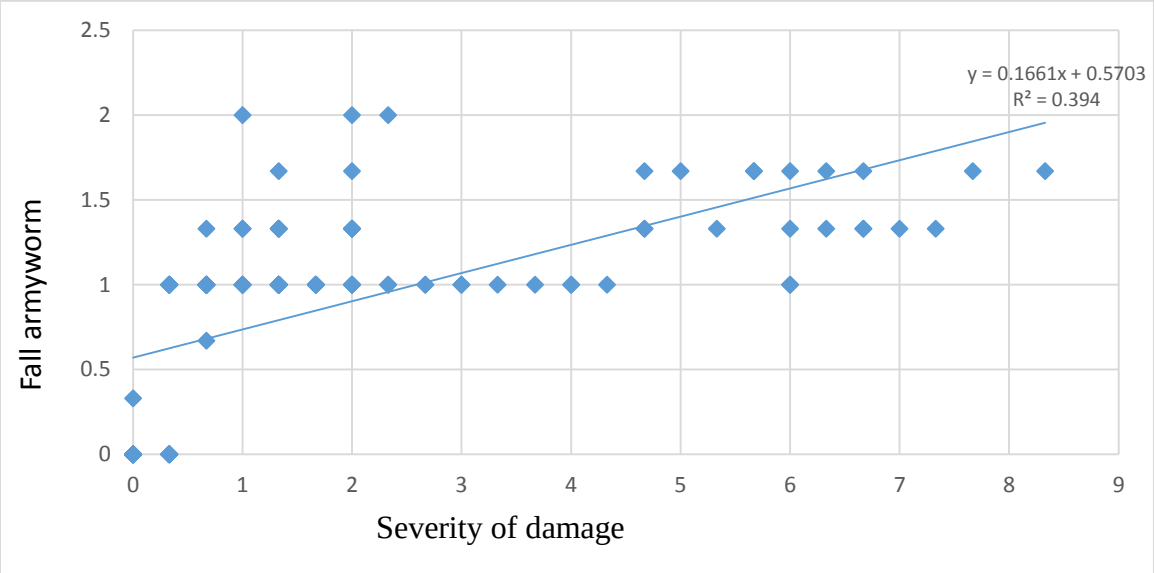

Fig. 4.4: Effect of FAW infestation on the severity of damage (Neem treatment)

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4.6 Loss assessment due to FAW

From Fig. 4.7 below, out of 1442.4g of maize harvested from the control field, a loss of 0.14% which represented the highest loss was recorded. Among the pesticide treatment fields, Ema-star treated field recorded a loss of 0.04% out of 2453.9g of maize harvested and represented the second-highest loss. Neem and Bt. treated fields both recorded the least post-harvest loss of 0.01% from 2918.6g and 2799.7g, respectively.

