TEMPORAL DYNAMICS OF FALL ARMYWORM, *Spodoptera frugiperda* (J.E. SMITH), STEMBORER PESTS AND ASSOCIATED NATURAL ENEMIES IN MAIZE FIELDS IN SEMI-ARID ZONE, MACHAKOS, KENYA

BY

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DECLARATION AND APPROVAL

Declaration

This thesis is my original work that has not been presented to any other University for the award of a degree

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DEDICATION

This thesis is dedicated to my late mother Grace Tokosang, father Edward Samuel and my late brother Henry Khamis

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AEZs	Agroecological zones
CABI	Centre for Agriculture and Biosciences International
CIMMYT	International Maize and Wheat Improvement Centre
FAO	Food and Agriculture Organization of the United Nations
FAW	Fall armyworm
GLMM	Generalized Linear Mixed Mode
GM	Genetically Modified
Icipe	International Centre of Insect Physiology and Ecology
IITA	International Institute of Tropical Agriculture
IPM	Integrated Pest Management
IPPC	International Plant Protection Convention
KARLO	Kenyan Agricultural and Livestock Research Organisation
SSA	Sub-Saharan Africa

ABSTRACT

Maize is one of the principal food security crops in sub-Saharan Africa (SSA). In Kenya maize is a staple food crop and source of employment and income for millions of farming communities. Due to poor maize yields, production rarely meets local population demand. The low yield of maize production is associated with many challenges including stemborer species. Key among them include *Busseola fusca* (Fuller), *Sesamia calamistis* (Hampson) and *Chilo partellus* (Swinhoe). In addition, the recent invasion by Fall armyworm (FAW), *Spodoptera frugiperda* (J.E Smith) in SSA from America poses a serious food security threat in the continent. However, little is known about FAW seasonal dynamics in different Agro-ecological zones and in particular, its interaction with stem borer pests. Thus, this study was initiated to determine the temporal dynamics of FAW and its interaction with stem borer pests and associated natural enemies in the semi-dry region of Machakos County, Kenya. The study was conducted at KALRO Katumani and two other farmers' fields in Mwania and Mikuyu villages during the short rain growing season (Oct, 2019-Jan, 2020). In a pre-planting survey of FAW in the cultivated and non-cultivated areas, 2 FAW egg batches and 90 larvae were collected in the cultivated maize area in Mwania adjacent to the research farm. Males were monitored using sex pheromone traps deployed across the farms but no catches were made. However, during the study a total of 449 FAW males were caught in six sex pheromone traps in deployed in the three sites. The FAW male catches per trap varied among different maize growth stages. The first males were detected during 2-4 leaf stage in Mikuyu and later during 5-7 leaf stages of maize plant in Mwania and Katumani, and later peaked among tasselling stages (11.5±11.8 and 0.85±0.95) in Mwania and Mikuyu respectively, and later among maturity stage (2.42±2.18) in Katumani. In a random zigzag transect a total of 1593 FAW larvae were collected in all sites. After 2-4 leaf stage, larvae increased steadily and high densities were observed among 8-11 leaf (1.78 ±0.33 and 2.63±0.41) larvae per plant in Mwania and Mikuyu respectively, and later among 12-15 leaf stage (3.13±0.52 in Katumani. Among the natural enemies of FAW identified included *Zygobothria ciliata* (Diptera: Tachinidae) and two other predators, *Myrmicaria opaciventris* (Hymenoptera: Formicidae) and *Paederus sabaeus* (Coleoptera: Staphylinidae). In four plots per farm selected randomly, two stem borers, *B. fusca* and *S. calamistis* were recovered in all the farms and were found in association with FAW notably *S. calamistis* species which were observed in maize cobs of the same plants. The implication of the findings is that FAW larval densities varied greatly among the different maize phenological stages despite recruitment of its local parasitoid species in the studied areas. This suggests that not one single control strategy is viable against fall armyworm management but rather it will form the basis upon which realistic Integrated Pest Management (IPM) package could be explored. More so, similar studies need to be extended to other agroecological zones of Kenya for broader understanding. Lastly, the few recoveries of stemborers (*B. fusca and S. calamistis*) among other factors suggest that FAW is capable of displacing stemborer pests from maize fields due to its cannibalistic nature hence expansion of its range and this necessitates future studies on its interaction with other key lepidopteran pests in other similar agroecological zones in Kenya.

CHAPTER ONE

INTRODUCTION

1.1 Background

Maize (*Zea mays L.)* is a central food crop and critical to food security in sub-Saharan Africa (SSA). It covers approximately 25 million hectares largely on small-scale farming and accounts for about 20% calorie intake of 50% of the population in SSA (Gianessi, 2014). In East Africa and Kenya in particular, maize doubles as the main staple food crop and source of employment and income for millions of farming communities in the region (Ndwiga *et al*., 2013). However, the low yield production of maize crops is associated with a number of challenges including lepidopteran stem borer pests. Key among them include *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae), *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae) and *Sesamia calamistis* (Hampson) (Lepidoptera: Noctuidae) (Goftishu *et al*., 2018; Samuel *et al*., 2018).

Similarly, the invasion of Fall Armyworm (FAW), *Spodoptera frugiperda* (JE Smith), (Lepidoptera, Noctuidae) in the recent past in Africa has escalated the problem of maize production (Hailu *et al*., 2018). Fall Armyworm is native to Americas and it was later detected in the recent past in sub-Saharan Africa (SSA) in 2016 (Goergen *et al.,* 2016, IITA, 2016; IPPC, 2016) and spread very fast to other countries in Africa. Currently, more than 44 countries together with the island countries such as São Tomé, and Príncipe, Madagascar, Seychelles and Cape Verde have detected the pest within borders (Rwomushana *et al*., 2017; CABI, 2018). Furthermore, FAW has exponentially extended its world distribution, India in 2018 and East-Asian countries in 2019 (Kalleshwaraswamy *et al*., 2018, Lee *et al.,* 2020). Recently, FAW has been reported in Germany, Netherlands and Australia (Montezano *et al*., 2019; Nagoshi *et al.,* 2020). In Africa, studies suggest that the FAW present is the haplotype that originates from Caribbean and South Florida. However, the mode, date(s), location(s) and number of introductions are unknown though single gene genetically modified *Bt* maize response and anecdotal observation in East and South Africa suggests that, the pest might have been present in Africa at least several years before the official reports (Prasanna *et al*., 2018).

Fall armyworm is a polyphagous insect which attacks over 353 plant species belonging to 76 families including new records of host plants species notably Poaceae, Asteraceae and Fabaceae (Montezano *et al*., 2018). The larvae mainly feed on maize or rice though most are conditioned to the host on which they initially feed, generally plants on which eggs were laid. As a result of this conditioning, FAW has two strains, the corn (C-strain) that mainly attacks corn, cotton and sorghum whereas the rice (R-strain) is largely associated with rice and many pasture grasses in the aborigine home (Dumas *et al*., 2015). Following its introduction into SSA in 2016, FAW has greatly impacted livelihoods of small-scale farmers in Africa. For example, in 2017, a survey carried out by Centre for Agriculture and Biosciences International (CABI) indicated that, in Zambia, the national mean losses of maize crops due to FAW damage was estimated to be 40% with a range of (25-50%) whereas in Ghana was about 45% with a range of (22-67%) (Day *et al*., 2017). In Kenya and Ethiopia maize crops damage were estimated to be 47.3% and 32% respectively with yield reduction between (0.8-1) metric tonnes/ha (Kumela *et al*., 2019).

In Kenya and Africa in general local population dynamics of FAW is likely to be driven by several factors: the influx of adults from natural habitats at the beginning of growing season and favourable tropical conditions mainly high temperatures, humid conditions and presence of main host and alternative hosts. All of these favor a population build up throughout the year (Mwangi, 2018; Prasanna *et al*., 2018). According to (Sokame *et al.*, 2020) *S. frugiperda* has wider larval dispersal ability through ballooning in a greenhouse study. These factors coupled with the observation that the pest has become locally resident (CIMMYT observation) over large areas in Africa complicate available management practices. The recommended FAW management options include, scouting for FAW eggs and larvae and squashing them, spraying with any of the insecticides with a range of active ingredients (Prasanna *et al*., 2018; Kansiime *et al.*, 2019). Furthermore, the climate-adapted push-pull technology in East Africa was reported effective and superior in reducing FAW crop infestation and damage, and presents first documentation of the technology that can promptly be considered for deployment beyond the region (Midega *et al.,* 2018).

Besides, biological control offers an economic and environmental alternative to chemical pesticides for control of FAW (Kenis *et al*., 2019). In the native region of FAW, many parasitoids and predators attack FAW eggs, larvae and pupae in maize fields. For example, in central Mexico, the main egg parasitoids include *Trichogramma atopovirilia* Oatman and Platner, and *Trichogramma pretiosum* Riley (Hymenoptera; Trichogrammatidae) the only species used in an integrated pest management in the region, and *Chelonus insularis* Cresson (Hymenoptera; Braconidae) was the key egg-larval parasitoid (Jaraleño-Teniente *et al.*, 2020). Most importantly, *Telenomus remus* Nixon (Hymenoptera; Scelionidae) the main FAW egg parasitoid used in the augmentative programmes in America has been identified now in East, South and West Africa (Kenis *et al*., 2019). In Northern Florida, the larval-pupal parasitoids include, *Lespesia archippivora* Riley (Diptera; Tachinidae) and *Cotesia sp.* as larval parasitoids among others (Hay-Roe *et al.,* 2016**).** Predators of FAW are generalist that include, *Doru taeniatum* Dohrn (Dermaptera: Forficulidae) and Mites from genus *Balaustium* as main egg predators and *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae) as larval predator among others (Ordóñez-García *et al*., 2015; Jaraleño-Teniente *et al.*, 2020)

1.2 Statement of problem and justification

Since its invasion in early 2016, FAW has become one of the significant field pests of maize in Kenya and Africa in general. Due to high magnitude of maize losses associated with its infestation, management of its population has been given priority by various government departments, researchers as well as farmers. Some of the management practices include insecticide and bio-pesticide applications. Despite these practices, FAW still persists in maize fields, an observation attributed to limited information on the species infestation dynamics at the beginning and throughout the crop season. Knowledge is needed on the FAW local infestation dynamics and how it generally relates with stem borer pests and natural enemies. This study has thus been initiated to generate information on the temporal infestation dynamics of FAW and their interaction with stem borers and determine diversity of associated natural enemies in semi-arid agroclimatic zone in Machakos, Kenya. This study will advance concepts in timely management of FAW and other major lepidopterous pests of maize.

