UNIVERSITY OF NAIROBI

EFFICACY OF PHEROMONE-BASED MASS TRAPPING IN MANAGEMENT OF FALL ARMYWORM *Spodoptera frugiperda* (Lepidoptera: Noctuidae) IN MAIZE FARMS

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DECLARATIONS

I declare that this thesis is my original work and has not been submitted elsewhere for examination or award of a degree. Where other people's work or not my own work has been used, this has properly acknowledged and referenced.

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DEDICATION

This thesis is dedicated to the wonderful women in my life, my mother, Anne Ambia, sister Julie Ambia and Ms Rinje Njenga.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
CABI	Centre for Agriculture and Biosciences International
CIMMYT	International Maize and Wheat Improvement Center
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Statistics
FAW	Fall armyworm.
IPM	Integrated Pest Management
IQR	Interquartile range
KALRO	Kenyan Agricultural and Livestock Research Organisation
KMD	Kenya Metrological Department
KNBS	Kenya National Bureau of Statistics
MoALF	Ministry of Agriculture, Livestock and Fisheries

ABSTRACT

Fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) has rapidly spread in Kenya and has emerged as a major pest of maize (*Zea mays* L). To manage fall armyworm (FAW) infestations in maize, many small scale farmers have relied heavily on use of synthetic chemical insecticides that has been associated with environmental pollution, food crop contamination, development of insecticide resistances in the pests and high costs. Various organizations, including international research organizations based in Kenya, have advised farmers on cost-effective integrated pest management (IPM) strategies, but some of the advice is not applicable to the farming practices and systems of smallholder farmers. The use of semiochemical-based pest management practices as part of IPM strategies suitable for smallholder farmers, on the other hand, has not been evaluated. This study addressed this knowledge gap by determining the efficacy of pheromone-based mass trapping as a means of reducing FAW infestation levels in maize plant. The study was conducted at Kenyan Agricultural and Livestock Research Organisation (KALRO) Katumani Research Centre in Machakos County, the maize seeds (Variety - KDV-1) were planted on 4th April 2021 and harvested on 13th August 2021. Data from 13th April (after emergence) to 13th August 2021 was used in the analysis in this study. The experiment utilized a randomized block design with four treatments, four replications and a control plot, with each experimental plot measuring 25 x 50 meters (0.125 hectares). The four treatments and four replications of the experimental blocks involved randomly placing female sex pheromone traps at four different densities of 8, 16, 24, and 32 traps/ha. The extent of FAW infestation and the number of captured FAW adult male moths per trap, per plot and maize phenological stages were tabulated twice a week. In this study, the prevalence of fall armyworm infestation was higher than the recommended action threshold level in all the treated experimental plots At the early whorl stage, against a recommended action threshold of 20%, the infestation rates ranged

from 58.45% to 79.1%, while at the late whorl stage, the infestation levels ranged from 53.6% to 73.6% against a recommended action threshold of 40%, and finally, at the reproductive stage, the infestation rates ranged from 65.5% to 75.0% against a recommend action threshold of 20%. FAW infestation varied significantly across maize phenological stages ($F_{7, 284} = 28.33$, $p < 0.001$) and trap densities ($F_{4, 284} = 52.39$, $p < 0.001$), with the phenological stages and trap densities interacting significantly ($F_{28, 284} = 1.83$, $p = 0.008$). There was no point of intersection between moth catches and FAW infestation levels per trap density, indicating that the two parameters did not have an inverse relationship in this experiment. In conclusion, mass trapping with synthetic sex pheromones was ineffective in suppressing FAW populations or reducing FAW infestation damage on maize plants, and thus should not be used as a "stand alone" control method but can be developed as part of an IPM package for FAW management.

CHAPTER ONE

1.1 Introduction

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) is a polyphagous lepidopteran pest native to tropical and subtropical America, where it is an important pest of maize (Sarmento *et al*., 2002). It is a species in the genus Spodoptera that cause a significant financial loss to agriculture worldwide (Pogue, 2002). The pest invaded Africa in early 2016, when it was reported in central and western Africa (Goergen *et al*., 2016) from where it migrated and spread. By 2017, it was found in the majority of sub-Saharan Africa countries (Day *et al*., 2017), where it poses serious threat to food security (FAO, 2019).

All major plant damage caused by the fall armyworm has been reported on maize in Africa, with little or no damage reported on other crops (Rwomushana *et al.,* 2018). Maize is a staple food in Kenya and its availability is tantamount with food security (Kariuki *et al*., 2020). In 2017, a total of 250,000 hectares of maize crop in Kenya was affected, causing an estimated loss of 1.05 (90 kg) bags (MoALF, 2018). In 2019, Maize production decreased by 10.8% from 45 million bags in 2018 to 40 million bags, this decrease was largely attributed to drought in several areas, as well as an infestation by FAW (KNBS, 2020). From 2018 to 2020 Kenya's maize production has decreased by 5.6% from 4.0 million to 3.8 million tonnes (FAOSTAT, 2022). If left unchecked FAW can cause a significant damage to maize yields (20 – 50%) in Africa (Day *et al*., 2017).

To mitigate the impact of FAW, most African governments opted to distribute pesticides to their farmers (Prasanna *et al*., 2018). The implementation of this policy also led to a dramatic increase of pesticide use among smallholder maize farmers (Rwomushana *et al*., 2018), who previously were using cultural methods and not pesticides to control pests in their maize crops (Abate *et al*., 2000). To ensure the efficacy of chemical insecticides, some farmers in the FAW's native region spray twice or three times per crop cycle (Blanco *et al*., 2014). However, there are drawbacks to insecticide use, such as environmental pollution, contamination of harvested agricultural produce, and development of resistance in the targeted pests (Ahmad and Kamarudin, 2011). Synthetic pesticides are also expensive and their use is probably not economically justifiable and sustainable for small scale African maize farmers (FAO., 2018).

Reducing the amount of chemical insecticides applied in agroecological areas is a major objective that drives the research for semiochemicals and their potential in pest management (El-Sayed *et al*., 2006). Semiochemicals can be used alone in pest management and control as mass trapping or mating disruption (Byers, 2008). Mass trapping can offer alternatives to broad-spectrum synthetic insecticides (El-Sayed *et al*., 2006). In the case of lepidopterans, the lure is typically based on a female sex pheromone with high species specificity, a low concentration required to evoke a specific behaviour, and nontoxicity to other organisms (Cork, 2016). The concept of mass trapping for lepidopteran pests entails placing pheromone-baited traps in the target area with the objective of delivering a measure of protection by trapping and removing a reasonably substantial percentage of males (Yamanaka, 2007).

1.2 Statement of problem and justification

The fall armyworm is a difficult pest to control due to its ability to migrate, multiple generations and polyphagous nature. In Kenya, the management of FAW is heavily reliant on the use of chemical insecticides that may not sustainable. The usage of chemical insecticides has been associated with numerous negative health effects to vertebrates, environmental pollution, destruction of biodiversity, food crop contamination, development of insecticide resistances in the pests and high costs. Hence, the need to introduce eco-friendly (e.g., species-specific, and nontoxic) pest management technology such as pheromone-based pest management strategies that are suitable and cost-effective, especially for smallholder farmers. The purpose of this study was to evaluate and provide information on the efficacy of pheromone-based mass trapping towards the management of the fall armyworm in maize farms.

1.3 General objective

To determine the effectiveness of pheromone-based mass trapping as an efficient means of reducing fall armyworm infestation levels in maize plants.

Specific objectives

i. To determine the effectiveness of mass trapping as a means of reducing fall armyworm infestation levels at different maize phenological stages.
ii. To determine the optimum trap density required for the management and control of fall armyworm.

1.4 Research hypotheses

i. Pheromone-based mass trapping effectively reduces fall armyworm infestation levels in maize fields.
ii. An optimum trap density effectively manages fall armyworm infestations in maize fields.

CHAPTER TWO

2.0 Literature Review

2.1 Biology and behaviour of fall armyworm

The complete life cycle of FAW (Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae)) is in four stages (egg, larva, pupa, and adult). This life cycle takes about 30 days during summer and 60 – 90 days in the cooler months (Capinera, 2020). Since FAW has no diapause mechanism, they cannot survive in low temperatures (Capinera, 2020).

After mating with males during the night (Sparks, 1979), the adult female lays her eggs within the first five days of life (Prasanna *et al*., 2018). Primarily, 100 – 200 egg masses are deposited on the surface of leaves, and an adult female can produce 1,500 eggs during her lifetime. Under ideal temperature conditions of 21–27 °C, the eggs hatch within four days (Prasanna *et al*., 2018).

After hatching from eggs, the larvae quickly disperse to find food and avoid cannibalism and intraspecific competition (Rojas *et al.*, 2018). The larval stage has six instars which lasts for 14 days in hot weather and 30 days in cool weather (Capinera, 2020). The larva length ranges between 2 mm in the first instar to 34 mm in the sixth instar. The larva starts feeding on the leaf tissues from the first instar to the sixth instar, however, most of the feeding takes place during the fifth and sixth instar (Luginbill, 1928). The larvae are highly polyphagous and have been known to attack more than 350 plant species belonging to 76 plant families (Montezano *et al*., 2018). In the maize plant, the larva feeds on leaf tissue during early whorl stage, while it feeds in the ear zone and silk tissues as the maize plant matures because the leaf tissue have become unsuitable (Pannuti *et al*., 2016b).

The larva becomes a pupa beneath the soil at a depth of 2 to 8 cm (Sparks, 1979). During summer, the pupal stage is completed within nine days, while this may last between 20 and 30 days in cooler temperatures (Silva *et al*., 2017).

Adult FAW are nocturnal, and have an average lifespan of 10 days, but some can live up to 21 days (Capinera, 2020). The FAW are considered to be r-strategist because they easily exploit new environments (Wightman, 2018). Fall armyworm is divided into two biotypes (host strains), corn (C) and rice (R), with the "rice-strain" preferring millet and pasture grass species and the "corn-strain" preferring corn and sorghum. The biotypes are morphologically identical but can be distinguished by mitochondrial or Z-chromosome-linked markers. (Nagoshi *et al*., 2018).