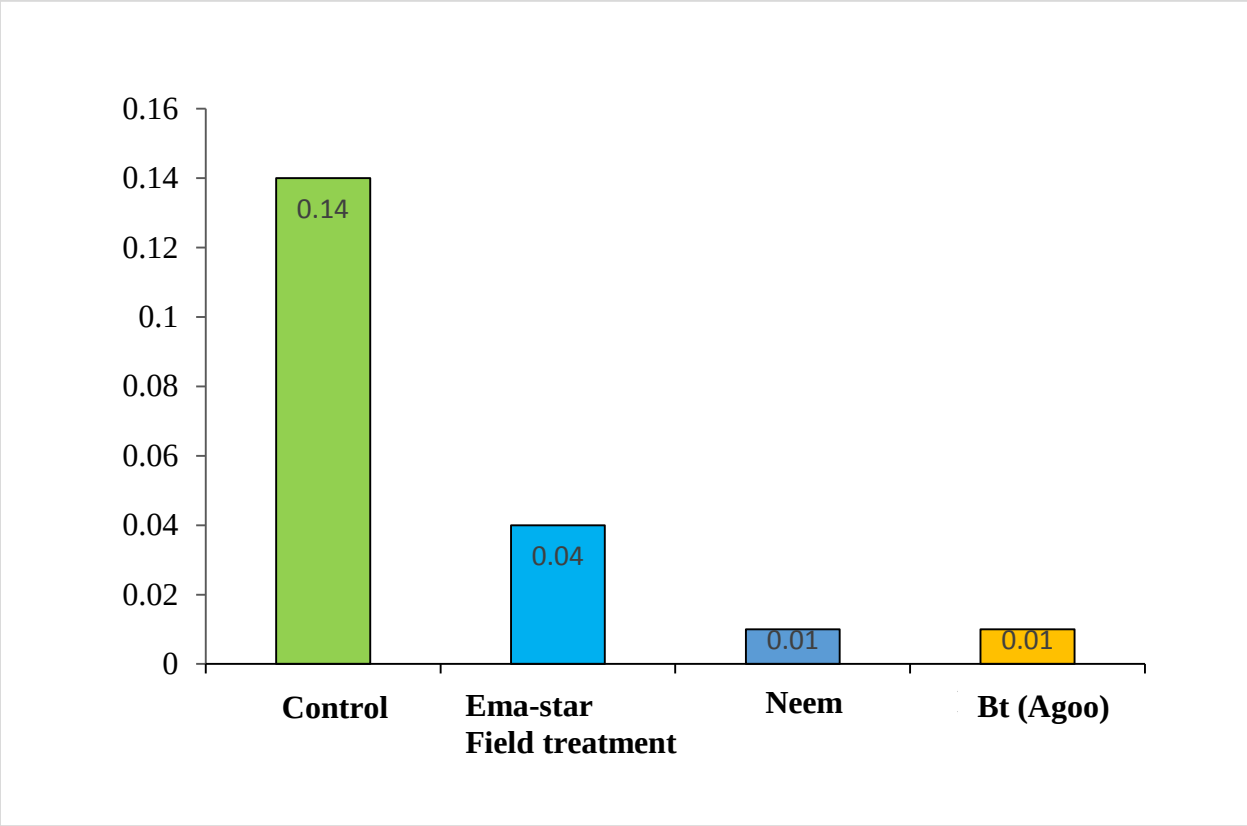

Fig 4.5: Loss assessment (%) of control and pesticide-treated plots.

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CHAPTER FIVE

5.0 DISCUSSIONS

5.1 Infestation and impact of the fall armyworm along the phenology of the maize plant under field conditions.

The Fall Armyworm (FAW), *S. frugiperda*, is an insect that is native to tropical and subtropical regions of the Americas. The larvae of FAW can cause significant damage to crops, if not well managed. In this study, the average level of FAW infestation recorded for both the control and treated plots at the growth stages (seedling, vegetative, and tasseling) was approximately 1. Environmental factors such as temperature and rainfall also play a role in regulating FAW populations. At the fruiting/maturity stage, no FAW was recorded for the treatment fields. This may be due to the fact the FAW might have reached the pupal or adult stage. Besides, the FAW larvae develop rapidly and survive better when it is feeding on actively growing (early) stages of the plant accounting for their presence in the early growth stages.

The severity of damage was highest at the seedling and vegetative growth stages and lowest at the flowering and fruiting stages with all plants surviving to maturity and dryness. This suggests that seedling and vegetative growth states of the maize plants are highly susceptible to the FAW destructions as the plant might have the required nutrients for the FAW at those developmental stages hence, the greatest the destruction observed at the seedling and vegetative growth stages whilst tasseling and cob formation stages were highly resilient to the FAW destructions. The damage caused is therefore dependent on the development stage of the plant, the severity (larval density) per plant, and the development stage of the larvae. Damage can, therefore, be severe on at the early growth stage (actively growing maize leaves, tassels, and developing cobs). In some situations, larvae can behave as cutworms to kill seedlings.

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5.2 Critical stage for fall armyworm control along the maize phenology in a screen house

The screen house cohorts were infested with the worm differently at the four developmental stages along the plant's phenology and were followed to maturity to assess the level of destruction and survival among the treated plants. The study reveals that an average of 1 FAW larva was present on both plants in the screen house even though three of the second instar larvae were used to infest each plant at the screen house. This finding corresponds to findings from previous studies (Capinera, 2014) and maybe a result of intraspecific competition among the FAW which is a unique survival feature in the ecosystem.

The study also reveals that, when the infestation was done at the seedling and vegetative growth stages, respectively for the screen house cohorts, all the plants were severely damaged by the FAW and died before the fruiting/maturity stage. This implies that the critical period for FAW control is not at one stage but control at seedling and vegetative stages may be essential. This finding is consistent with the earlier findings by Hruska and Gladstone (1988) who reported that there is no one period for armyworm control and their effect on yield reduction (Hruska & Gladstone, 1988). Because the screen house was shielded from natural enemies to FAW, the pests were free from predators and succeeded in causing severe damages to the plants especially at the seedling and vegetative growth stages.

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5.3 Effects of different treatments on maize recovery and yield after fall armyworm infestation.

The advent of the FAW has affected hectares (ha) of farmlands in Ghana, with much pressure on food security due to the failure of management strategies in the country (FAO, 2018) probably as a result of the lack of knowledge on the critical stages along maize phenology for controlling the worms or better still the poor choice of insecticides used to control the worms at that time. As little as 5 larvae per plant can reduce yield by 6% in maize (Day *et al.*, 2017). When natural enemies are unable to help control pests, pesticide usage becomes the immediate reliable alternative for controlling pests. Several insecticide applications are required to kill larvae feeding deep in the whorl of plants. Ema-star, Neem oil, and *B. thuringiensis* (*Bt.)* insecticides are among the common pesticides used by farmers across the country for controlling FAW larvae. It was observed that the insecticides had a varied effect on the different growth stages of the maize plant. For instance, at the seedling stage, less damage was recorded on the plot treated with *B. thuringiensis* (*Bt.)* (1.33 ± 0.09) than Neem oil (1.5 ± 0.09) and Ema-star (1.49 ± 0.54). On the other hand at the vegetative growth stage, significantly less damage was recorded at the plot treated with Ema-star (2.21 ± 0.04) than the other treatments (Neem oil and *B. thuringiensis*). This implies that each growth stage of the maize plant may require different insecticide treatment for the control of FAW population especially at the seedling and vegetative stages where damage is high. Contrary to the finding of this study, Neem oil has been reported to be more effective at a one-week interval in reducing the incidence (21%) and severity (54%) of FAW population (Kammo *et al.*, 2019). This could be due to different formulations of the Neem oil extract used and the comparisons different from insecticides.