1.3 General objective

This study was aimed at determining temporal dynamics of FAW and its interaction with stem borer pests and associated natural enemies in maize fields in semi-arid zone Machakos County.

1.3.1 Specific Objectives

i. To determine the temporal dynamics of fall armyworm (adults and larvae) in different maize growth stages in maize fields in semi-arid zone in Machakos
ii. To assess the diversity of natural enemies of fall armyworm and determine stem borers composition and their interactions with FAW in maize fields in semi-arid zone in Machakos

CHAPTER TWO

LITERATURE REVIEW

2.1 Fall Armyworm and related species

The Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), is a lepidopteran insect pest that belongs to the largest family Noctuidae (Goergen *et al*., 2016). This pest has two strains (rice and corn) that vary among plant hosts in dispersal (Meagher *et al.,* 2011).). Fall armyworm cannot diapause but in the mild climates of Texas and South Florida it can overwinters. The adult is nocturnal in its mating and feeding activities, and the females perhaps mate several times by attracting the males through their sex pheromones (Sparks,1979). The genus *Spodoptera* consists of many species that are economically important to crops worldwide. They include *S. frugiperda*, yellow striped armyworm, *S. ornithogalli* (Guenee), Egyptian cotton leaf worm, *S. littoralis* (Boisduval), beet armyworm, *S. exigua* (H€ubner), African armyworm, *S. exempta* (Walker) and tobacco caterpillar, *S. litura* (Fabricius) (Belay 2011).

2.2 Origin, distribution and biology of Fall Armyworm (FAW)

2.2.1 Origin and distribution of FAW

Fall armyworm is native to the tropical and subtropical areas of America. In 2016 it invaded West Africa and reported from Togo, Nigeria, Benin, Sao Tome and Principe (Goergen *et al*., 2016). By 2016 and 2017, FAW spread to Angola, Botswana, Namibia, Malawi, Zambia, Mozambique, Zimbabwe, Ghana, Sierra Leone, Niger, Burundi, Ethiopia, Kenya, Uganda, Rwanda and Tanzania. Fall armyworm is expected to spread further and has the potential to cause serious damage and yield losses (FAO, 2017)

2.2.2 Biology of Fall armyworm

In the Americas, the lifecycle of FAW takes about 30 days in summer at daily temperature of about 28°C, 60 days in spring and autumn and about 80-90 days in winter, see (Fig.1). The FAW lacks the capacity to hibernate but infestations continuously occur all year round (Capinera, 2017; Prasanna *et al*., 2018).

Eggs are dome shaped, base flattened and curve upward to a broadly rounded point at the tip. Egg measurement is approximately 0.3 mm in height and 0.4 mm in diameter. Number of eggs per mass varies significantly but are usually 100 - 200 eggs. Total egg production per female averages 1500.with maximum of above female 2000 with. The eggs are occasionally dropped in layers but spread mostly over a single layer attached to the leaf. Females can also deposit greyish scales layer between egg mass and over, giving a mouldy or furry look (Capinera, 2017).

Larvae are usually six instars. The head capsule measures roughly 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm in widths for instars 1-6 respectively (Capinera, 2017). The various larval instars attain approximately 1.7, 3.5, 6.4, 10.0, 17.2, and 34.2 mm in lengths respectively. First instars are greenish with a black head, head of second instars turn orangish, third instars body turn brownish in the dorsal surface and lateral white lines start to develop, fourth to sixth instars head become reddish brown and mottled with white. Brownish body bears white subdorsal and lateral lines (Capinera, 2002). Larva has four large spots on the dorsal part of its body in a square form and mature stages face is characterized by a white inverted “Y” shape. During the brightest time of the day larvae tend to hide. Larval period is approximately 14 days in summer and 30 days in cool weather. However, the mean developmental period was examined to be 3.3, 1.7, 1.5, 1.5, 2.0, and 3.7 days for the six larval instars respectively, when reared at 25°C in laboratory (Pitre and Hogg 1983).

Pupa is reddish brown, measuring about 4.5mm in width and (14-18) mm in length. Larvae usually pupate in soil at depth of (2-8) cm. Larvae construct loose cocoons usually (20-30) mm in length and oval whereby soil particles are tied together with silk. If the soil is too hard, larvae might web leaf debris and other materials together to form cocoons on soil surface. In Florida pupation takes about 8-9 days in summer, but about 20-30 days in winter (Capinera, 2002). The pupal stage cannot withstand extended periods of cold weather. For instance, (Petri and Hogg 1983) studied pupal survival in winter periods in Florida resulting in 51% in Southern Florida, 11.6% in northern Florida and 27.5% in central Florida.

Adults have wingspans of about 32-40 mm. The male forewing has a triangular white spot at the tip close to the centre of the wing shaded grey and brown. However, the female forewings are less distinctly marked ranging from a uniform greyish brown to a fine mottling grey and brown. In both sexes, hind wings are iridescent silver-white with narrow dark borders. Moths are very active throughout warm, humid evenings and are nocturnal. The female lay eggs mostly during its first 4 -5 days of life after a preoviposition period of 3- 4 days. At some point oviposition happens up to three weeks with an average adult life of 10 days with a range of 7-21 days (Luginbill, 1928; Sparks 1979)

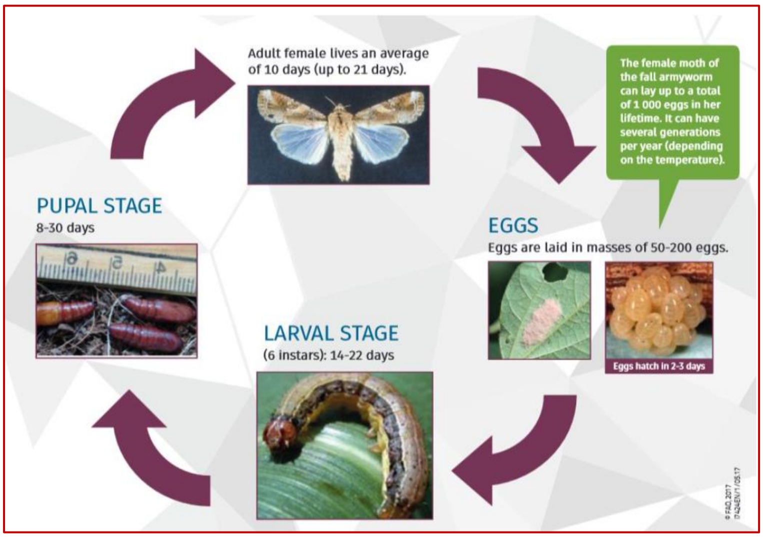


Figure 1: Lifecycle of the Fall armyworm

Source (FAO 2017) African Department of Agriculture, Forestry, and Fisheries

2.3 Mobility and dispersal of FAW

Similar to other lepidopterans in the genus *Spodoptera*, FAW adults have more localized dispersal and migratory habits in its native region. For example, in a migratory habit, a flight of 1600 km from Mississippi to southern Canada took 30 hours (Rose *et al*. 1975). In Central America, moths usually disperse a distance of 500km from dry season habitats to wet areas before oviposition (Johnson ,1987). Fall armyworm is extremely mobile and does not survive protracted periods of cold temperatures but have to move northward each spring if it has to re-infest temperate cropping regions (Westbrook *et al*., 2016). In many parts of North America, FAW arrives seasonally and perishes in cold winter periods. However, FAW generations in SSA, can continue all year round as long host plants, irrigated and off-season crops are available and favourable climatic variables (Prasanna *et al*., 2018). Although, patterns of population dispersal, migration and persistence in SSA are unknown, favourable conditions in Africa notably bimodal rainfall patterns suggest that FAW could persist all year round, become naturalised, endemic (Prasanna *et al*., 2018).