2.2 Invasion in Africa

The FAW is a native to the Americas (Sparks 1979) was first detected in sub-Saharan Africa in 2016 (Goergen *et al.*, 2016). Fall armyworm may have been contained in cargo that arrived in Western and Central Africa (Goergen *et al*., 2016). As of 2018, all countries in SSA had been invaded with FAW except Lesotho (FAO, 2020). Fall armyworm were first reported in Western Kenya in early 2017, and within 19 months, they had invaded 90% of the counties (MoALF, 2018, KALRO, 2017).

The FAW type introduced into Africa is the haplotype originating from south Florida (USA) and the Caribbean (Nagoshi *et al*., 2018). The same haplotype predominates (>90%) all locations in Africa. Therefore, this can be concluded that a single introduction was followed by rapid dispersion through natural and trade-related processes (Nagoshi *et al*., 2019). Some of the factors that helped FAW to spread quickly over the African continent were its propensity to attack a wide range of crops (Huesing *et al*., 2018); its ability to produce many eggs (Sparks, 1979); its preference for maize, the major cereal crop in Africa (Devi, 2018), its ability to migrate over long distances (Rose *et al*., 1975), and favorable climatic conditions for high levels of pest reproduction and infestation (Prasanna *et al*., 2018). Unlike FAW in the Americas, or the African armyworm (*Spodoptera exempta* (Walker) (Lepidoptera, Noctuidae)), which are migratory, FAW has become a resident pest in African farming systems (FAO, 2019).

2.3 Impact of fall armyworm infestation

In Africa, FAW plant damage has been recorded on maize plants only, with little or no damage on other crops (Rwomushana *et al*., 2018). The proportion of Kenyan farmers who reported FAW infestation increased from 60% in 2017 to 80% in 2018 (De Groote *et al*., 2020). However, the estimated maize yield losses showed a decrease during the same study period (50% in 2017 and 40% in 2018) (De Groote *et al*., 2020). Another Zimbabwean study that directly measured maize losses reported that farmers lost 12% of their yield due to FAW infestation in 2018 (Baudron *et al*., 2019). The discrepancies in the estimated yield losses in the Kenyan and Zimbabwean studies could be as a result of the study design. The Kenyan study retrospectively asked farmers to estimate the maize yield losses due to FAW damage. Whereas, the Zimbabwean study quantified the losses by harvesting of quadrants (Baudron *et al*., 2019).

The sustained use of insecticides in smallholder farms in Africa to manage FAW poses environmental risks and has a significant negative effect on human health and agricultural trade attributable to synthetic pesticide residues in food material (FAO., 2018). The indiscriminate application of toxic pesticides also has a negative effect on beneficial natural enemies, reducing the gains of biological control (Meagher *et al*., 2019) and this could probably lead to an increase or introduction of secondary pests (Tscharntke *et al*., 2016).

Fall armyworm is capable of a strong intra- and inter-specific competition (Goergen *et al*., 2016), and this is capable of leading to a decrease in species abundance in agroecological environments (Bentivenha *et al*., 2017), thus a decrease on the amount of damage caused by other pests (Rwomushana *et. al*., 2018).

Fall armyworm is currently regulated as a priority quarantine pest (A1 Quarantine pest - EPPO) in the European Union with emergency measures put place to avert an introduction and spread within the countries of the Union, resulting in restrictive trade operations on some agricultural produce and products (EFSA *et al*., 2020). Consequently, Asian, North African and European nations are managing this risk by imposing additional handling or production requirements for exports from fall armywormaffected countries, which has additional cost implications on the exporters (Day *et al*., 2017).

2.4 Management options

Due to its ability to migrate, multivoltine and polyphagous nature, FAW is a difficult pest to control (Sisay *et al*., 2019). Synthetic pesticides and genetically modified crops are used to manage FAW in the Americas, where it is native (Abrahams *et al*., 2017). In contrast, the majority of African agriculture is still traditional, with small-scale farmers, it is labour-intensive, with none or little external inputs. Rather of being a distinct, well-defined activity, pest control is a built-in process in crop production systems (Abate *et a*l., 2000). Farmers in Africa are receiving advice on FAW control from a variety of stakeholders with varying goals, expertise, and knowledge. Since many of these requirements are specific contextually, no single piece of instruction will apply to all farmers in all circumstances (Rwomushana *et al*., 2018).

2.4.1 Pesticides

Pesticides are the main tools used by most African governments to control FAW (Prasanna *et al*., 2018). As at September 2018, the Kenya government through the Ministry of Agriculture it had authorized 10 pesticides for interim use pending registration (MoALF, 2018). For the pesticides to be effective, farmers are advised to apply the pesticide early following FAW invasion (Studebaker *et al*., 2021). To control FAW, most Kenyan farmers used synthetic pyrethroid with an active ingredient of Lambda-cyhalothrin or Alphacypermethrine, followed by an insect growth regulator (active ingredient - Lufenuron), non-systemic pesticides (active ingredient - Profenofos and Pyrethroid Cypermethrin) (Kumela *et al*., 2019). Although a study conducted in Ghana observed that Lambda-cyhalothrin active ingredient had 75 – 85% FAW mortality in maize (USAID, 2018). However, 60% of the Kenyan farmers reported that pesticides they had used were not effectual in controlling fall armyworm (Kumela *et al*., 2019). These synthetic insecticides may not be effective because of resistance, improper application, such as applying at the wrong time or with the wrong quantity, or the insecticide itself may not be effective due to adulteration or false labeling (Rwomushana *et al*., 2018). According to Togola et al. (2018), economic threshold values are not taken into account when deciding whether or not pesticides are necessary, resulting in misuse and excessive usage of chemical based controls, potentially leading to development of resistance, damage to crops, environmental pollution and human health hazards (Togola *et al*., 2018).

2.4.2 Biological control

a) Natural enemies

There are about 150 parasitoids in the western hemisphere that attack fall armyworm (Molina-Ochoa *et al*., 2003). In Kenya, insect parasites such as the tachinid fly (*Palexorista zonata* (Curran) (Diptera:Tachinidae)), and wasps (*Charops ater* (Szépligeti) (Hymenoptera: Ichneumonidae), *Cotesia icipe* (Fernández-Triana & Fiaboe) (Hymenoptera: Braconidae) and *Coccygidium luteum* (Brullé) (Hymenoptera: Braconidae)) have been shown to suppress the numbers of FAW by feeding on their eggs and larvae (Sisay *et al*., 2019). FAW predators are generalists that feed on the lepidopteran larvae of other species, and a number of predators have already been identified in Africa (Prasanna *et al*., 2018). Small animals (rodents and reptiles) and birds are among the predators that prey on fall armyworm pupae and larvae (Capinera, 2020). Egg masses deposited by the female FAW are also easily destroyed by a single action by humans and natural enemies (Wightman, 2018). Because maize plot sizes in Africa are typically small (less than 2 hectares), direct mechanical control (handpicking larvae and egg mass) is feasible (Hruska, 2019).

b) Biopesticides

According to reports, the fall armyworm is vulnerable to sixteen different types of pathogens (Assefa and Ayalew, 2019). The entomopathogens, *Bacillus thuringiensis* (Berliner) (Bt), *Metarhizium anisopliae* (Metchnikoff) Sorokin, and *Beauveria bassiana* (Bals. -Criv.) Vuill have demonstrated to induce significant mortality in fall armyworm population densities and to minimize plant leaf defoliation (Molina-Ochoa *et al*., 2003).

Bateman *et al*. (2018) established that among nineteen African countries surveyed, Kenya had the most registered products (85) and biopesticide active components (20) that might be used to control fall armyworm (Bateman *et al*., 2018). Despite the fact that Kenya has a large number of biopesticide registered products, local availability and demand for these products was low, as only 10% of smallholders' farmers were using biopesticides (Constantine *et al*., 2020). The main reason for the low usage were availability, affordability, perceptions of efficacy (speed of action) and limited spectral of activity (Constantine *et al*., 2020).

2.4.3 Agroecological practices (habitat management)

Cultural and agronomic practices can reduce the probability or severity of fall armyworm infestations. Intercropping maize with legumineous crops (beans (*Phaseolus vulgaris* (L.) (Fabaceae), soybeans (*Glycine max* (L.) (Fabaceae) and groundnuts (*Vigna unguiculata* (L.) Walp. (Fabaceae)) appears to be beneficial in trials done in Africa, and could reduce fall armyworm damage levels by more than 20% (Hailu *et al*., 2018). However, several of the legumineous crops used for intercropping have been described as fall armyworm hosts and often germinate earlier, their role in perpetuating the pests that may cause infestation on maize plants warrants further research (Rwomushana *et al*., 2018).

Usage of trap plants (*Brachiaria cv* Mulato II (Poaceae)) and companion crops (repellents, *Desmodium intortum* (Leguminosae)) have also been used to control FAW in East Africa. In this study, it was observed that less than 20% of the plants had larvae or plant damages due to FAW infestation (Midega *et al*., 2018). In this push (repellents plants) and pull (trap plants) technology, the maize yield was thrice higher than the monocropping plots (Midega *et al*., 2018). Despite its apparent effectiveness, adoption of push and pull is relatively modest. Many explanations have been offered, including the rise in labour input required for the system's three constituent parts, its complexity or knowledge intensiveness, access to seed, the time required for companion crops establishment and technology adaptation to the current farm practise operations (Kassie *et al*., 2020).

Planting time is also important in controlling FAW. Planting promptly in some circumstances may assist the maize crop to avoid fall armyworm attack. According to FAO, farmers should avoid staggered and late planting because this continuously provides the preferred food of fall armyworm larvae (i.e., maize seedlings). Farmers at the Kenya farmer field school observed considerable yield decrease to fall armyworm on later planted maize farms in comparision to neighboring previously planted crops (FAO., 2018).

2.4.4 Host plant resistance

Currently there is no African maize hybrids with fall armyworm esistances that has been scientifically validated (Prasanna *et al*., 2018). To remedy this deficiency, CIMMYT has boosted its efforts to test maize in-bred lines rigorously, and ten potential maize inbreds have already been found in Kenya (Rwomushana *et al*., 2018).

