SEASONAL ABUNDANCE OF AMARANTH LEPIDOPTERAN DEFOLIATORS AND THE ROLE OF INDIGENOUS PARASITOIDS AND PHENYLACETALDEHYDE IN THEIR CONTROL IN NAIROBI COUNTY, KENYA

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DECLARATION

Declaration by candidate

I declare that this thesis is my original work and has not been presented for the award of a degree in any other university or any other award

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Supervisors' approval:

We confirm that the work reported in this thesis was carried out by the candidate under our supervision and has been submitted with our approval as supervisors

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DEDICATION

This thesis is dedicated to

My loving and caring mother

Florence Othim

My loving and dearest wife

Diana Nyanting'a who has been my source of inspiration

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ABBREVIATIONS AND ACRONYMS

Abuk	Var. Abuku Amaranth
AIVs	African Indigenous Vegetables
ANOVA	Analysis of Variance
ASL	Above Sea Level
AVRDC	The World Vegetable Centre
BM	β myrcene
BMZ	The Federal Ministry for Economic Cooperation and Development
Bt	*Bacillus thuringiensis*
CJ	cis jasmine
GLM	General Linear Model
GPS	Global Positioning System
ICIPE	International Centre of Insect Physiology and Ecology
IPM	Integrated Pest Management
KU	Kenyatta University
LIN	Linalool
MMB	Methyl-2-Methoxy Benzoate
NAFIS	National Farmers Information Services
OR	Odds Ratio
PAA	Phenyl acetaldehyde
RCBD	Randomized Complete Block Design

ABSTRACT

Amaranth is one of the African indigenous vegetables that is gaining popularity due to its nutritional, medicinal and economic values. Its potential as a source of food security in East Africa and most parts of the world has heightened demands for the once neglected crop. In Kenya and Tanzania, the Lepidopteran defoliators are important pests of the crop which can cause up to 100% yield loss. Little information on the population dynamics of these pests make their management difficult. Indiscriminate use of synthetic chemicals have raised environmental and health concerns creating a need for other environmentally safe and sustainable control strategies. The objectives of this study were to assess the seasonal abundance of the leaf webbers and their associated parasitoids, investigate the efficacy of Phenylacetaldehyde (PAA) as lepidopteran attractant and effect of amaranth lines on pest abundance. Damage by lepidopteran defoliators and performance of endoparasitoid *Apanteles hemara* on the two leaf webber species were also evaluated. Field experiments were set up at Kenyatta University and the International Centre of Insect Physiology and Ecology in a randomized complete block design with six replicates. Performance studies were carried out in the laboratory at ICIPE to assess the acceptability and suitability of *Spoladea recurvalis* and *Udea ferrugalis* to *A. hemara.* Abundance of leaf webbers (P=0.537) and leaf worms (P=1.0) and their associated parasitoids (P=0.083) did not differ significantly between the wet (Nov, 2014-Jan, 2015) and dry (Jul-Sep, 2014) seasons. Phenylacetaldehyde plots had significantly higher number of leaf webbers than the control plots (P=0.014). Phenylacetaldehyde traps also attracted significantly higher number of moths than the traps in the controls in both dry and wet seasons (P<0.001). Both *S. recurvalis* and *U. ferrugalis* were accepted by and suitable for the parasitoid *A. hemara*. Successful oviposition was significantly higher (P=0.018) when *A. hemara* was reared on *S. recurvalis* and exposed to the same host than when reared on *U. ferrugalis* and exposed to *S. recurvalis.* Rearing host did not, however, significantly affect successful oviposition (P=0.782) when tested on *U. ferrugalis*. The sex ratio of the parasitoid was female biased when reared on *S. recurvalis* while on *U. ferrugalis*, it was male biased. Parasitism rate was significantly higher (P=0.025) in *S. recurvalis* (64.4%) than *U. ferrugalis* (48.6%). Non-reproductive mortality was not significantly different from natural host larval mortality in both *S. recurvalis* (P=0.782) and *U. ferrugalis* (P=0.115). These results show that lepidopteran defoliators of amaranths occur throughout the crop cycle calling for efficient and adequate management strategies. Abuk2 amaranths were shown to exhibit certain levels of non-preference by these pests hence should be targeted by breeding programs to produce resistant lines. High levels of parasitism exhibited by *A. hemara* on both *S. recurvalis* and *U. ferrugalis* makes it a suitable candidate for biological control of these leafwebbers in amaranth production.