2.4 Fall armyworm host range and damage

The FAW has a wider host range of about 353 recorded plant species (Montezano *et al*., 2018). It prefers rice, sorghum, maize, Bermuda grass and other grass weeds including *Digitaria spp*. Other crops frequently attacked include, clover, oat, cotton, millet, Sudan grass, rye grass, sugar beet, alfalfa, barley, buckwheat, soybean, timothy, peanut sugarcane, tobacco and wheat (Capinera, 2017). Fall armyworm can feed on both vegetative and reproductive structures of maize crops (Alves *et al*., 2014; Day *et al*., 2017). Larvae usually burrow into growing points of the crops (whorls or buds) and destroy the potential growing parts. In maize, they burrow into ears and feed on kernels like corn earworm (Capinera, 2002). Neonates feed on one side of leaf tissue, leaving the opposite epidermal layer intact. The (2^{nd}- 3^{rd}) instars create holes in leaves and consume the leaf edge inwards. Older instars can cause wider defoliation of maize plants leaving ragged or torn appearance. Larval densities are reduced normally to one or two per plant as a result of cannibalism (Capinera, 2017). In absence of any suitable management strategies FAW has the potential to cause yield loss and stunted growing points (Abrahams *et al.*, 2017). In Africa, estimated maize yield loss of about (8.3 - 20.6) million tonnes out of 39 million tonnes of total expected yield production per year from 12 countries This represent an average yield loss ranging from US$2,481m to US$6,187m per year with a total expected value of US$11,590.5m (Abrahams *et al.*, 2017).Following the FAW invasion in Africa, the moth has been intercepted twice in 2017 on exports to EU from Africa including 17 interceptions from the first 8 months of 2018 in a range of crops including *Zea mays, Solanum, Rosa, Pisum, Eustoma, Eryngium, Coriandrum and Capsicum* (CABI, 2017). For example, in June 2017, first shipment of roses contaminated with FAW from SSA was intercepted in Europe, (Abraham *et al.*, 2017

2.5 Lepidopteran stem borers pests

Stem borers are major economic pests of cereal crops (rice sorghum, maize, millet) in Africa (Kfir *et al.*, 2002).With exception of spotted stemborer, *Chilo partellus* which invaded Africa from India other borer pests are aboriginal to Sub Saharan Africa (SSA) and are presumed to have co-evolved with some indigenous sedges and grasses (Ong'amo *et al*., 2014). In East Africa, *Sesamia calamistis (*Hampson), *Busseola fusca* (Fuller), *Chilo partellus* (Swinhoe), *Eldana Saccharina* and *Chilo orichalcociliellus a*re the most notorious maize and sorghum pests (Bonhof *et al*., 1997).

2.5.1 The African stem borer, *Busseola fusca* (Fuller)

2.5.1.1 Geographic distribution

The African stem borer pest has a wider distribution across SSA. The pest seems to have adapted itself to various environments but limited to mid-and high altitudes (>600m) in East and Southern Africa compared to those in western Africa. In West Africa *B. fusca* is found in all altitudes and most abundant in dry savanna zones. Countries with *B. fusca* record include Botswana, Guinea, Benin, Ethiopia, Angola, Cameroon, Burkina Faso, Mali, South Africa, Côte d'Ivoire, Mozambique Malawi, Nigeria, Lesotho, Somalia, Rwanda, Kenya, Zaire, Swaziland, Uganda, Tanzania, Ghana, Sierra Leone, Zimbabwe and Zambia (Harris and Nwanze, 1992).

2.5.1.2 Biology of *Busseola fusca* (Fuller)

Female lays hundred eggs in batches of 30-50 eggs that are inserted between stem and sheath. Incubation period is about a week. After hatching, larvae feed on young leaf whorl blades and spread to nearby plants after suspension from silk strands. Usually, growing points of crops are destroyed and larvae burrow downward the stem through the whorl base. Lifecycle is completed in 30-45 days with 6-8 moults, see Fig.2. The larva chews an exit for moth before pupation in the tunnel. Pupation takes about 10-20 days. *B. fusca* may have four generations yearly. The last generation enters diapause in sorghum and maize stubbles or wild grasses at the end of the rain growing season and pupate a few months later, just before the beginning of next rain season (Overholt *et al*., 2001).

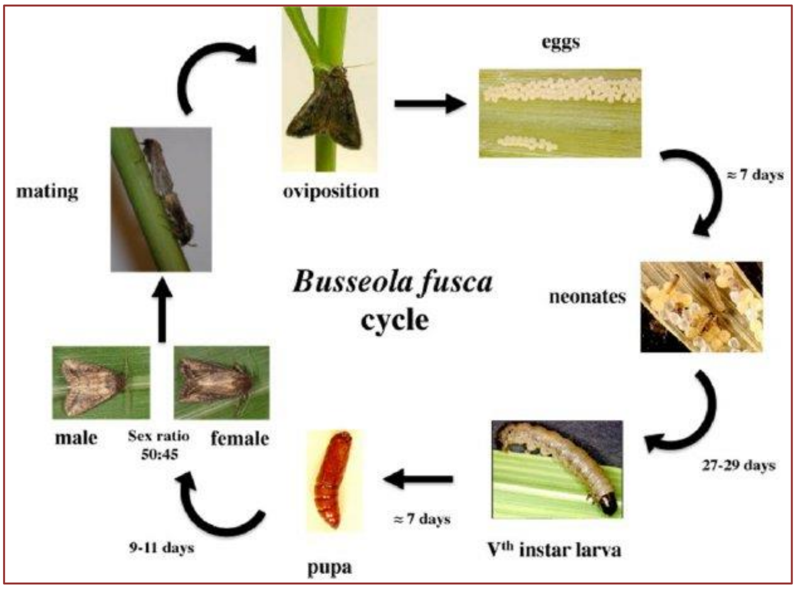


Figure 2: Lifecycle of *Busseola fusca* under optimal environmental conditions on artificial diet (photos on mating and oviposition from Felix, A.-E, 2008)

Source: (Journals of Insect, 2014)

2.5.2 Spotted stem borer, *Chilo partellus* (Swinhoe)

2.5.2.1 Geographic distribution

Chilo partellus is a major pest of sorghum and maize in SSA after it has invaded SSA from Asia. In 1930, *C. partellus* was reported in Africa notably Malawi and spread to many countries in Eastern and Southern Africa including Sudan, Ethiopia, Kenya, Somalia, Tanzania, Uganda, Mozambique and South Africa (CAB, 1977). Botswana, Swaziland and Zimbabwe (Sithole, 1990). Madagascar and Cornaro Islands (Bleszynski, 1970; Delobel, 1975).

2.5.2.2 Biology of *Chilo partellus* (Swinhoe)

Moths emerge either in late midday or early evening from the pupae. Moths are active at night and rest during the day on plants or plant debris. Soon after emergence, female mates and oviposits about 10-80 overlapping eggs batches in 2-3 subsequent nights on upper or underside of leaves near midribs or stem. Moths live 2-5 days and usually do not disperse far from emergence places. After 4-8 days of egg laying, eggs hatch in early morning (0600-0800 h) and neonates move into leaf whorls and start feeding. Older larvae burrow into stem tissues and pupate for about 5-12 days after 2-3 weeks of feeding. Lifecycle takes about 25-50 days under favourable conditions, and about 5 or more generations in one maize growing season. Larvae may diapause in stems, stubble and other plant remains during cold or dry periods and spend about 6 months before pupation when conditions become normal in the next growing season. Some of the stalk borers remain active during the dry season in wild grasses (Overholt *et al*., 2001)

2.5.3 Pink stem borer, *Sesamia calamistis* (Hampson)

2.5.3.1 Geographical distribution

In Africa *Sesamia calamistis* occurs mostly in tropical zones. Countries of records include, Zimbabwe, Uganda, Malawi, Kenya, South Africa, Madagascar, Angola, Mauritius, Tanzania, Reunion, Nigeria, Zanzibar, Côte d'Ivoire, Cameroon, Senegal, Ghana, Gambia, (Tams and Bowden, 1953), Ethiopia (Gebre-Amlak, 1985), Mozambique (Cugala *et al*., 1999).

2.5.3.2 Biology of *Sesamia calamistis*

Female lays about 350 eggs, and in batches of 10-40 in 3-5 days. Eggs are arranged in 2-4 contiguous rows. Female deposits eggs between stems and lower leaf sheaths. Upon hatching, larvae vacate oviposition areas and enter the stems directly or after consuming leaf sheath. Larval development takes about 30-60 days depending on environmental conditions and usually involves 5-6 moults. Number of young stems are successively attacked and usually one immature larva is observed in the young stem or tiller. Pupation usually takes place in the stem. Pupation takes about 10-12 days at 25 °C. under tropical conditions. The pink stem borer may have 5-6 generations per year and breeds all year round without diapause (Overholt *et al*., 2001).

2.5.4 Damage symptoms of lepidopteran stem borers

Lepidopteran stem borers feed on leaves, in stems and cobs. Early stages of *Chilo* species. and *B. fusca* usually migrate the oviposition sites to the crop whorls in which the first two or third instars feed on young succulent leaf tissues. This kind of feeding is characterized by window panes and 'pinholes'. Window panes are described as transparent thin layer of leaf epidermis in which the leaf is not chewed completely by larvae while pin holes are linear series of small holes chewed horizontally on developing leaf in the whorl by larvae (Overholt *et al*., 2001). Third instars of *Chilo* species and *B. fusca* usually burrow and feed within the stem until pupation. At times larvae bore directly into stem from the whorl causing dead hearts and eventual death of the growing points. Feeding of early instars of *Sesamia* species is on leaf sheath (between leaf and stem) before tunnelling into the stem. (Overholt *et al*., 2001). Generally, stem borer larvae chew an exit hole called window before pupation for the emergence of moths. The chewed hole is not completely opened through the stem but transparent leaf epidermis is left (Overholt *et al*., 2001).

2.6 Composition of stem borer pests in maize fields

Surveys conducted in various countries in Africa have documented complex stem borers species in maize fields. For instance, In Katumani of Machakos County, Kenya, *C. partellus*, *B. fusca* and *S. calamistis* (Lepidoptera: Olethreutidae) were collected (Songa *et al.*, 2002). In Cameroon *B. fusca*, *E. saccharina* and *Chilo spp.* (Ndemah, 2007) while in Kisangani DR Congo, borers were composed of *S. calamistis*, *B. fusca, E. saccharina*, *C. aleniellus* (Strand) and *Mussidia nigrivenella* (Kankonda, 2017).