Another strategy for effectively controlling fall armyworm damage in maize is to use genetically modified or transgenic crop variants that express lepidopteran resistance genes, but in Africa, it is only in South Africa that Bt maize is currently commercially available (Prasanna *et al*., 2018). Usage of Bt maize has resulted in reduced pesticide usage, the preservation of predators and parasitoids, pest reduction and greater yields for farmers (FAO, 2018). But these advantages might only last a short while, according to Fatoretto et al. (2017), after three years of introduction, the majority of Bt maize varieties lost the ability to suppress FAW (Fatoretto *et al*., 2017).

Wightman (2019) identified many barriers to the introduction of transgenic maize in Africa, including governments being convinced to pass legislation prohibiting the use of genetically modified foods. Crop life companies making life harder for 'non-GM' farmers farming near their consumers, as well as small scale farmers who are not willing to plant crops that is perceived not to "taste right" as they raise food crops for their families' sustenance (Wightman, 2018).

2.4.5 Mechanical and cultural control

Small scale farmers in Africa mostly use cultural control methodologies to manage pests, such manually killing pest larvae, maize intercropping, and applying soil and ashes to leaf whorls (Abate *et al*., 2000). Furthermore, pest populations have been shown to be reduced by land preparation activities such as tilling, weeding, and fertilization (Litsinger, 1994). However, for cultural methods to be effective, they must be combined with another strategy to control FAW (Cock *et al*., 2017).

To minimize the effects of fall armyworm, the majority of Kenya's subsistence farmers are using plant extracts such as tobacco, hot pepper and neem, as well as handpicking larvae and adding soil to the whorls (Wightman, 2018, Kumela *et al*., 2019, Constantine *et al*., 2020). The most widely used botanical extract is azadirachtin (neem) (Constantine *et al*., 2020). However, because it is highly photosensitive, it has a short residual life in the field (Forim *et al*., 2010).

2.4.6 Integrated pest management

Cost-effective integrated pest management (IPM) techniques for FAW control are being actively developed for the African environment. International research organizations based in Africa have been working towards developing effective IPM strategies for fall armyworm management that will combine a number of approaches including: (1) cultural control, (2) host plant resistance, (3) biological control, and (4) safer insecticides (Kasoma *et al*., 2021). As in all intergrated programs, decisions on synthetic insecticide use for fall army management is focusing on when the other management measures fail to reduce the infestations and the economic threshold level is activated and on economically feasible actions with the lowest possible danger to human health and the environment (Prasanna *et al*., 2018).

2.4.7 Pheromone-based traps

Agricultural insect pest management is heavily reliant on synthetic pesticides, which do not accomplish long-term pest population reductions, particularly in areas with warm climates and extended growing seasons (Witzgall *et al*., 2010), whereas continuous long-term pheromone-based control reduces population levels of targeted pest species (Weddle *et al*., 2009). This is due to their species-specificity and nontoxicity to nontarget organisms (beneficial organisms), as well as pheromone potency at low population densities (Witzgall *et al*., 2010).

Because the pheromone lures and appropriate traps apparatus may be difficult to obtain locally, pheromone-based traps are currently being used as a monitoring tool for FAW populations rather than management in Africa (FAO., 2018). Pheromones aid in pest control techniques by altering insect behavior, and mainly by capturing the adult pest stages with the goal of reducing pest populations (Ahmad and Kamarudin, 2011). The lure for lepidopterans is generally based on the sex pheromone emitted by females (Cork, 2016).

Mating disruption, monitoring and mass trapping are the major techniques of lepidopteran pest management that use female sex pheromones (Silverstein, 1981), and they can be utilized alone, as in mating disruption or mass trapping, or in conjunction with pesticides, entomopathogens, and sterilants (El-Sayed *et al.*, 2006).

2.4.7.1 Mass trapping as a pheromone-based pest control method.

The primary purpose of mass trapping in the management of plant pests is to catch a large number of insects in a specific area prior to reproduction or causing plant damage (El-Sayed *et al.*, 2006). Lepidopterous insects have been the subject of numerous mass-trapping experiments, but only a small number of them have shown positive results (Yamanaka *et al.*, 2001). This is most likely because it is widely considered that capturing 80-95% of males is required to control population increase (Knipling and McGuire, 1966). The following points are critical to an effective mass trapping program: that the traps deployed emit a pheromone (lure) that a significant population of the treated area's target insects detect (El-Sayed and Trimble, 2012); natural methods of luring, such as emitting virgin females, are less successful at attracting insects than lures (Jones, 1998); the traps are successful at capturing and retaining targeted insects prior to mating or ovipositing (Mõttus *et al.*, 1996); throughout the adult emergence and mating season, the lures and traps are effective (Cork, 2016); and the expenses of trapping apparatus and manpower are lower than the economic advantage of other treatment options that may increase crop production (Barclay and Li, 1991).

Effective mass-trapping also necessitates optimum trap density, trap positioning, dispenser placement and replacement frequency, trap coloration, and field configuration (El-Sayed *et al.*, 2006). A consistency in distribution of traps appears to be an efficient utilization of resources. However, simulated models have demonstrated randomly distributed traps would capture nearly a similar number insect pests as placing traps in a uniform grid (Byers, 1993).

2.4.7.2 Mass-trapping as a form of stand-alone pest control

There have been attempts to manage pests by using stand alone mass trapping methods and the results of these experiments can be classified into three groups based on the outcome achieved (El-Sayed *et al.*, 2006), i.e. a significant decrease in the density of the targeted pest's population or the destruction action of the pest (Zhang *et al.*, 2002), moderate to small declines of the target insect population or damage to plant crops, have been regarded by some programs which were unlikely to provide sufficient protection (Pasqualini *et al.*, 1997), and finally, mass trapping projects that did not show population declines or reduction of damages, these were considered to provide information under situations in which mass trapping was not suited or should not to be recommended, although technological advancements may change this perspective in the future (Yamanaka *et al*., 2001).

2.4.7.3 Comparing mass trapping with other types of pest control programs

In numerous trials comparing mass trapping to other control strategies, mating disruption proved more efficient than mass trapping (Ahmad and Attique, 1993). While others found mass trapping on hilly sites better than mating disruption (Trematerra, 1993), whereas some felt that mating disruption was too costly because of the pheromone cost (Sternlicht *et al*., 1990).

El-Sayed *et al*. (2006) suggested that in some circumstances mass trapping and mating disruption might work well together, i.e., the use of kairomones to catch female moths and lures to impair male orientation to females (El-Sayed *et al*., 2006).

Similarly, comparisons with insecticide use were diverse. Onucar and Ulu (1999) established that pesticides were far more effective than mass trapping (Önuçar and Ulu, 1999). While Huber *et al*. (1979) devised a mass trapping approach for the pinkbollworm (*Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae) that was effective in delaying pesticide application and cost the same as one insecticide spray (Huber *et al*., 1979). According to Sternlicht et al. (1990), pesticide application was more expensive compared to mass trapping (Sternlicht *et al*., 1990).

2.4.7.4 Measuring efficacy of pheromone-based pest control

There are four main strategies of assessing the efficacy of mass trapping. Firstly, mark and release-recapture sampling methods have been used to determine the success of mass trapping (Reddy and Urs, 2009). Secondly, tracking trap captures and monitoring the quantity of insects captured provides an indirect indicator of insect elimination (Fadamiro *et al*., 1999). Thirdly, measuring changes in the sex ratio of the population and documenting the infertility/fertility level of egg masses in the trapping (treated) areas (Patel *et al*., 1984). Lastly, damage assessment by evaluating crop loss in both experimental and control plots can be used to determine the efficacy of pheromone-based pest control (Baker and Heath, 2005).

CHAPTER THREE

3.0 Materials and Methods

3.1 Study area

The study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) Katumani Research Centre in Machakos County, located on coordinates 1º35'S and 37º14'E in an elevation of 1200 m above sea level. The area experiences a bimodal rainfall pattern that commences with the long rains in the month of March, April and May, followed by a dry season from June to September, before the short rains occur in October, November and December (Huho, 2017). The annual average rainfall (for the last 10 years – 2011 to 2020) was 721mm, and average temperature for the same period was 20 °C (Unpublished data – KMD Katumani Station).

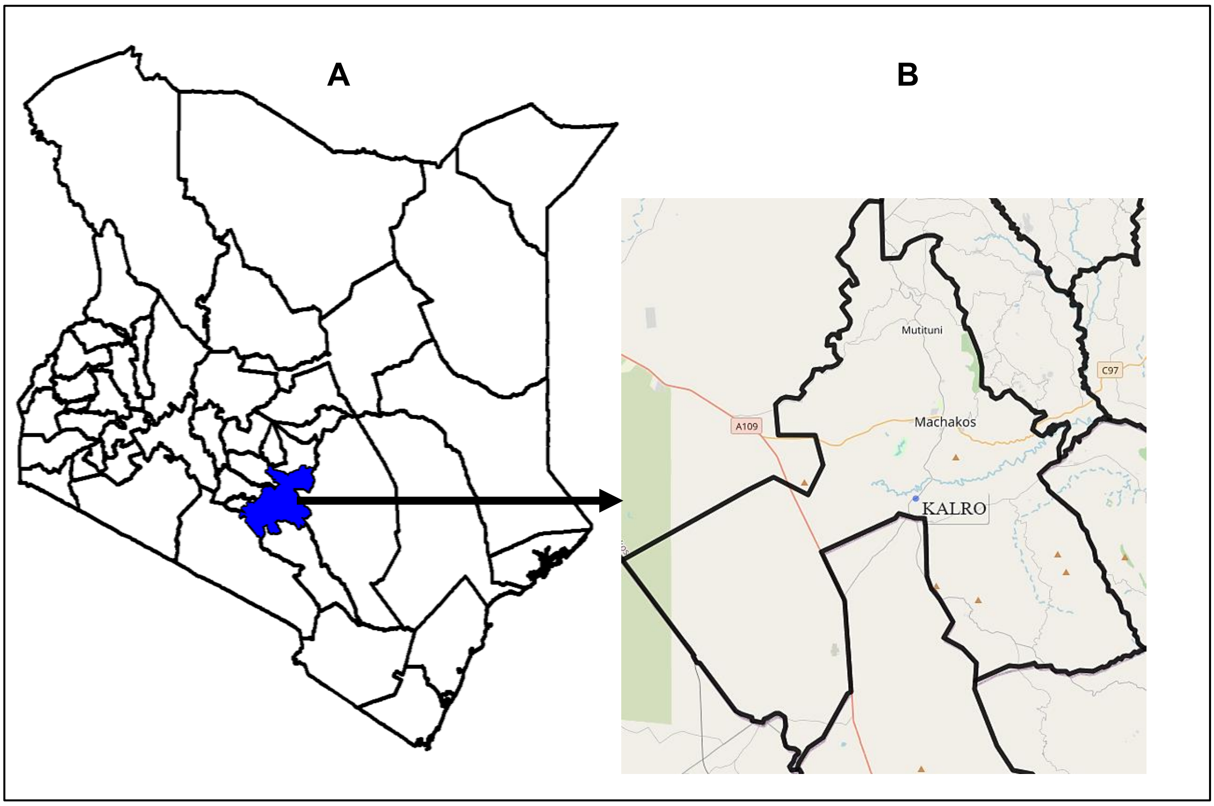

Figure 3.1: A) Map of Kenya with the location of Machakos County highlighted in blue. B) Map of Machakos County with a blue dot representing the study area (KALRO, Katumani Research Center).