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From this study, all three pesticides *B. thuringiensis (Bt)*, Emamectin benzoate + Acetamiprid (Ema-star), and Neem oil had similar yields, as no significant difference was observed among them, except when compared with the control plot. The efficacy of these three chemicals recorded in this study are consistent with the earlier report by Siebert and colleagues (Siebert *et al.*, 2008) and could be beneficial for armyworm control to improve yield.

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CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Findings from this study revealed that FAW of the maize plant was found mostly at the vegetative and seedling growth stage. The average number of FAW on the maize plant differed significantly from each other for the treatment and control plots at all the growth stages (seedling, vegetative, tasseling and fruity/maturity). Severity of damage caused by FAW did not differ significantly for all the insecticides used at the seedling stage ($P = 0.38$, $F = 0.99$), Tasseling stage ($P = 0.07$, $F = 2.71$) and fruity/maturity stage ($P = 0.43$, $F = 0.86$).

For the screen house experiment, the seedling and vegetative growth stages were the stages mostly affected by FAW and so are the most critical stages to target for effective control. The number of FAW present in the field positively correlated with the severity of the damage. The yield of maize was similar among the different insecticide treatments but significantly higher than the control plots. Although all the three insecticides, *B. thuringiensis (Bt),* Emamectin benzoate + Acetamiprid (Ema-star), and Neem oil had similar yields and were efficacious for FAW control, yields from *B. thuringiensis* treated plot significantly had the least loss and may be recommended to farmers for FAW control.

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6.2 Recommendations

From the findings of the study, the following recommendations are made:

1. Strategies and policies aimed at controlling the fall armyworm on maize should concentrate on the seedling and vegetative growth stages as the most critical stages where damages are more likely to be higher which is to result in significant yield losses.
2. Although numerous synthetic pesticides have been reported to kill FAW, for effective control of FAW and higher grain yield, it is recommended to treat plants with Agoo (*Bacillus thuringiensis*+Monosultap), Ozoneemm and Ema-Star (Emamectin benzoate + Acetamiprid).
3. Farmers must be made aware of the critical stage of FAW control, i.e. at the early growth stage (seedling and vegetative).

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APPENDIX

DATA SHEET

Davis visual rating scale on whorl stage maize plant in screen house for resistance to fall armyworm

Date	No. of larvae on plant	1	2	3	4	5	6	7	8	9
Whorl										
Leaves										
Stalk										
Tassel										
Cob										
Silk										
Ear										

Key:

a: pin-hole, b: small circular, c1: small elongated, c2: medium-sized elongated, c3: large elongated, d1: small uniform to irregular shape, d2: medium-sized uniform to irregular shaped, d3: large uniform to irregular shaped, e: short hole, f: leaf sheath

1: no injury or few pin-holes,

2: few short holes/shot holes on several leaves

3: short holes on several leaves

4: several leaves with short holes and a few long lesions

5: several holes with long lesions

6: several leaves with lesions less than 2.5cm

7: long lesions common on one-half of the leaves

8: long lesions common on one-half to two-thirds of the leaves

9: most leaves with long lesions and complete defoliation was observed

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Plant 1	pinhole	Short-hole	Lesions	Defoliation					
Leave									
eye									
Whorl									
stalk									
Cob									
Silk									
Plant 2	pinhole	Short-hole	Lesions	Defoliation					
Leave									
eye									
Whorl									
stalk									
Cob									
Silk									
Plant 3	pinhole	Short-hole	Lesions	Defoliation					
Leave									
eye									
Whorl									
stalk									
Cob									
Silk									
Plant 4	pinhole	Short-hole	Lesions	Defoliation					
Leave									
eye									
Whorl									
stalk									
Cob									
Silk									
Plant 5	pinhole	Short-hole	Lesions	Defoliation					
Leave									
eye									
Whorl									
stalk									
Cob									
Silk									

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DATA SHEET FOR TRIAL ON FAW INFESTATION (FIELD)

Date: …… Plot no.: ……. Plant Growth Stage……
Sampler……. Treatment type ……. Natural Inf. …….

Plant No.	No. of FAW Larvae / Stages			No. of FAW Egg batches	Damage rating (0-9)	Tassel Damage	Cob Damage	Other Insects (natural enemies)
	1 – 2 Young	3 – 4 Mid	5 – 6 Matured					
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								