2.7 Interactions of stem borer pests and FAW in maize fields

In parts of Tanzania and Kenya, stem borers interaction in maize fields varied among AEZs. In the lowland tropical zone, *C. partellus* was dominant, about 90% infestation, in the highland tropical zone, *B. fusca* was 79% and in both zones *S. calamistis* was low (Ntiri *et al.*, 2019). In the other agroecological zones *C. partellus* was dominant, about 57% in dry mid-altitude and about 60% in dry transitional zone. In moist transitional zone *B. fusca* was the dominant species about 69% and about 71% in moist mid-altitude while *S. calamistis* was lower with varying proportions in all the AEZs (Ntiri *et al.*, 2019). Generally, the three species varied in all the zones. Nonetheless, the interactions between FAW and stem borer species are not known simply because FAW is still new in Africa and more studies are required

2.8 Management of stem borers and Fall armyworm

2.8.1 Management of lepidopteran stem borer pests

In sub-Saharan Africa (SSA), different control measures have been used to lower levels of stem borers population in fields. These includes biological, chemical, cultural methods and host plant resistance (Mugo *et al.*, 2001; Kfir *et al.*, 2002).

2.8 1.1 Chemical control

Chemical control of insect pests remains an important part of IPM. Nonetheless, stem borers management with chemicals is relatively more problematic as the pests' burrow into maize or sorghum stems than insects feeding on shoots and foliage. Spray formulations of most insecticides and foliar applications have proven ineffective (Jotwani, 1983).

2.8.1.2 Cultural control

Cultural practices were found promising to control stem borers by small scale farmers. For example, in eastern Ethiopia, intercropping, crop rotation, disposal of crop residues, post-harvest tillage and manipulation of planting dates were among the methods used (Goftishu *et* *al*., 2016). In addition, a 'Push-Pull' technology developed by the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya for the control of stemborers was found effective. It involves use of companion cropping systems such as trap and repellent crops (Midega *et al*., 2015).

2.8.1.3 Biological control

Biological control of stem borers includes parasitoids, parasitoids and pathogens that suppress pest population. In East Africa, different stem borers eggs, larval and pupal parasitoids were identified (Bonhof *et al*., 1997). They include, *Trichogramma spp.* and *Telenomus spp.*as egg parasitoids, *Cotesia sesamiae* Cameron (Hymenoptera: Braconidae) and *Sturmiopsis parasitica* Curran (Diptera: Tachinidae) as larval parasitoids and *Pediobius furvus G*ahan (Hymenoptera: Eulophidae) and *Dentichasmias busseolae* Heinrich (Hymenoptera: Ichneumonidae) among the pupal parasitoids. Information on predators and entomopathogens are less extensive. However, some predators like spiders, earwigs and ants were reported to cause high mortality on stem borers eggs and small larvae (Bonhof *et al*., 1997)

2.8.2 Management of Fall armyworm

The FAW rapid spread requires multiple management approaches ranging from biological, chemical and botanical methods. For example, in South and North America GMO crops and pesticides are the main control options used against fall armyworm (Abrahams *et al.*, 2017)

2.8.2.1 Field Monitoring

The monitoring of FAW is key in the decision-making process for its management. In Latin America pheromone traps, light traps and scouting have been used to indicate FAW moth population, overall plant damage, presence of eggs and different larval sizes in an area through field scouting (Abrahams *et al*., 2017). An android app (FAMEWS) tool developed by FAO for recording scouting and pheromone trap data improves monitoring in the field (CABI, 2018). Report by (Bratovich *et al.*, 2019) in Argentina indicated that synthetic version of FAW sex pheromone has variable success simply because female sex pheromone composition from other geographical regions differs. According to (CABI, 2018), two approaches are being considered, mating disruption and trapping. In East Africa, mating disruption is undergoing trials which involves releasing many pheromones into the surrounding to confuse FAW males in finding females whose pheromones emission are lost in the cloud. Three compounds release by FAW females include, (Z)-11-hexadecenyl acetate (Z11-16: OAc), (Z)-7-dodecenyl acetate (Z7-12: OAc) and (Z)-9-tetradecenyl acetate (Z9-14: OAc), (Cruz-Esteban *et al.*, 2018).

2.8.2.2 Chemical control

Different synthetic insecticides in America were used to control FAW. However, chemical reliance to manage FAW has led to development of resistant in many regions in the US. For example, FAW population in some Mexican States exhibited high resistance ratio to chlorpyriphos, permethrin and flubendiamide while those populations in Puerto Rico showed lower resistance ratio to spinosad, chlorantraniliprole, flubendiamide, methomyl, emamectin benzoate, thiodicarb, permethrin, chlorpyriphos, cypermethrin, deltamethrin, triflumuron, spinetoram, and abamectin insecticides in the fields though they are still effective in controlling FAW resistance in Puerto Rico (Gutirrez-Moreno *et al*., 2019). In North Florida, FAW strains collected showed resistant to organophosphates for example (chlorpyrifos, methyl parathion, malathion), pyrethroids (permethrin, cyhalothrin, cypermethrin) and carbamates (methomyl, carbaryl, thiodicarb) among others (Yu, 1991).

2.8.2.3 Cultural and agronomic practices

In Southern states of America, early maturing varieties and early planting were the most practices used. Early harvest of maize ears enables crops to escape the high magnitude of FAW that develop later in the season (Mitchell, 1978). In Africa, a survey conducted in eastern Zimbabwe indicated that weeding has significantly reduced FAW infestation (Baudron *et al.*, 2019). Other cultural techniques reported and used by many farmers in Africa as the first line of protection against FAW .include handpicking of FAW egg batches and larvae (CABI, 2018). Maize Intercrop with legume crops (groundnut, soybean and beans), and companion crops (trap and repellent) were reported to reduce damage (CABI, 2018). Report by (Midega *et al.,* 2108) indicated that climate-adapted push-pull technology is effective to control FAW in East Africa.

2.8.2.4 Biological control

Biological control is an important method in suppressing pests and aims at generating higher profits while preserving the environment and human health. In America FAW parasitoids and predators have the potential to reduce FAW population and damage. Native natural enemies have been discovered with about 70% parasitism (CABI, 2018; FAO, 2018; Kenis *et al*., 2019).

2.8.2.5 Parasitoids and predators

Surveys of FAW in America have documented complex natural enemies of FAW. For instance, In Mexico, ten parasitoids species were recovered from FAW larvae representing Braconidae, Ichneumonidae, Eulophidae, Trichogrammatidae and Tachinidae families (Hoballah *et al*., 2004; Ordóñez-García *et al*., 2015). In South America, *Archytas marmoratus* (Tns.), *Archytas incertus* (Macq.), *Meteorus laphygmae* (Viereck) and *C. insularis* were the common parasites (Molina-Ochoa *et al*., 2003). In South Florida, *Chelonus insularis* (Cresson) and *Cotesia marginiventris* (Cression) were dominant (Meagher *et al*., 2016). More importantly, an inventory of natural enemies of FAW in Caribbean Basin and America has documented a total of 150 parasitoid species indicating prospects for potential biological control of FAW (Molina-Ochoa *et al*., 2003). In Kenya tachinid fly, *Palexorista zonat*a Curran (Dipteran: Tachinidae), *Coccygidium luteum* (Brullé) (Hymenoptera: Braconidae) and *Charops ater* Szépliget (Hymenoptera: Ichneumonidae) were the dominant larval parasitoids (Sisay *et al.,* 2018). *Chelonus curvimaculatus* Cameron (Hymenoptera: Braconidae) the egg-larval parasitoid and *Telenomus remus* (Hymenoptera: Scelionidae) the egg parasitoid (Sisay *et al*., 2019). Predators of FAW are general enemies of other lepidopteran pests. In America some of the common species include insidious flower bug, *Orius insidious* (Say) (Hemiptera: Anthocoridae) and numerous spiders (Isenhour *et al*., 1989; Pfannenstiel, 2008). Earwig *Doru taeniatum* (Dorhn), including some species from Carabidae, Pentatomidae and formicidae families (Wyckhuys and O'Neil, 2006, Ordóñez-García *et al*., 2015).

2.9 Seasonal dynamics of FAW in different maize growth stages

A study of FAW adult dynamics and larval damage on sole maize crop were conducted in northern Ghana for two seasons. First, FAW sex pheromone traps were deployed in the three regions of Upper East, Northern, and Upper West region in which a total of 2601 FAW males were caught over two seasons (Nboyine *et al.,* 2020). Generally, male catches increased progressively from maize emergence and peaked at reproductive stages. After the vegetative stages, male catches and larval abundance declined greatly (Nboyine *et al.,* 2020). In Northwestern Argentina, Tafí Viejo region, no larvae were collected among V1-V3 leaf stages during the early planting date. Overall, year 1 and 3 had high larval densities among V3-V6 leaf stages but higher densities were recorded in year 2 and 4 towards the end of vegetative stages. The mean of larvae per 10 plants 0.58, 0.013, 0.89, and 0.88 in year (1, 2, 3, and 4) respectively (Murúa *et al.,* 2006). In the Vipos region, high densities of FAW larvae were collected among V1-V3 leaf stages during year 1 and 2. The larvae showed consistency during the vegetative period throughout the years. After this stage, larval densities dwindled with crop age that led to less larvae collected at the onset of reproductive stages. Mean of larvae per 10 plants (2.59, 2.17, 1.25, and 1.83) in year 1, 2, 3, and 4 (Murúa *et al.,* 2006). According to (Hernández-Mendoza *et al.*, 2008), 10 leaf stages were more infested than the other vegetative stages in maize fields in Colima, Mexico.