3.2 Weather data

Data on rainfall and temperature was obtained from the Kenya meteorological department, Machakos weather station located in KALRO Katumani Station, from April to August 2021.

3.3 Experimental plots design and materials

The experiment consisted of four treatments in a randomized block design with four replications and a control plot (Fig. 3.2). Each experimental plot measured 25 × 50 metres (0.125 hectares). The distance between treated plots was kept at 10m and a gap of 30m was set between the treated block and replications, while the control plot was located 1,200 metres away from the treated blocks.

The maize seeds (Variety - KDV-1) were obtained from KARLO Katumani station and planted on 4th April 2021 and harvested on 13th August 2021. Data from 13th April (after emergence) to 13th August 2021 was used in the analysis. The maize seeds were sown at a depth of 8 cm to 10 cm and the individual maize plants separated by 30 cm. The rows were 25 m long, with a distance of 0.75 m between the rows. The maize plants were rainfed and no fertilizer was applied throughout the planting season.

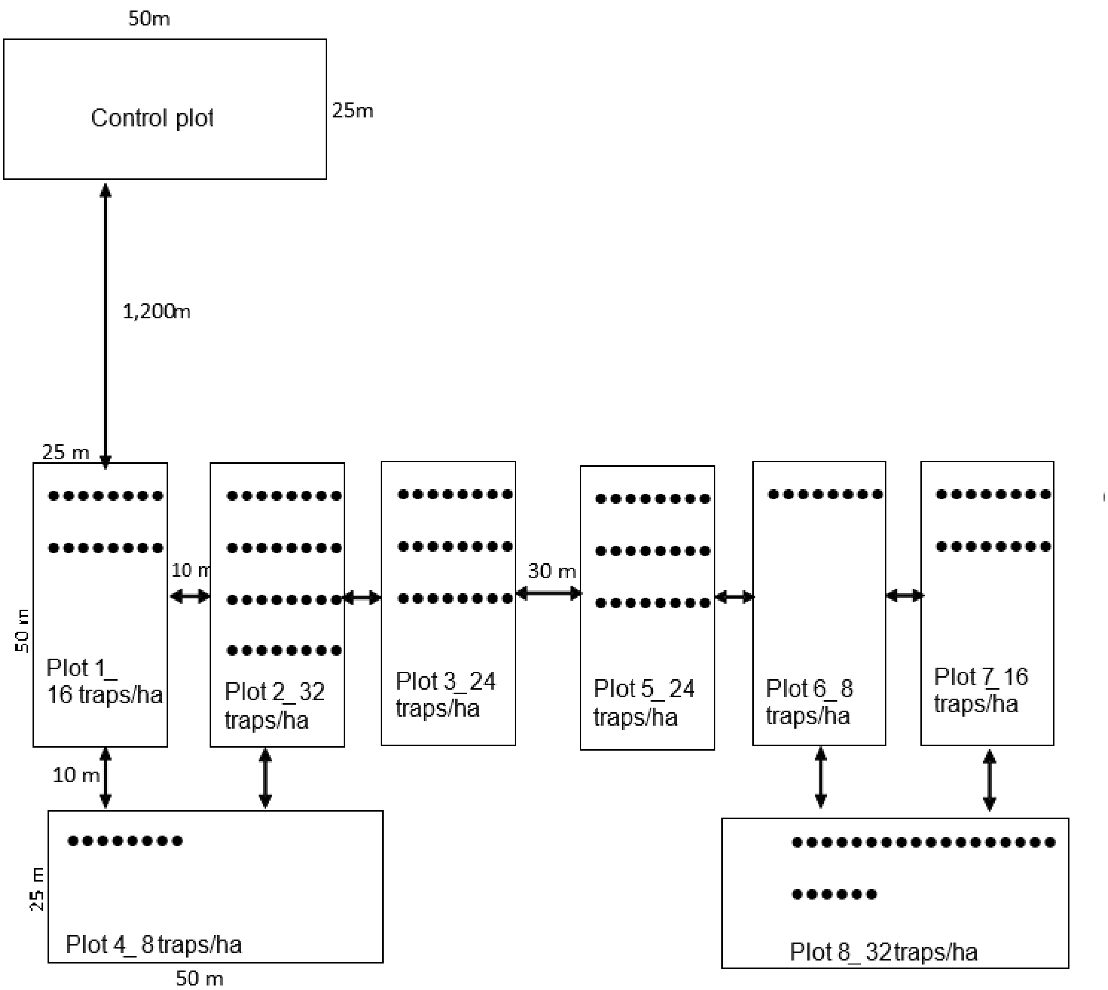

Figure 3.2: Field layout of the experimental plots

3.4 Mass trapping as a means of reducing FAW infestation levels at different maize phenological stages

3.4.1 Identifying maize growth stages

The stages of maize growth were divided into vegetative (V), reproductive stages (R) and the harvest stage (H). The stages were then simplified to; a) VE – V7 stages (early Whorl) b) V8 – V15 stages (Late whorl) and, c) R1 - R3 stages (Reproductive) and d) H - harvest stage. Notably, rather than counting the total number of leaves, the V stages (vegetative stage) of the maize were determined by the proportion of leaves with a leaf collar.
Maize crop growth stage was sampled at different maize phenological stages as shown on Table 3.1.

Table 3.1: Maize phenological stages used for sampling

Growth Stage	Description
VE	Emergence
V2 – V4	2-4 leaves fully emerged
V5 – V7	5-7 leaves fully emerged.
V8 – V11	8-11 leaves fully emerged
V12 – V15	12-15 leaves
R1 – R2	Tasseling/silking fully formed.
R3	Maturity (drying)
H	Harvest

Sources: CABI survey scoring sheet for FAW 2019

3.4.2 Field sampling for Fall armyworm infestation

Sampling was carried out on all the study plots twice a week (Tuesday's and Friday's) in a semi-systematic fashion and was concentrated on measuring the extent of infestation of FAW that was expressed as a percentage of infested plants. At the "early whorl" stage, sampling concentrated on searching for symptoms of fall armyworm eggs and neonates (first instar) larvae feeding. i.e., ‘windowpanes’, and frass. Examination for the Late Whorl Stage (V8-V15) focused on the newest three to four leaves arising from the whorl and the emerging tassel. While at the Reproductive Stage (R1-R3), sampling concentrated on the leaf axils, the ear/cob base, ear/cob sheath and/or the tip of the ear. Finally, at the harvest stage, sampling was on the leaf axils, ears sheath, ear/cob base, and the tip of the ears. Additional FAW infestation symptoms used for sampling were, large feeding on leaves, plants cut at the base by large larvae, presences of dead hearts, fresh holes tunneled on the stem’s sheath for late larvae stages and fresh bores through the kernels and cobs.

3.4.3 Sampling pattern

The appropriate sampling pattern was used to sample the field, based on the maize plant growth stage. The zigzag transect pattern (“W” pattern) was used until Stage VE –V15 (Vegetative stage) of the maize crop (Figure 3.3).

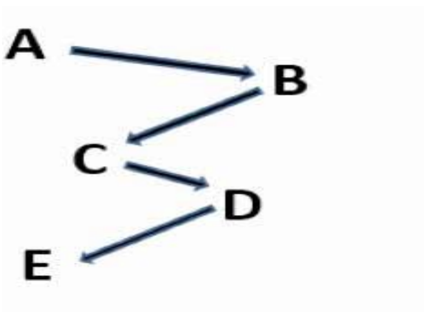

Figure 3.3: FAW infestation sampling pattern for experimental plots at the early and late whorl phase stages. (Source: Prasanna *et al.*, 2018).

At the tassel stage and beyond, the canopy increases significantly causing the maize plants to become more densely packed making it difficult to sample using the “W” pattern. This limited the randomness of the method and therefore introduced bias. The “Ladder” pattern was then used (Figure 3.4). Rows A-D were used as alleys to pass more quickly in a semi-systematic way around the plots.

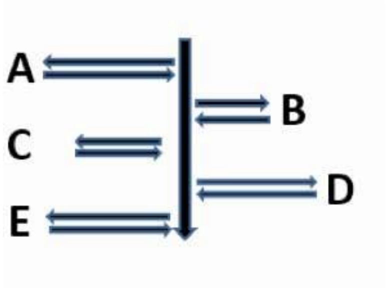

Figure 3.4: FAW infestation sampling pattern for experimental plots at the reproductive and harvest stages. (Source: Prasanna *et al*., 2018).

For the two sampling patterns above, the sampling started 5m from the edge and 4 stops were done at 4 different locations, at each checkpoint 10 plants were randomly sampled for signs of FAW feeding.

3.5 Assessment of the optimum trap density required for the management and control of the fall armyworm

3.5.1 Sex pheromone lure used in the experiment

The Scentry (L105A)® was used as the sex pheromone lure in this experiment to target the adult Male moths. The Scentry (L105A)® is a 4-component lure containing (Z)-9-tetradecen-1-ol acetate, (Z9-14Ac), (Z)-7-dodecen1-ol acetate, (Z7-12Ac), (Z)-9-dodecen-1-ol acetate, (Z9-12Ac) and (Z)-11-hexadecen-1-ol acetate, (Z11-16Ac).

3.5.2 The traps

The universal bucket trap (funnel trap) was used for this study, each trap consisted of a lure basket, a green lid, yellow funnel, and a white bucket. The sex pheromone lure was placed in the lure basket on top of the trap. An insecticidal strip was placed inside at the bottom of the bucket to kill the trapped male moths (Figure 3.5).

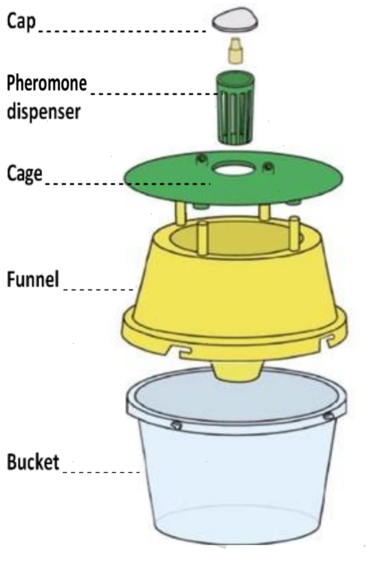

Figure 3.5: Universal bucket trap
Source: FAO Guidance Note 3 - Fall armyworm trapping (FAO, 2018).

3.5.3 Trap setup

Twenty universal bucket traps were used for this study. The four treatment and four replications of the experimental blocks involved application of the sex pheromone traps randomly placed at 4 different densities of 8, 16, 24 and 32 traps/ha The sex pheromone and insecticide strip were replaced once every month. The traps were placed on the central (mid) line, i.e., 12.5m away from the edges, running lengthwise of each treatment block. All traps were spaced apart equidistantly within each treatment block. The traps were suspended from a long pole in a vertical orientation. At the early whorl stage, the trap was placed 1.25m from the ground. However, as the maize plant grew taller the traps were moved 30cm above the plants. During the entire experimental period, the traps were emptied twice every week (Tuesday's and Friday's) and the FAW moths counted.

3.6 Statistical analysis

3.6.1 Data management

Maize was planted on 4th April 2021 and harvested on 13th August 2021. Data from 13th April (after maize plant had emerged from beneath the soil) to 13th August 2021 was used in the analysis.

The proportion of maize plants that exhibited FAW signs of damage as well as the presence/absence of eggs and larvae was determined using equation 1.

$$\text{FAW infestation} = \frac{\text{Number of infected plants}}{\text{Total number of plants observed}} \qquad (1)$$

The numbers of FAW male moths captured per trap density was converted to percentages of the total number of moths captured within each trap density based on the simplified maize growth stage.

3.6.2 Data analysis

Data analysis was performed using R (R Development Core Team, 2021). FAW infestation data was overdispersed, thus square root was used to transform this variable. One-way Analysis of Variance (ANOVA) was used to test; (1) mean differences in the trap densities on FAW infestation levels and (2) the difference between experimental plots (Plot IDs) and FAW infestation. Two- way ANOVA was used to compare differences between trap densities and phenology on FAW infestation levels. Tukey's HSD post hoc test was used to separate means where p-value was less than 0.05 after ANOVA statistical test.

CHAPTER FOUR

4.0 Results

4.1 Fall armyworm infestation by phenological stage and trap densities

Fall armyworm infestation rate by phenology and trap density is shown on Table 4.1, while Figure 4.1 (a – h) shows the images of infestation symptoms.

In the treated experimental plots, the 32 traps/ha had the lowest infestation in all phenological stages except at the emergence and 2-4 leaves stages. In the emergence stage, the 24 traps/ha plot had the lowest infestation rate, while the 8 traps/ha density plot had the lowest infestation levels in the 2-4 leaves stage.

In all the experimental plots, the 24traps/ha had the highest infestation rates in all the phenological stages except the emergence stage, while the control plot recorded the lowest infestation levels in all the phenological stages.

Table 4.1: Percentage of FAW infestation by trap density and maize Phenological stages

Phenology	8 traps/ha (%)	16 traps/ha (%)	24 traps/ha (%)	32 traps/ha (%)	Control (%)
Emergence	50.0	51.3	48.8	58.8	42.5
2-4 leaves	46.9	66.9	74.4	58.8	27.5
5-7 leaves	76.8	87.0	89.0	64.5	34.0
8-11 leaves	78.3	82.3	95.3	64.0	37.0
12-15 leaves	49.0	53.3	55.6	45.0	35.8
Tasseling	60.8	65.0	68.9	57.3	32.5
Maturity	77.7	79.6	83.1	76.5	61.7
Harvest	87.5	82.5	96.3	81.3	62.5
Average	65.2	71.3	76.3	61.3	39.3

(a)

(b)

(c)

(d)

(e)

(f)

(g) **(h)**

Figure 4.1: Images of fall armyworm infestation symptoms on maize plants in the experimental plots. (a) fresh feeding marks by larvae on maize leaves, (b) moist sawdust-like frass in the maize plant funnel, (c) fresh holes tunneled by larvae on the stem's sheath, (d) presence of a dead heart, (e) larvae feeding on tassel, (f) fresh bores caused by larvae through the kernels and cobs, (g) large feeding on leaves by larvae, (h) trapped adult FAW male moths.

4.2 Fall armyworm infestation levels by trap density and simplified maize growth stages

Fall armyworm infestation levels were highest in the 24 traps/ha plots (76.3%), while the control plot had the least levels of FAW infestations (39.3%). The 16 traps/ha plots had the second highest levels of FAW symptoms on maize plants (71.3%). The proportion of maize plants with FAW infestation symptoms in the 8 traps/ha plots was 65.2%, while 61.3% of the maize plants in the 32 traps/ha were infested by FAW.

For the 16, 24, and 32 traps/ha plots, the late whorl stage recorded lower infestation levels compared to the other 3 simplified stages, however for the 8 traps/ha plot and control plot, it was the early whorl stage. The harvest stage of all the experimental plots showed the highest levels of infection.

Table 4.2: Percentages of fall armyworm infestation per trap density by simplified maize growing stages

Maize growth stages	Description	Trap densities (traps/ha) Fall armyworm infestation (%)				
		8	**16**	**24**	**32**	**Control**
Early whorl (VE – V7)	Emergence, 2-4, & 5-7 leaves	58.4	75.4	79.1	61.6	32.3
Late whorl (V8 – V15)	8-11 & 12-15 leaves	62.3	66.5	73.6	53.6	36.4
Reproductive (R1 - R3)	Tasseling & maturity	68.0	71.3	75.0	65.5	45.0
Harvest	Harvest	90.0	82.5	96.3	81.3	62.5
Average infestation		65.2	71.3	76.3	61.3	39.3

4.3 Comparison of Fall armyworm infestation by phenological stage per trap density

FAW infestation varied significantly among phenological stages within each experimental plot, i.e., for 8 traps/ha ($F_{7, 64} = 6.611$; $p < 0.001$), 16 traps/ha ($F_{7, 64} = 7.287$; $p < 0.001$). 24 traps/ha ($F_{7, 64} = 11.78$; $p < 0.001$) 32 traps/ha ($F_{7, 64} = 5.695$; $p < 0.001$) and Control ($F_{7, 64} = 6.694$; $p < 0.001$). The treated experimental plots had high infestation rates on the 5-7 leaves, 8-11 leaves, maturity and the harvest stages, while low FAW infestation rates were recorded during the emergence, 2-4 leaves, 12-5 leaves and tasseling phenological stages. However, of these four stages, the 12-15 leaves stage had the lowest FAW infestation levels.

All the phenological stages for the control plot had low infestation rates, except the harvest and maturity stages.

Table 4.3: Fall armyworm infestation levels (mean ± SE) by phenological stage within trap densities and control plot

	FAW infestation (mean ± SE)				
	8 traps/ha	**16 traps/ha**	**24 traps/ha**	**32 traps/ha**	**Control**
Emergence	4.47 ± 0.16 ^{ab}	4.51 ± 0.55 ^{b}	4.41 ± 0.24 ^{b}	4.84 ± 0.37 ^{ab}	4.12 ± 0.00 ^{ab}
2-4 leaves	4.23 ± 1.00 ^{b}	5.15 ± 0.56 ^{ab}	5.39 ± 0.92 ^{a}	4.79 ± 0.81 ^{ab}	3.30 ± 0.41 ^{ab}
5-7 leaves	5.49 ± 0.82 ^{a}	5.89 ± 0.40 ^{a}	5.94 ± 0.63 ^{a}	5.03 ± 0.74 ^{a}	3.64 ± 0.67 ^{ab}
8-11 leaves	5.56 ± 0.70 ^{a}	5.70 ± 0.67 ^{ab}	6.17 ± 0.16 ^{a}	5.05 ± 0.37 ^{a}	3.83 ± 0.40 ^{ab}
12-15 leaves	4.39 ± 0.58 ^{ab}	4.57 ± 0.67 ^{b}	4.70 ± 0.38 ^{b}	4.19 ± 0.66 ^{b}	3.77 ± 0.41 ^{ab}
Tasseling	4.90 ± 0.62 ^{ab}	5.07 ± 0.59 ^{b}	5.23 ± 0.47 ^{ab}	4.76 ± 0.50 ^{ab}	3.57 ± 0.57 ^{ab}
Maturity	5.56 ± 0.38 ^{a}	5.63 ± 0.31 ^{ab}	5.76 ± 0.23 ^{a}	5.52 ± 0.26 ^{a}	5.52 ± 0.26 ^{a}
Harvest	5.91 ± 0.24 ^{a}	5.74 ± 0.25 ^{ab}	6.20 ± 0.06 ^{a}	5.70 ± 0. 19 ^{a}	5.00 ± 0.00 ^{a}
F statistics	6.611	7.287	11.780	5.695	6.694
Degrees of freedom	7, 64	7, 64	7, 64	7, 64	7, 28
p - value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Means followed by the same letters within columns are not significantly different.