2.10 Interactions between FAW and the climatic variables

In temperate regions, the FAW cannot survive extended periods of freezing temperatures and migrates from such places to infest preferred crops in areas with favourable climatic conditions (Westbrook *et al.,* 2016). In warmer conditions, agricultural insect pests including FAW tend to multiply very fast hence occurrence of new generations and abundance (Cammell and Knight, 1992). Like other agricultural pests, FAW is affected by climatic factors. Their survival, reproduction, development and distribution are frequently limited by unfavourable conditions notably in winter (Cammell and Knight, 1992; Nurzannah *et al.,* 2020). In West Africa, the average life cycle of *S. frugiperda* under laboratory conditions was 25 days at 25˚C. and about 15 generations a year (Tendeng *et al*., 2019). In Northern Ghana a study revealed positive significant correlation between FAW moths and rainfall in Upper East, Northern, and Upper West regions in 2017 and 2018 except 2018 in Upper West region (Nboyine *et al.*, 2020). According to (Du Plessis *et al.,* 2020), the FAW development rate in South Africa indicated that the minimum temperature threshold of FAW egg, larvae and pupae were (13.01, 12.12 and 13.06◦C) respectively. The optimum temperature range for egg-adult was between 26-30 ◦C and therefore, FAW cannot persist or develop below the minimum temperature threshold especially in regions where temperatures decrease during winter months The optimal range for egg, larval and egg-to-adult development of FAW was between 26 and 30 ◦C. Murúa *et al.,*

(2006) reported that, rainfall and temperature affected FAW larval density in Northwestern Argentina contrary to the findings by Nurzannah *et al.,* (2020) who reported significant and positive correlation between rainfall and FAW in Karo District, North Sumatera, Indonesia.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

The study was carried out in three maize fields in a semi-arid region of Machakos County Kenya. One at KALRO Katumani research station located at (1◦34'54' N 37◦14'31", about 1608 masl) and two other farmers' fields in Mikuyu located at (1◦33'59' N 37◦13'12" W at about 1572 masl) and Mwania at (1◦33'46' N 37◦15'30" W at about 1548 masl). The other two farms were about 3-6km away from KALRO Katumani research station. The maize farms were purposively selected due to reported prevalence of FAW and accessibility of data collection after consultation with farmers. Katumani Research Station is located in Machakos County, 80km south-east of Nairobi at an altitude of 1600 masl, latitude (01◦34'S and longitude 37◦14 E). The area is characterized by bimodal annual rainfall with an average mean of 711 mm per year. Long (LR) rains start from (March-May) and short (SR) rains from (October-December) ranging between 301mm and 283mm respectively with short rains being more reliable than long rains for crop production (Kwena *et al.,* 2017).

3.2 Weather data

The weather equipment were temperature/humidity loggers see (Fig.3a) which are devices that automatically record temperature every 10 minutes and the rain gauge see (Fig.3b) measure rainfall amount in millimetre (mm). The equipment were installed in Mikuyu, Mwania and Katumani farms. The temperature loggers were attached to wooden poles using a screw and installed in the interior of each farm. One logger at 2 meters above ground and the other one at the maize canopy moved upwards following maize height. All the loggers were cased into radiator shields for protection. Temperature data were downloaded using Hobomobile app on an android phone using Bluetooth. To measure actual rainfall amount received. one rain gauge each was deployed in Mwania and Mikuyu. At Katumani site, rainfall data was obtained in Katumani meteorological station. Each rain gauge was attached to a wooden pole and installed at one-meter height and 5cm over the top of the pole. All the rain gauges were deployed at 2m from the farm in open areas. The amount of rainfall in the rain gauges were checked twice a week, emptied completely after every reading

(a) (b)

Figure 3: Equipment deployed in the farms (a) Temperature logger and (b) Rain gauge

3.3 Pre-planting survey of fall armyworm in cultivated and non-cultivated areas

The FAW (eggs, larvae and adults) were assessed one week before the experimental trials in Katumani, Mwania and Mikuyu. The surveys were done in the surrounding wild vegetation, including cultivated areas around the experimental farms. The FAW (eggs and larvae) resident population were assessed at a distance of about 50 meters from the study farms. At each side of the farms, 1 quadrant of one-meter square was randomly laid at the suspected grass patches and an existing maize farm that belonged to a farmer in Mwania. The grass tillers and maize plants were searched, dissected and inspected. Adults were monitored using sex pheromone traps deployed in the experimental farms a week before maize germination. Two (2) traps per farm were deployed. Data was collected two times

3.4 Assessment of temporal dynamics of FAW in maize fields

Three maize farms were sampled; one in Katumani and two other farmers' fields in Mwania and Mikuyu villages. Areas of selected farms were estimated 0.297, 0.154 and 0.099 acres in Katumani, Mwania and Mikuyu respectively. The farms were planted on 03/Oct/2019 with (KDV-1) maize variety. Cultural practice (weeding) was basically undertaken. Data were collected for 15 weeks which started from (15 Oct, 2019 - 31 Jan, 2020). For the first two weeks after crop emergence, data were collected three times a week and continued for two weeks. Afterwards, from 3rd week sampling frequency was done twice a week until physiological maturity. Samplings were done randomly always starting at a different corner of the experimental farms while maintaining 2m away from the edge to avoid edge effects. All the research fields were sampled on the same day. In each farm, a total of sixteen (16) plants were randomly sampled, 2 plants selected at each of the 8 checkpoints along a zigzag transect. Checkpoints were distributed 5 meters apart. Plants showing symptoms of FAW infestations were randomly sampled, dissected and collected larvae per plant were all observed, and identified where possible. Unidentified larvae were individually collected into vials and petri dishes and reared on maize leaves to adult stage in the Entomology laboratory in KALRO Katumani for further identification

Dynamics of FAW adult catches

At each research site, two funnel traps impregnated with FAW sex pheromone marked A and B were deployed in each farm. The traps marked A were mounted close to the edge of each farm whereas the traps marked B were placed towards the interior on a linear transect following the upwind direction, see (Fig. 4). Traps were placed 2 meters above ground level and hung on wooden poles at a distance of 10 meters between each other. Each funnel trap was impregnated with one sex pheromone lure and replaced after every three weeks. In addition, insecticidal strips were also placed at the bottom of the funnel traps to preserve the adults caught in the traps. These insecticidal strips were changed after every six weeks

Figure 4: Fall armyworm sex pheromone lure trap deployed in Mwania farm

Different maize phenological stages

During the study, maize crops were sampled during the short raining season described in the methodology above. Different maize growth stages were recorded right from germination to MaturityTable.1)

Table 1: Maize phenological stages and corresponding weeks

Maize phenological stages	No of weeks	Corresponding stages by (Prasanna *et al.*, 2018)
Emergence	0	VE
2-4 leaves fully emerged	1	V2
5-7 leaves fully emerged	3	V5
8-11 leaves fully emerged	5	V8
12-15 leaves	7	V12
Tasselling/silking fully formed	9	R1
Maturity/drying	11	R5
Harvest	15	

3.5 Assessment of natural enemies' diversity of FAW and stem borers composition

During the study, each experimental farm in Katumani, Mwania and Mikuyu was divided equally into subplots of 5x5 meters. Among the subplots 4 were randomly selected in each sampling time. In each farm 16 plants were equally distributed into 4 subplots and randomly sampled. In each subplot,4 plants that showed FAW or stem borers infestation symptoms were purposively selected and 4 plants each sampled at random. Sampled plants were cut at ground level, split, searched and inspected for stem borers and fall armyworm larvae. Collected *S. calamistis, B. fusca and S. frugiperda* larvae were individually put into petri dishes and vials. Fall armyworm and stem borers larvae were reared on maize leaves and stems respectively until pupation. The stem borers larvae were only monitored to identify the species composition and their possible interaction with FAW in the field level. All the insects were reared and maintained in the laboratory in KALRO Katumani under room temperature of about 24 -26 C, 50-70% RH and a photoperiod of (12:12 L D) hour. Fall armyworm larvae were monitored after every 24 hours for possible emergence of parasitoids. Parasitoids that emerged from FAW larvae were preserved in 70% alcohol. For predator' direct observation method was used during the survey. Predators observed feeding on FAW larvae were collected into vials and preserved in 70% alcohol and later all the predators and parasitoids species were identified at the Invertebrate Zoology Laboratory of National Museum of Kenya, Nairobi

3.6 Data collection

The number of FAW larvae, stemborers larvae in each plant, FAW male adult catches per trap and maize phenological stages were recorded. Collected FAW and stem borers larvae from the three fields were reared on maize leaves and stems respectively in KALRO Katumani laboratory. Fall armyworm larvae were monitored every twenty-four hours for possible emergence of larval parasitoids while stem borers larvae were reared until adult stage for possible identification. However, predators observed feeding on FAW larvae in the fields were collected into vials, recorded and preserved for identification. Temperature data were downloaded from the loggers using Hobomobile app in an android phone while Rainfall (data) in Mwania and Mikuyu were obtained by checking the amount of rainfall in millimetre in the rain gauges installed in the farms. Rain gauges were emptied after every reading. At Katumani KALRO, rainfall data were obtained from Katumani meteorological station. Generally, data were collected thrice a week immediately after crop emergence and continued for two weeks and afterwards twice a week until physiological maturity of maize.