4.4 Fall armyworm trap captures by trap density and simplified maize growth stages.

The percentage of FAW adult male moths captured in various phenological stages by trap density is shown on Table 4.4. In all the treated experimental plots, the reproductive stage captured the highest number of FAW adult males, followed by the early whorl stage, reproductive stage, and harvest stage respectively.

A total of 1,053 FAW adult male moths were captured (Appendix B) and by trap density, the highest number of FAW adult male moths were captured in the 32 traps/ha plot (n = 358; 34.0%), followed by 16 traps/ha (n = 302; 28.7%), 24 traps/ha (n = 275; 26.1%), and 8 traps/ha (n = 118; 11.2%).

Table 4.4: Percentages of fall armyworm trap captures per trap density by simplified maize growing stages

Maize growth stages	Description	Trap densities (traps/ha) Fall armyworm trap captures (%)			
		8	16	24	32
Early whorl (VE – V7)	Emergence, 2-4, & 5-7 leaves	33.9	27.81	31.27	27.93
Late whorl (V8 – V15)	8-11 & 12-15 leaves	27.12	22.52	25.09	27.09
Reproductive (R1 - R3)	Tasseling & maturity	34.75	47.35	40.0	42.18
Harvest	Harvest	4.24	2.32	3.64	2.79

4.5 Comparison of Fall armyworm infestation levels by trap density

Comparison of the impact of five trap densities on FAW infestation (mean ± SE) is shown in Table 4.5. The one-way ANOVA indicated that there was a significant difference in FAW infestations between the trap densities ($F_{4, 319}$ = 31.31, p <0.001). FAW infestation levels were highest in 16 and 24 trap/ha density plots, and lowest in the control plot. The 8 and 32 traps/ha density plots had similar FAW infestation levels.

Table 4.5: Fall armyworm infestation (mean ± SE) levels by trap density

Trap densities	Fall armyworm infestation (Mean ± SE)
8 traps/ha	5.04 ± 0.09 ^{bc}
16 traps/ha	5.29 ± 0.12 ^{ab}
24 traps/ha	5.48 ± 0.12 ^{a}
32 traps/ha	4.90 ± 0.12 ^{c}
Control	3.90 ± 0.15 ^{d}
$F_{4, 319}$	31.31
P value	<0.001

Means with the same letter are not significantly different.

4.6 Fall armyworm infestation by trap density and phenological stages

Two-way ANOVA was used to determine the effect of different trap densities and eight phenological stages on FAW infestation levels (Table 4.6). There was a significant interaction between phenology and trap densities on FAW infestation levels ($F_{28, 284} = 1.83$; $p = 0.008$). There was a statistically significant effect of phenology on FAW infestation ($F_{7, 284} = 28.33$, $p < 0.001$). Also, there was a significant effect of trap density on FAW infestation levels ($F_{4, 284} = 52.39$, $p < 0.001$).

In the emergence stage, FAW infestation levels between the trap densities were the same ($F_{4, 4} = 0.755$; $p = 0.604$). Mean FAW infestation levels was highest in the 24 traps/ha plot, during harvesting (6.20 ± 0.06), and lowest in the control plot in 2-4 leaves stage (3.30 ± 0.41).

Table 4.6: Comparison of FAW infestation levels (mean ± SE) in four trap densities, control and phenological stages

	8 traps/ha	**16 traps/ha**	**24 traps/ha**	**32 traps/ha**	**Control**	**F statistics**	**Degrees of freedom**	**P value**
	Fall armyworm infestation (mean ± SE)	**Fall armyworm infestation (mean ± SE)**	**Fall armyworm infestation (mean ± SE)**	**Fall armyworm infestation (mean ± SE)**	**Fall armyworm infestation (mean ± SE)**			
Emergence	4.47 ± 0.16 ^{abcde}	4.51 ± 0.55 ^{abcde}	4.41 ± 0.24 ^{abcde}	4.84 ± 0.37 ^{abcde}	4.12 ± 0.00 ^{cde}	0.755	4, 4	0.604
2-4 leaves	4.23 ± 1.00 ^{bcde}	5.15 ± 0.56 ^{abc}	5.39 ± 0.92 ^{abc}	4.79 ± 0.81 ^{abcde}	3.30 ± 0.41 ^{e}	5.769	4, 31	0.001
5-7 leaves	5.49 ± 0.82 ^{abc}	5.89 ± 0.40 ^{ab}	5.94 ± 0.63 ^{a}	5.03 ± 0.74 ^{abcd}	3.64 ± 0.67 ^{e}	12.450	4, 40	< 0.001
8-11 leaves	5.56 ± 0.70 ^{abc}	5.70 ± 0.67 ^{abc}	6.17 ± 0.16 ^{a}	5.05 ± 0.37 ^{abc}	3.83 ± 0.40 ^{de}	19.660	4, 40	< 0.001
12-15 leaves	4.39 ± 0.58 ^{bcde}	4.57 ± 0.67 ^{abcde}	4.70 ± 0.38 ^{abcde}	4.19 ± 0.66 ^{cde}	3.77 ± 0.41 ^{e}	3.369	4, 49	0.016
Tasseling	4.90 ± 0.62 ^{abcde}	5.07 ± 0.59 ^{abc}	5.23 ± 0.47 ^{abc}	4.76 ± 0.50 ^{abcde}	3.57 ± 0.57 ^{e}	13.390	4, 67	< 0.001
Maturity	5.56 ± 0.38 ^{abc}	5.63 ± 0.31 ^{abc}	5.76 ± 0.23 ^{ab}	5.52 ± 0.26 ^{abc}	5.52 ± 0.26 ^{abcde}	7.445	4, 49	< 0.001
Harvest	5.91 ± 0.24 ^{ab}	5.74 ± 0.25 ^{abc}	6.20 ± 0.06 ^{a}	5.70 ± 0. 19 ^{abc}	5.00 ± 0.00 ^{abcde}	6.548	4, 4	0.048
F statistics	6.611	7.287	11.780	5.695	6.694			
Degrees of freedom	7, 64	7, 64	7, 64	7, 64	7, 28			
p - value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001			

Means followed by the same letters are not significantly different.

4.7 FAW infestation levels and FAW adult male moths captured per trap densities

The graphical presentation of FAW infestation and the numbers of FAW adult male moths captured by the 8, 16, 24 and 32 trap/ha density plots is illustrated in Figure 4.2. Overall, the FAW infestation was lowest during emergence and 12 – 15 leaves stage. No point of intersection was observed between the number of FAW adult male moths captured and the number of plants with FAW damage symptoms in the four trap densities.

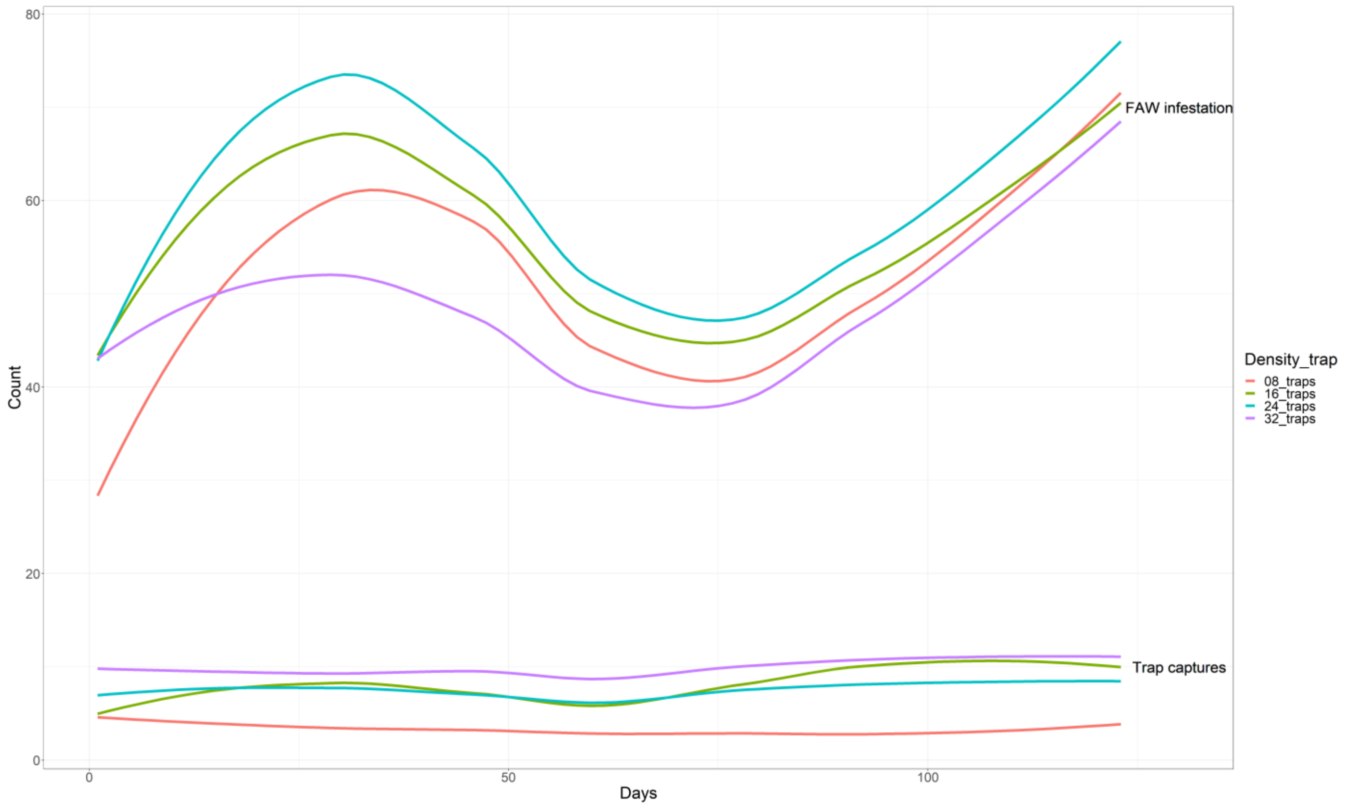

Figure 4.2: FAW infestation and FAW adult male moths captured by trap density.

CHAPTER FIVE

5.0 Discussion, Conclusion and Recommendations

In this study, the prevalence of fall armyworm infestation was higher than the recommended action threshold level in all the treated experimental plots during the entire maize phenological stages. At the early whorl stage, against a recommended action threshold of 20% (Prasanna *et al*., 2018), the infestation rates ranged from 58.45% to 79.1%, while at the late whorl stage, the infestation levels ranged from 53.6% to 73.6% against a recommended action threshold of 40% (Prasanna *et al*., 2018), and finally, at the reproductive stage, the infestation rates ranged from 65.5% to 75.0% against a recommend action threshold of 20% (Prasanna *et al*., 2018). Contrary to expectations, the control plot had the lowest FAW infestation levels in all phenological stages, and during the late whorl stage, it was the only experimental plot with a FAW infestation rate (36.4%), that was less than the recommended action threshold level of 40% (Prasanna *et al*., 2018).

Fall armyworm infestation varied significantly among maize phenological stages and trap densities, with the phenological stages and trap densities interacting significantly. Maize in the 24 and 16 trap/ha density plots had the highest mean FAW infestation compared to other density traps, while the control plot, which lacked pheromone-based traps, had the lowest FAW infestation levels. Relative to other trap density plots, FAW adult male moth captures were highest in the 32 traps/ha and lowest at the 8 traps/ha. However, there was no point of intersection between moth catches per trap densities and infestation levels. In this regard, the insect lures may have not reduced FAW infestation levels in this region.

5.1 Maize phenology and fall armyworm infestation

Despite FAW larvae being highly polyphagous, on availability they tend to confine their feeding to maize, sorghum, and grasses (Luginbill, 1928). In addition, they have an adaptive dispersal ability that can enable them to switch feeding sites by ballooning and crawling (Rojas *et al.*, 2018), and depending on the phenological stage of the maize plant, it causes damage to different sections of the plant although the level of susceptibility differs (Marenco *et al*., 1992).

The first generation of FAW larvae hatched during the early whorl stage. This stage was mainly composed of young leaf tissue which are suitable for FAW larvae growth and survival (Pannuti *et al*., 2016a). Symptoms that were observed included, feeding on young leaf tissue, presence of fecal matter (frass), and large leaf feeding. FAW infestation levels peaked at the 5–7 leaf stage, primarily as a result of multiple FAW larvae infestations as indicated by various instar stages found on maize plants.

The late whorl stage occurred between 35 to 50 days after the emergence stage and during this period the second generation of FAW larvae is estimated to have emerged and re-infested the maize crops. When compared to the other three simplified phenological stages, this stage generally had lower infestation levels and the larvae were observed eating on emerging leaves from the whorl and the tassels that are emerging within the whorl. Fresh holes were tunneled in the stem sheaths by the larger larvae, however, this holes were of minor importance (Ghidiu and Drake, 1989).

The 12-15 leaves stage of the late whorl stage, had the lowest FAW infestation levels of the phenological stages. One plausible explanation is that, as tassel emerged from the whorls the larvae were pushed out into the open, where they were exposed and were vulnerable to biotic (natural enemies) and abiotic (environmental) variables (FAO, 2019). Another possible reason is that, while the closed tassel was adequate for survival and suitable for initial feeding, it results in poor growth because tassel tissue is suboptimal as food for developing larvae (Pannuti *et al*., 2016a).

Compared with the vegetative stage, the reproductive stage is the most sensitive to damage in terms of yield production (Buntin, 1986). Damage caused by FAW larvae to the ears can cause fungal infections and aflatoxins, as well as the destruction of silks and developing tassels, limiting pollination and fertilization (FAO, 2019). At this stage, plants lacked tender leaves and since leaf tissue on mature plants is unsuitable for the development of FAW larvae (Capinera, 2020), the young larvae were observed on the silk threads, while the larger larvae were sited on the ears sheath and on the ears feeding on the developing kernels. The larvae feeding on the kernels and sheltering on the silk threads may have aided the rebound in FAW infestation at this stage after the late whorl stage, as larvae reared solely on kernels develop faster than larvae reared on other tissues, with the silk threads providing shelter and an ideal microclimate for the early larvae stage (Pannuti *et al*., 2016b).

The FAW infestation symptoms observed at the harvest stage on all the maize plants were bores through the kernels and the cobs, as this was the only remaining habitable location for the FAW on the plant. Based on the time period since the maize was planted, the third generation from the initial FAW infestation at the early whorl stage may have hatched during the reproductive stage before the commencement of this stage leading to an increased larvae density on the maize field. Considering that the kernels seem to have a positive effect on larval development (Pannuti *et al*., 2016b), the FAW at this stage were protected and receiving optimal food substrate for their growth and development, thus a high infestation rate.

Temperature and rainfall are essential weather components in the dynamics of insect populations, with temperature being the most important environmental element regulating insects distribution, development, reproduction, behaviour and survival (Briere *et al*., 1999). Temperatures that result to a linear increase in FAW larval development range from 21 to 33ºC, but outside this range the development rate becomes nonlinear (Ali *et al*., 1990). Under constant temperatures, the larvae developmental times are significantly longer at a temperature of 18 ◦C (34 days) compared to 22◦C (21 days), 26◦C (15 days), 30◦C (11 days) and 32 ◦C (10 days) (Du Plessis *et al*., 2020). The average temperature in this region in April was 23ºC, followed by 20ºC in May and 19ºC, 18ºC, and 19ºC, in June, July and mid-August respectively. Thus, the low unfavorable temperature experienced during the months of June, July and August meant that the larval stage (damaging stage) was able to develop for a much longer period, causing a continuous and prolonged infestation to the maize plants.

Compared with the average amount of rainfall received from 2011 - 2020 in the month of April, May, June, July and August (246mm) (Unpublished data – KMD Katumani Station), the total amount of rainfall received from April to August 2021 was low (163mm). As a result of the low rainfall, mortality factors related to FAW egg dislodgement by rainfall were reduced (Varella *et al*., 2015). Because they were not washed off by rain or drowned (in surface water or water in the leaf axils), most of the FAW larvae may have remained on the plants and caused feeding damage until pupation. In addition, the adult moths also benefited from reduced rainfall amounts since the rainy season (wet weather) can restrict adult insect activities such as mating and egg-laying (Beirne, 2012).

5.2 Trap densities and fall armyworm infestation

A research gap exists on the seasonal abundance or population dynamics of the FAW in Machakos County or a similar semi-arid region in Kenya. Consequently, it was not possible to determine baseline FAW population estimates in this region.

The experimental plots were located near a seasonal stream, and some nearby farms were irrigated, these water sources supported natural vegetation and crops all year or at least for long periods of time, and in heavily infested areas, these plant patches support long term fall armyworm populations (Wightman, 2018). In this study, the pheromone traps captured adult FAW male moths before the maize plant emerged from the soil, and FAW infestation occurred immediately after the emergence of maize plants because FAW females from the surrounding area must have flown in and oviposted on the maize plants. At the emerging stage, FAW infestation levels were similar across the trap densities.

The trap used for this study was the universal bucket trap that is an omnidirectional trap, allowing moths to approach the trap from any direction while causing minimum disruption to the plume structure (Jutsum and Gordon, 1989). In a study conducted in Togo, bucket traps captured more FAW than the other trap types regardless of sex pheromone used (Meagher *et al.*, 2019). The highest insect pest captures are achieved at or just above crop height for most annual field crops (Byers, 2008). To be effective in pest captures, the trap placement in the treated experimental plots were placed 30cm in a vertical orientation above the maize plant at all phenological stages, this positioning of the traps was influenced by the location in which FAW females position themselves when calling for mates which is near the top of the crop canopy (Sparks, 1979).

The results in this study showed that the pheromone-based mass trapping failed to reduce FAW infestation levels below the recommended action thresholds and maize plants in the 24 and 16 trap/ha density plots had higher mean FAW infestation rates compared to the 32 and 8 traps/ha density plots. A plateau in total trap captures with increasing sex pheromone trap density could indicate trap interference, which would prevent mass trapping and instead cause mating disruption (McMahon *et al.*, 2010). But this was not observed in this study as the plots with the highest trap density (32 traps/ha) did not experience a reduction in trap catches.

As the trap density increases it is expected that the targeted pest trapped would also increase (Hajatmand *et al*., 2015). However, contrary to expectation the 16 traps/ha captured more moths compared to the 24 traps/ha. The plausible explanation for this anomaly can be explained based on location. Location of the site in an open area, away from trees is important in collecting a high numbers of moth (Meagher *et al*., 2013). The treated experimental plots were surrounded trees, shrubs, and thickets thus the influence of surrounding vegetation was similar in all cases, except the longitudinal side of Plot 7 (16 traps/ha) that was located next to an open field (approximately 150 x 100 m in size) and this may have contributed towards higher trap captures in the 16 traps/ha density plots than the 24 traps/ha plots.

Divergent to the expected trend, maize in the 24 and 16 trap/ha density plots had the highest mean FAW infestation, and it is suspected that the preceding crops on the experimental plots may have played a significant part in terms of soil fertility thus manipulating the environment, favorable for growth, reproduction, and development of insects (Arshad *et al*., 2013). Plots 1 (16 traps/ha), 2 (32 traps/ha) and 3 (2 traps/ha) had cassava (*Manihot esculenta*). While plots 5 (24 traps/ha), 6 (8 traps/ha) and 7 (16 traps/ha) were preceded by green grams. Plots 4 (8 traps/ha) and 8 (32 traps/ha) were preceded by thickets and shrubs and finally the control plot was preceded with maize plants. Both the treatments and replicates for the 16 and 24 traps/ha densities, were the only treatments found in plots that had cassava and green grams crops as the preceding crops.