3.7 Data analysis

The FAW adults and larvae data were modelled using a generalized linear mixed model (GLMM) as a function of different sites and phenological stages (time) using R package lme4 (Bates *et al*., 2015). Negative binomial regression was selected as an extension of Poisson distribution to counter the significant proportion of zero values. Means were separated using Tukey test whenever there was a significant difference among the means (p <0.05). Similarly, FAW larvae and moth data were square-root transformed after it was tested for normality and compared using Pearson correlation analysis to determine their interactions with temperature and rainfall. However, the predators and parasitoid species including the stemborers in the sampled fields were simply described as the taxa do not meet the test for diversity. All other statistical analysis were conducted in R software version 3.6.3 (Core team, 2019).

CHAPTER FOUR

RESULTS

4.1 Pre-planting fall armyworm survey results

Prior to the experimental studies, Cultivated and uncultivated areas or wild grasses were sampled. Fall armyworm were not found in the uncultivated areas or wild grasses in all the sites, see Fig.5a. However, 92 FAW larvae of varying instars including 2 egg batches were collected among the maize crops in the cultivated maize field adjacent to the experimental farm in Mwania, see (Fig.5b)

(a) **(b)**

Figure 5: Surveyed areas(a) Wild grass habitats and (b) Cultivated maize field in Mwania

4.1.1. Temporal dynamics of FAW male catches among different maize growth stages

A total of 499 FAW males were caught in six sex pheromone traps deployed in the three farms; Katumani (90), Mwania (382) and Mikuyu (27) males. The FAW male catches per trap per week varied among different maize phenological stages see (Fig.3a.) The first males were detected in Mikuyu among 2-4 leaf stages and later among 5-7 leaf stages of maize plants in Mwania and Katumani. The catches peaked during tasselling in Mwania and Mikuyu, and later among physiological maturity stages in Katumani. GLMM results revealed statistical differences of FAW male catches per trap per week among different phenological stages (*F*= 64.75; *df* = 7; *p* < 0.001) and site (*F* = 48.53, *df* = 2; *p* < 0.001). The stages were tasselling (11.5±11.8 and 0.85±0.95) in Mwania and Mikuyu, and later among maturity stages (2.42±2.18) in Katumani. Among 12-15 leaf (3.50±1.50 and 0.5±0.5) in Mwania and Mikuyu and among 8-11leaf (0.20±0.29) and (2-4 leaf (0.13±0.25) in Mikuyu. The interactions between male catches, phenological stages and sites were not statistically different (*F* = 13.06; *df* =12; *p* = 0.36)

4.2.2 Temporal dynamics of FAW larvae among different maize growth stages

A total of 1593 FAW larvae were collected from three farms, Katumani (515), Mwania (470) and Mikuyu (608). First larvae were observed among 2-4 leaf stages in Mikuyu and later among5-7 leaf stages in Katumani and Mwania. After 2-4 leaf stages, larval population increased rapidly and high densities were recorded among 8-11 leaf stages in Mwania and Mikuyu, and later among 12-15 maize leaf stages in Katumani. There was evidence of variation in larval densities among different growth stages in Katumani, Mwania and Mikuyu (Fig.3b). GLMM results on FAW larvae revealed statistical differences among different maize phenological stages (*F* = 1032.15; *df* = 6; *p* < 0.001) and among sites (*F* = 10.65; *df* = 2, *p* < 0.01). Among stages, 8-11 leaf (2.63±0.41) in Mikuyu, 5-7 leaf (0.33± 0.24) in Mwania, 12-15 leaf (3.13±0.52) in Katumani, Maturity (0.11±0.09 and 0.45±0.23) in Mwania and Mikuyu respectively. The interactions between FAW larvae, phenological stages and sites are statistically different (*F*= 67.84; *df* = 12; *p* < 0.001).

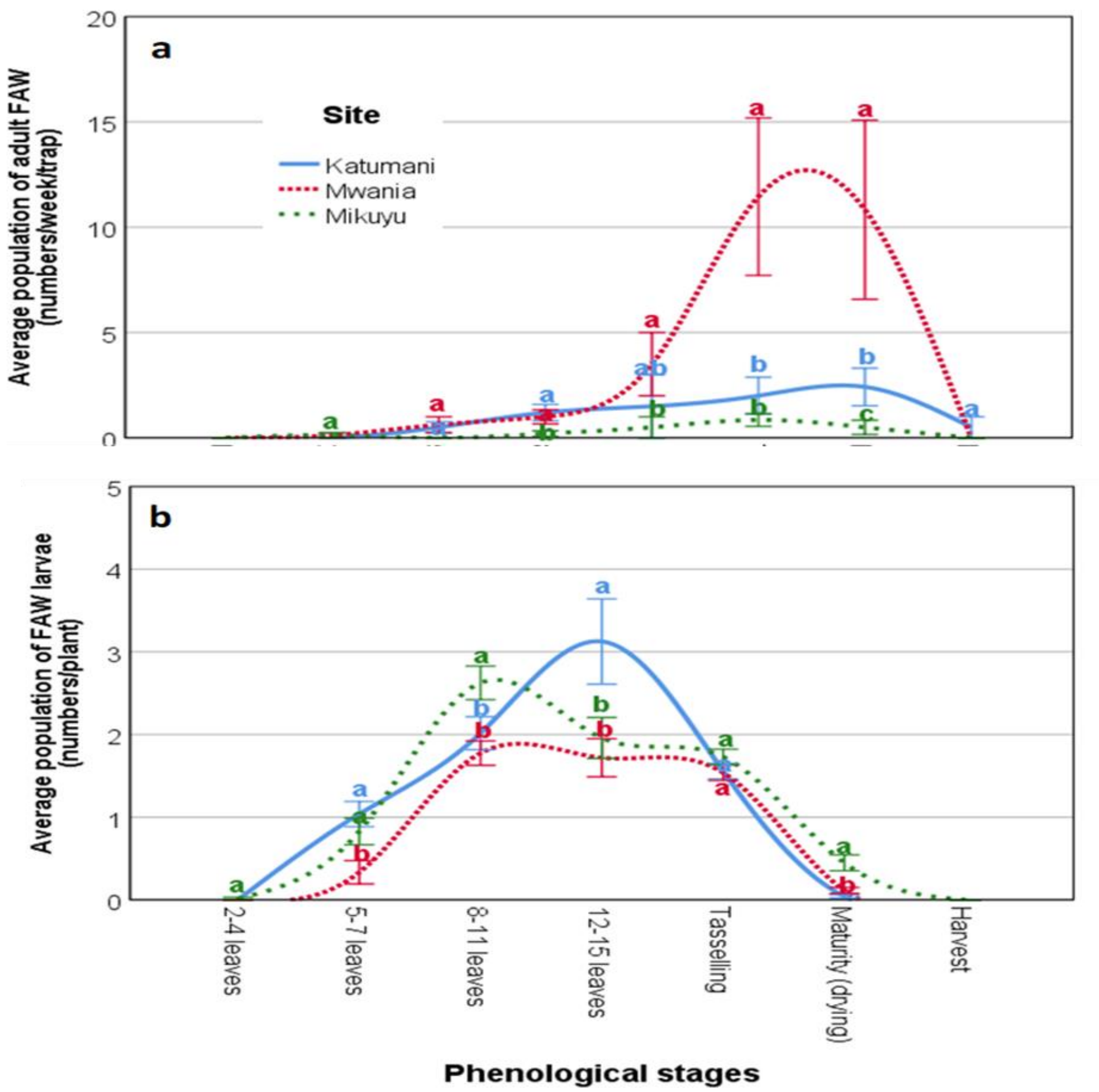


Figure 6: Temporal dynamics of *S. frugiperda* (a) adult catches per week and (b) larval densities in different maize growth stages during the short rain growing season. Means ± SEs showing different letters are statistically different.

4.3 The relationship between FAW (adults and larvae) and climatic factors

The mean temperatures and rainfall for Katumani, Mwania and Mikuyu were (20.22˚C, 20.95 ˚C and 20.37 ˚C), and (185.35 mm, 148.85 mm and 183.1 mm) respectively. Pearson correlation results revealed positive significant correlation between FAW larvae, temperature and rainfall in Katumani (0.21) and Mwania (0.13) but negatively correlated in Mikuyu. Besides, rainfall was significantly and positively correlated with FAW larvae (0.13, 0.36 and 0.16) in Katumani, Mwania and Mikuyu respectively. Fall armyworm larval densities were significantly influenced by temperature and rainfall in Katumani, Mwania and Mikuyu. However, FAW male catches were negatively correlated (0.28) with rainfall in Mwania

Table 2: Pearson correlation between FAW and selected climatic variables

Fall armyworm	**Site**					
	Katumani		**Mwania**		**Mikuyu**	
	Climatic variables					
	Temp (˚C)	RF (mm)	Temp (˚C)	RF (mm)	Temp (˚C)	RF (mm)
Larvae	0.21***	0.13**	0.13**	0.36***	0.10*	0.16***
Adults	0.13	0.01	0.01	0.28*	-0.06	0.11

Key Temp = Temperature and RF = Rainfall. The correlations between the larvae and climatic variables marked with asterisks are significant. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

4.4 Diversity of natural enemies of fall armyworm

A total of three (3) natural enemies of FAW were identified during the study. They included two predators, *Myrmicaria opaciventris* and *Paederus sabaeus* and one parasitoid species, *Zygobothria ciliata* see (Table 1)

4.4.1 Predators

a) The ants, *Myrmicaria opaciventris* (Hymenoptera: Formicidae) see (Fig.8 a) were observed predating on (2nd and 3rd) larval instars of FAW in the maize farm in Mikuyu and on 2nd instars both in Katumani and Mwania maize farms. In Mikuyu *M. opaciventris* could be considered as a resident predator since it had built one wide nest within the farm. These ants were mostly observed predating on the FAW larvae during the maize reproductive stages especially in Mikuyu

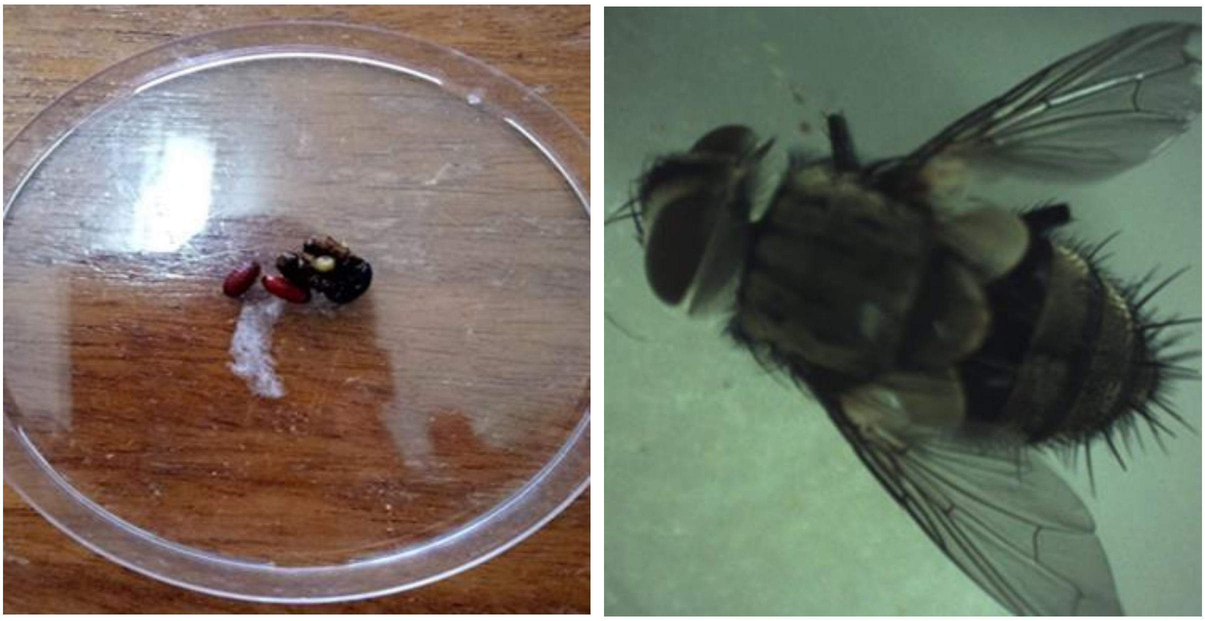
b) The rove beetle, *Paederus sabaeus* (Coleoptera: Staphylinidae) see (Fig.8 b) were observed feeding on 2nd larval instars of FAW in Katumani, Mwania and Mikuyu. Most of this predator were observed and collected inside maize whorl, folded leaves and tassels

(a) **(b)**

Figure 7: Predators of FAW larvae, (a) *Myrmicaria opaciventris* and (b) *Paederus sabaeus*

4.4.2 Parasitoid

The tachinid fly, *Zygobothria ciliata* (Diptera: Tachinidae) see (Fig.8a and b) was the only larval parasitoid species that emerged from the collected FAW larvae in Katumani, Mwania and Mikuyu. This parasitoid species was high in Katumani followed by Mikuyu and lastly Mwania. However, the recovery of this parasitoid species across the three maize fields were not equally corresponding to the exponential increase of the FAW larval population.



(a) **(b)**

Figure 8: Parasitoid of FAW larvae, *Zygobothria ciliata* (a) Cocoons and (b) Adult

Table 3: Diversity of Fall armyworm natural enemies

Parasitoid and Predators species		Number per Location		
Parasitoid	**Species**	**Katumani**	**Mwania**	**Mikuyu**
	Zygobothria ciliata	24	10	20
Predators				
	Myrmicaria opaciventris	0	0	226
	Paederus sabaeus	28	40	31

The species presented see (table 3) could not statistically be performed for diversity as the species taxa do not meet the test for diversity. However, *Z. ciliata* and *P. sabaeus* were found in all the three farms of Katumani, Mwana and Mikuyu while *M. opaciventris* species were observed only Mikuyu farm

4.5 Stem borers composition and their interactions with fall armyworm

The stem borers observed included, African stemborer, *Busseola fusca* and Pink stemborer, *Sesamia calamistis* species. *B. fusca* larvae were collected among 2-4 leaf stages after germination and none were observed later on in the season. Whereas *S. calamistis* larvae were observed among 8-11leaf and tasselling stages in Mikuyu and Mwania. Although, *B. fusca* and *S. calamistis* were found in some particular growth stages, observed were minimal throughout the study. However, high numbers of FAW larvae were collected among all growth stages from 5-7 leaf stage and none at harvesting stages.

In Mikuyu *S. calamistis* in some instances were found together with FAW in the same plants notably maize cobs with varying numbers unlike *B. fusca* which were observed with no presence of other *S. calamistis* or *S. frugiperda* in all. *S. calamistis* were also observed alone

Table 4: Percentage of each stemborer and FAW species in different maize growth stages

Maize growth stages		Site								
		Katumani			Mwania			Mikuyu		
		S. frugiperda, B fusca, **and** ***S. calamistis*** **and their** ***interactions***								
	N	SF%	BF%	SC%	SF%	BF%	SC%	SF%	BF%	SC%
Emergence	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-4 leaves	6	0.00	33.33	0.00	0.00	50.0	0.00	0.00	16.67	0.00
5-7 leaves	126	57.94	0.00	0.00	16.67	0.00	0.00	25.4	0.00	0.00
8-11 leaves	387	32.56	0.00	0.00	27.65	0.00	0.00	39.53	0.00	0.26
12-15 leaves	98	58.16	0.00	0.00	23.47	0.00	0.00	18.37	0.00	0.00
Tasselling	604	37.75	0.00	0.17	35.43	0.00	0.17	24.67	0.00	1.82
Maturity	19	52.63	0.00	0.00	0.00	0.00	0.00	47.37	0.00	0.00
Harvest	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Key N = Total number of stemborers and FAW species, SF = *Spodoptera frugiperda*, BF = *Busseola fusca* and SC =*Sesamia calamistis*

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 Discussion

5.1.1 Dynamics of FAW adults and larvae in the maize fields

This study showed that the highest FAW male catches were among maize tasselling in Mwania (382) and Mikuyu (27) males, and later among maturity stage in Katumani (90) males. The peak variation among sites and in particular the high male catches among maturity stages in Mwania must have been due to the irrigated maize field infested with FAW prior the experimental trial or effective handling of FAW sex pheromone lures during replacement of the old lures in the funnel traps deployed. Similarly, the high peak catches of FAW males among maize maturity stage in Katumani must have been attributed also to good handling of FAW pheromone lures or neighbouring maize fields cultivated later in the season 4 weeks after the experimental farm by KALRO Katumani. This observation in Mwania and Katumani sites led to the conclusion that, the highest peak of FAW male catches among the maturity stages might have been attributed to proper handling of FAW sex pheromone lures after the first installations or population of the second generation that explode from the experimental trials or from the neighbouring maize fields planted later in the season.

Sokame *et al.,* (2020), reported that FAW larvae have wider dispersal ability through ballooning within or between plants and that most ballooned larvae were females in a greenhouse study in ICIPE, Kenya. Fall armyworm adult male catches increased from crop emergence and peaked during tasselling in Mikuyu. This results corroborate previous findings in northern Ghana in which Nboyine *et al.,* (2020) reported increase in male catches after maize emergence and peaked when the crops were developing into reproductive stages and significantly declined thereafter.

In this study, a total of 1593 FAW larvae were collected in three maize fields in which the larvae increased rapidly after 2-4 leaf stages (1st week) and later high larval densities were collected among 8-11leaf (5-6weeks) in Mwania and Mikuyu, and later among 12-15 leaf stages (7-8 weeks) in Katumani. These results corroborate previous findings by Murúa *et al.,* (2006) who reported higher densities at the end of vegetative stages in year (2 and 4) during a study in north-western Argentina. This led to lower collection of FAW larvae at the onset of reproductive stage (Murúa *et al.,* 2006, Nboyine *et al.,* 2020). Hernández-Mendoza *et al.,* (2008) also reported high infestation among 10 leaf stage of maize than other vegetative stages in Colima, Mexico.

In the current study, no insecticides were sprayed to control FAW, the catches and the larval densities therefore present a case of no intervention. The current results suggest that farmers growing should start monitoring their maize crops by the 2nd week of planting and applying management options as recommended. Recommendations for FAW management include monitoring and scouting maize fields for eggs and squashing them, handpicking of larvae and early application of insecticides (Kansiime *et al.*, 2019). Due to repeated egg laying, hatching and infestation throughout the active growth stages of maize, early sprays is perhaps necessary beginning from 3rd week after maize emergence that corresponds to 5-7 leaf stage (about 5 weeks) may offer protection against FAW. According to (Nboyine *et al.,* 2020) spraying insecticides for 9th weeks after maize emergence may offer protection of maize crops against fall Armyworm.