The plots that previously had the cassava plant benefited from the nitrogen released by the decomposition of cassava leaf litter as most of the nutrients absorbed by cassava during growth are found in the plant tops (Adjei-Nsiah and Sakyi-Dawson, 2012). Similarly, the plots that had green grams as the preceding crop benefited from additional nitrogen in the soil.

Green grams, a leguminous plant, can biologically fix atmospheric nitrogen to the soil (ranging from 30 to 251 kg/ha), allowing it to not only meet its own nitrogen requirements but also benefit following crops (Peoples and Craswell, 1992; George *et al*., 1995). Nitrogen is essential for crops, which is itself crucial for phytophagous insects (Arshad *et al*., 2013). Many insects' development efficiency is related to plant nitrogen content, which is a correlate of protein content. Insects grow increasingly adept at converting plant material into body tissue as the nitrogen concentration of their meal increases (Mcneill, 1977). The increased nitrogen supply would increase the creation of protein and reduce the amount of carbohydrates, resulting in the development of a thinner cell wall and weakening of the tissues, which ultimately attracts insects and intensifies harm from the insects (Janssen, 1996; Arshad *et al*., 2013). For example, Arshad *et al* (2013) observed that, increasing nitrogen application to maize plants led to an increase in *Chilo partellus* (Swinhoe) development, population, and infestations on maize crop (Arshad *et al*., 2013).

Contrary to expectation, the control plot had the lowest FAW infestation levels despite not having any pheromone trap. The landscape where the control plot was located had a boundary of trees on two sides (longitudinal sides) and the general area was surrounded by shrubs and thickets and the approximate distance to the closest farm/plot with the same crop (maize) or sorghum was 700m away. The landscape topography may have contributed to these unexpected findings as varied landscapes provide shelter (cover) and perches for natural enemies that can potentially reduce the infestation by fall armyworm (Prasanna *et al*., 2018), in contrast, simpler landscapes often contain fewer resources to support natural enemies (Landis *et al*., 2000). An interesting finding by Wyckhuys and O'Neil, (2006) showed that small scale farmers in Guatemala and Honduras whose farms were situated in a varied lanscape that included forest patches did not consider fall armyworm to be a serious pest because it only caused minor damage to the maize fields, and did not require the use of pesticides (Wyckhuys and O'Neil, 2006). Another likely cause for the low infestation of the control plot is that a diverse landscape requires more dispersal activity than simple landscapes (O'Rourke and Petersen, 2017), as a result of the longer search times, dispersers are exposed to potentially adverse environmental conditions and predation (Sparks, 1985), and increased metabolic rates (Rankin and Burchsted, 1992) that significantly lower fat and carbohydrate reserve necessary for survival and reproduction (Zera *et al*., 1999; O'Rourke and Petersen, 2017). In addition, volatiles generated by non-host plants may disguise the odor of the host plant, making it difficult for the pest insect to locate the host plant (Schoonhoven *et al*., 1998).

The main reason of the low male moth capture in this study is not known, but several factors may be involved, one possibility is based on several aspects of the biology and ecology of the pest which can impede mass trapping (El-Sayed *et al*., 2006). Those that hinder related to FAW in this study, include its ability to have several generations in a cropping season (multivoltinism), its polyphagous nature, it does not diapause, and has multiple mating frequency (Sternlicht *et al*., 1990, Prasanna *et al*., 2018). Female FAWs can mate multiple times but only once per night (Capinera, 2020), this behavior ensures that female moths have several chances of mating and reproducing. As a result, if mass trapping does not result in a significant proportion of male elimination (80 - 95%) (Knipling and McGuire, 1966), the remaining males will still have an opportunity to mate. Male FAW mate during most of their adult life, with the number of copulations increasing with age (Simmons and Marti, 1992). Despite an increase in FAW male captures in the current study, the infestation rate increased as the maize plant matured.

Trap-female competition is a significant factor leading to mass trapping's ineffectiveness in controlling high-density insect pest populations (Beroza and Knipling, 1972). According to Roelofs *et al*. (1970), mass trapping was anticipated to be successful only against pest populations with low densities. As pest populations decline, competition for male moths between lures and females reduces, making traps inversely density dependent (Roelofs *et al*., 1970). Based on the high infestation rate in this study, we may conclude that the FAW population density in this area is significant. Another possible explanation for the low number of trap captures is that during an FAW outbreak, the distance between male and female moths becomes small and despite the fact that the pheromone released by the synthetic lures affects the males, they may still be able to locate and mate with the female moths using visual cues. As a result, synthetic lures are unlikely to inhibit mating in such a scenario (Schwalbe *et al*., 1983; Webb *et al*., 1988).

The FAW variant in Sub-Sahara Africa (SSA) mainly originated from the USA (Goergen *et al*., 2016). Nagoshi *et al*. (2018) reported a fall armyworm variant of the R-biotype that is unique to Africa, having been found in Togo, Kenya, and the Democratic Republic of the Congo (Nagoshi et al., 2018). There is a possibility of genetic variation leading to the Scentry - L105A synthetic lure that was effective in capturing FAW adult male moths in the USA (Meagher *et al*., 2013) was not effective for this population. Genetic explanations for FAW trap capture inconsistencies include population isolation caused by the high migratory ability of the FAW leading to differences (lack of homogeneity) with the native population (Andrade *et al*., 2000), gene drifting that occurs during the expansion of the distribution range from the original habitat *(*Wakamura *et al*., 2021) and a significant change in moth pheromone blends when previously unexpressed genes controlling pheromone components become expressed in some females in a population (Roelofs *et al*., 2002).

5.3 Conclusion

The results in this study demonstrated that mass trapping using synthetic sex pheromone was ineffective in suppressing FAW populations or reducing maize plant infestation symptoms. These results lend support to the assertion that mass-trapping should be used as a monitoring and detection tool, together with scouting the fields to assist determine when pesticides should be used in a manner that is both environmentally and commercially sustainable. Developing mass trapping as an integrated pest management (IPM) package may offer an economic incentive for farmers to adopt this technology.

5.4 Recommendation

The use of FAW male-based pheromones may not have been sufficient in mating suppression. Therefore, there is need to determine the optimum formulation of synthetic sex pheromone for this specific population. This may be done by making a blend of synthetic pheromone more potent than calling females. Another consideration is that the invasion of mated females from neighboring areas is a key challenge in pheromone trapping management. Developing female attractants may enhance the elimination of virgin and the mated females. This approach may be combined with male removal.

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APPENDICES

Appendix A. Field temperature and rainfall data

Total amount of rainfall and median [interquartile range (IQR)] temperature from April to mid-August 2021 were collected and presented in Appendix A. The monthly median temperatures varied between 18.1ºC and to 22.9ºC. Overall, 162.7mm of rainfall was received during the study. The month of May received the highest amount of rainfall (94.5mm), while July had the lowest rainfall (0.4mm)

Appendix A. Monthly temperature and rainfall distribution at KALRO Katumani Research Centre during study period

Month	Rainfall in mm	Median temperature in ºC
April	62.8	22.9 (IQR: 22.4 – 23.1)
May	94.5	20.1 (IQR: 19.3 – 21.0)
June	1.0	18.9 (IQR: 17.7 – 19.9)
July	0.4	18.1 (IQR: 17.3 – 19.0)
Mid-August	4.0	18.9 (IQR: 16.9 – 19.7)

Appendix B. Fall armyworm adult male moths captured and FAW infestation symptoms by plot ID

Plot IDs 2 (32 traps/ha), 8 (32 traps/ha) and 7 (16 traps/ha) had the highest trap captures of FAW male moths of 182, 176 and 171 respectively, while plot IDs 6 (8 traps/ha) and 4 (8 traps/ha) had the lowest trap captures of FAW male moths of 61 and 57 respectively. Plot ID 9 (control) did not have any pheromone-based traps.

Plot ID 5 (24 traps/ha) had maize plants with the highest FAW infestation symptoms, while Plot ID 9 (Control) had the lowest number of plants with FAW symptoms.

Appendix B. Total number of FAW adult male moths captured and FAW infestation symptoms by plot ID

Plot ID	Trap density	Total FAW damage symptoms	Total number of FAW adult male moths captured
1	16 traps/ha	929	131
2	32 traps/ha	963	182
3	24 traps/ha	1,063	134
4	8 traps/ha	779	57
5	24 traps/ha	1,135	141
6	8 traps/ha	1,098	61
7	16 traps/ha	1,123	171
8	32 traps/ha	801	176
9	Control	566	0
Total		**8,457**	**1,053**

Appendix C. Comparison of FAW infestation by experimental plot ID

Comparison of the impact of FAW infestation in the nine plots on is shown in table appendix C. The one-way ANOVA indicated that there was a significant difference in FAW infestations between the plot IDs ($F_{8, 315} = 24.09, p < 0.001$). FAW infestation levels (mean ± SE) were highest in Plot ID 5 (5.57 ± 0.71) and lowest in plot ID 9 (3.90 ± 0.70). The FAW infestation levels, from high to low are denoted as a, ab, b and c, respectively. Plots that the experimental maize plants were preceded with thickets (Plot IDs 4 & 8) and maize (Plot ID 9) had lower infestation levels as compared to those that had Cassava (Plot IDs 1, 2 & 3) and green grams (Plot IDs 5, 6 & 7).

Appendix C. Effects of preceding crop on FAW infestation (Mean ± SE) by Plot ID

Plot ID	Trap density	Preceding crop	Mean ± SE
1	16 traps/ha	Cassava	5.04 ± 0.64^{ab}
2	32 traps/ha	Cassava	5.14 ± 0.59^{ab}
3	24 traps/ha	Cassava	5.39 ± 0.68^{a}
4	8 traps/ha	Thicket	4.60 ± 0.70^{b}
5	24 traps/ha	Green grams	5.57 ± 0.71^{a}
6	8 traps/ha	Green grams	5.48 ± 0.72^{a}
7	16 traps/ha	Green grams	5.55 ± 0.67^{a}
8	32 traps/ha	Thicket	4.67 ± 0.69^{b}
9	Control	Maize	3.90 ± 0.70^{c}
$F_{8,315}$			24.09
p value			<0.001

Means followed with the same letter are not significantly different.