5.1.2 Interactions between FAW (moths and larvae) and the climatic variables

In this study, the mean temperatures and rainfall were (20.22˚C, 20.95 ˚C and 20.37 ˚C), and (185.35 mm, 148.85 mm and 183.1 mm) in Katumani, Mwania and Mikuyu respectively. The results indicated a positive significant correlation between FAW larvae, temperature and rainfall whereas adult male catches were negatively correlated with rainfall in Mwania. The results corroborate previous findings in which Murúa *et al.,* (2006) reported rainfall and temperature as factors that affected FAW larval density in Northwest Argentina. Contrary to the previous findings by Nboyine *et al.,* (2020) who reported rainfall as the only factor that significantly and positively influenced moth abundance in all three regions in northern Ghana in both years; except in 2018 in Upper East region in one region.

In a semi-arid climate of Machakos, notably optimum temperatures, together with the feeding nature of FAW supported the rapid population increase during the short rain growing season. These results agree with previous findings in which Du Plessis *et al.,* (2020) reported that FAW egg, larvae and pupae cannot persist and develop at temperatures below (13.01, 12.12 and 13.06◦C) respectively, especially in regions where temperatures decrease during winter months and the optimum range of egg-adult development is between 26-30 ◦C. In Karo District of Indonesia, the climatic variable that had influence on the affected region by FAW was rainfall (Nurzannah *et al.,* 2020). Similar studies in Senegal indicated that the average life cycle of *S. frugiperda* under laboratory conditions was 25 days at 25˚C and about 15 generations a year (Tendeng *et al*., 2019). Due to favourable temperature, rainfall, FAW has remained an important pest of maize since its invasion in African region (Prasanna *et al.,* 2018). Temperatures can affect reproduction, development survival and movement of some agricultural pests. In temperate areas, survival and distribution of many pests is usually affected by low temperatures especially in winter. Warm conditions in such areas will likely make other insect pests to increase their abundance and extend their geographical range (Cammell and Knight, 1992).

5.1.3 Predators and parasitoids

In this study one FAW larval parasitoid species, *Zygobothria. ciliata* (Wulp) (Diptera: Tachinidae), and two predators *Myrmicaria. opaciventris* (Formicidae) and *Paederus. sabaeus.* (Staphylinidae) were identified. The natural enemies varied among the surveyed maize areas. This is the first report of *Z. ciliata* as a parasitoid of FAW in Kenya and globally. In the Philippines Barrion *et al*., (1991) reported *Z. ciliata* as a moderate larval parasitoid of rice leaffolder, *Cnaphalocrocis medinalis* (Lepidoptera: Pyrelidae). Many larval parasitoids of FAW were also reported in Kenya including, tachinid fly, *Palexorista zonata* Curran (Dipteran: Tachinidae), *Coccygidium luteum* Brullé (Hymenoptera: Braconidae) and *Charops ater* Szépliget (Hymenoptera: Ichneumonidae) (Sisay *et al*., 2018). Parasitoids complex suggests prospects for potential biological control of FAW (Molina-Ochoa *et al*., 2003; Vírgen *et al*., 2013). Other reports include recruitment of parasitoids species by invasive insect species after invasion (Vercher *et al*., 2006; Matošević and Melika, 2013).

A number of surveys conducted in various regions in America, the endemic FAW region have documented a complex of natural enemies of FAW. For instance, in Honduran highlands, *Campoletis sonorensis* (Cameron) and *Aleiodes laphygmae* (Viereck) were most prevalent (Wyckhuys and O'Neil, 2006). In Mexico, ten parasitoids species representing family Braconidae, Ichneumonidae, Eulophidae and Trichogrammatidae and Tachinidae were recovered from FAW larvae (Hoballah *et al*., 2004; Ordóñez-García *et al*., 2015). In South Florida, *Chelonus insularis* (Cresson) and *Cotesia marginiventris* (Cression) were the dominant species (Meagher *et al*., 2016) while in Argentina, *Campoletis grioti* (Blanchard), *Chelonus insularis* (Cresson), *Archytas spp*. and *Ophion sp*. (Hymenoptera: Ichneumonidae) were common (Murúa *et al*., 2006). In Caribbean and America, (Molina-Ochoa *et al*., 2003) documented a complex of 150 parasitoids species in an inventory of FAW natural enemies suggesting a potential biological control of fall armyworm.

The two predators, *Myrmicaria. opaciventris* and *Paederus. Sabaeus w*ere observed feeding on FAW in the surveyed farms in Mwania, Katumani and Mikuyu. This is the first record of *M. opaciventris* and *P. sabaeus* as predators of FAW in Kenya and globally. According to (Prasanna *et al.*, 2018), Predators of FAW are general enemies of other pests. For example, *P. sabaeus* (Erichson) was recorded as a predator of rice field pests in North Cameroon (Woin *et al*., 2010), and stem borers pests in Kenya but further investigation was needed (Midega & Khan, 2003). Report by (Berg and Cock, 1995) also indicated Ants, *Myrmicaria* species association with *Helicoverpa. armigera* in smallholder farmers' fields in Kenya. According to (Kenne *et al*., 2000) *M. opaciventris* can be an important biological control for termites under certain conditions. FAO, (2018) also reported ants as predators of fall armyworm. Report by Berg and Cock, (1995) indicated Ants, *Myrmicaria* species association with fall armyworm. In the Americas, some of the common predators observed feeding on FAW include insidious flower bug, *Orius insidious*, various spiders' species (Isenhour *et al*., 1989; Pfannenstiel, 2008), earwig, *Doru taeniatum* (Dorhn), *Podisus maculiventris* (Say), (Wyckhuys and O'Neil, 2006; Ordóñez-García *et al*., 2015). (Anyphaenidae) and *Cheiracanthium inclusum* (Hentz) (Miturgidae) (Pfannenstiel,2008)

5.1.4 Stemborers composition and their interactions with fall armyworm

Stem borers species were largely composed of *S. calamistis and B. fusca* in the surveyed farms in Katumani, Mwania and Mikuyu. Population of these pests nevertheless varied among the surveyed farms. Results of this study corroborate previous findings by Songa *et al.,* (2002) who reported that *B. fusca* and *S. calamistis* were among the stem borers composition in cultivated areas in Katumani. Reports by Kankonda, (2017) indicated similar composition of several species of stemborers in Kisangani DR Congo, including. *calamistis, B. fusca, E. saccharina* and *C. aleniellus* (Strand) (Kankonda, 2017).

According to (Ntiri *et al.,* 2016) stem borers pests can occur together in the same field at different elevations as community of interacting species. Surveys in Kenya and Tanzania indicated various infestation levels. In the lowland tropical zone, *C. partellus* was dominant, about 90% in the highland tropical zone, *B. fusca* was 79% and in both zones *S. calamistis* was low (Ntiri *et al.,* 2019). In the other agroecological zones *C. partellus* was about 57% dominant, in dry mid-altitude and about 60% in the dry transitional zone. In the moist transitional zone, *B. fusca* was about 69% and about 71% in moist mid-altitude while *S. calamistis* was lower with varying proportions in all the AEZs (Ntiri *et al*., 2019). Published information on interactions between FAW and stemborers does not exist. However, report by Sokame *et al.,* (2020) indicated that FAW larvae have wider dispersal ability through ballooning and a wide plant damage potential than *C. partellus, B. fusca* and *S. calamistis* in a greenhouse study in ICIPE, Kenya

5.2 Conclusion

This study found out that FAW (adults and larvae) varied among different phenological stages of maize. The high densities of FAW larvae were recorded among 8-11 leaf stage (5^{ft} week) in Mwania and Mikuyu, and among 12-15 leaf stages (7th week) in Katumani than the reproductive stages (9-11 week) in the surveyed sites. Although FAW larvae were detected as early as two weeks after crop emergence, high peak of adult catches was observed during reproductive stages (9-11 weeks). The observed late peak of male catches in Mwania and Katumani among maturity stages was due to interference from other maize farms cultivated 4 weeks after the experimental farms. Moreover, FAW was influenced by maize growth stages in which female moths laid eggs on tender leaves for the larval survival after egg hatching. This resulted into high crop infestation among the vegetative stages than the reproductive stages coupled with the conducive climatic factors notably temperature and rainfall.

These results indicate that FAW can be monitored in the field immediately after 2nd week of crop emergence as this period attracts FAW females to lay their eggs on the tender leaves and marks the beginning of crop infestation in the field. Through monitoring a farmer will be able to know the beginning of FAW infestation and population build up in the field. These results will guide farmers on when to administer chemical sprays and possibly from 2nd week after crop emergence for 7 weeks.

B. fusca, S. calamistis and *S. frugiperda* species occurred together in all the surveyed sites. *S. calamistis* and *S. frugiperda were* sometimes observed together in maize cobs of the same plant. These results indicate that FAW and *S. calamistis* may co-exist together though FAW is cannibalistic.

Due to the significance of *Z. ciliata* parasitizing FAW larvae in the surveyed fields, ecological management practices should be embraced and subsequently creating favourable conditions for the parasitoid to become abundant Nonetheless, the predators *M. opaciventris P. sabaeus* are just opportunistic which may not be important.

5.3 Recommendation

Farmers must start monitoring and scouting their maize fields one week after maize crop emergence since moths prefer young maize plants to lay their eggs and eventually become source of infestations. Besides, farmers must start controlling their crops against FAW one week after crop emergence with any of the available and effective control measures

Countrywide survey for Z. *ciliata* is needed in order to establish its range. parasitism levels, abundance and its association with other lepidopteran pests for better understanding and its possible use in an integrated pest management. Furthermore, mass rearing of *Z. ciliata* in laboratories for field trials is required.

More studies are needed on intercropping as an alternative for further management of fall armyworm in semi-arid zones

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