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Amaranth is one of the orphan (understudied) crops in the world. It is a herbaceous annual crop belonging to the order *Caryophillales*, Family *Amaranthaceae* and genus *Amaranthus* (Amicarelli and Camaggio, 2012). *Amaranthus* is a large genus that includes three recognized sub-genera and nearly 75 species with between 4,000 to 6,000 varieties. The most economically important is the subgenus *Amaranthus* which are monoecious and native to America, Africa, Australia, Asia and Europe (Mosyakin and Robertson, 2003; Infonet-biovision, 2012; Fatinah *et al*., 2013). These have a high plasticity and adaptability and can grow over a very broad range of climatic conditions (Infonet-biovision, 2012; Moskova, 2013).

Amaranth is a broad-leafed plant that could be mistaken for soybeans early in the growing season. The leaves are generally green or red. The plants form branched flower stalks which bear thousands of tiny seeds, variable in colour from cream to gold, pink to shiny black (Amicarelli and Camaggio, 2012). According to Amicarelli and Camaggio (2012), amaranth is not a true cereal like wheat or corn but it is rather considered a pseudo-cereal together with crops like quinoa (*Chenopodium quinoa*).

Amaranth has been exploited as a leafy vegetable, grain, animal feed and as an ornamental (NAFIS, 2011). The leaves have a high energy content and are rich in protein, calcium, potassium, iron, ascorbic acid, lysine and vitamins A, B

and C and have also shown potential benefits as medicinal plants in the management of diabetes, anaemia, anorexia, burning sensations, antitumor and antioxidant among others (Costea *et al*., 2004; Ouma, 2004; Kumar *et al*., 2014). The grains are equally very nutritious and are largely used in feeding children and the elderly to boost their immunity by supplying the much needed micro-nutrients (Gikonyo *et al.,* 2011). Amaranth is also rich in Squalene, a special component of amaranth oil which is used as an important cosmetic preparation, in pharmaceutical industries and as a lubricant in servicing computers and production of edible oil for domestic usage (NAFIS, 2011).

In Kenya, amaranth has for a long time been considered as a weed and therefore neglected like several other African Indigenous Vegetables (AIVs) by most households who have found a replacement in exotic varieties of vegetables (Ekesa *et al*., 2009). However, a rise in its consumption and demand has been reported over the past decade due to increasing awareness on its nutritional and medicinal values and as a source of income for either small scale or large scale farmers (Ouma, 2004; Kagali *et al*., 2013). According to the Horticultural Crops Development Authority (HCDA, 2012), leaf amaranths were cultivated in all the provinces of Kenya except North Eastern under a total area of 3,724 Hectares with a net production of 31,752 Metric tons valued at USD 5,824,240 in 2009.

The production of amaranth in different regions is however affected by numerous arthropod pests and diseases and therefore its optimum productivity has been seriously affected (Aderolu *et al*., 2013; Kagali *et al*., 2013). The pests reported infesting amaranths across the world are varied and include *Spoladea*

recurvalis (F.), *Herpetogramma bipunctalis* (F.), *Sylepta derogata* (F.), and *Psara basalis* (Walker) (Lepidoptera: Crambidae); *Spodoptera eridania* (Stoll), *S. exigua* (Hübner) , *S. Frugiperda* (J.E. Smith), *Helicoverpa armigera* (Hübner), *S. litura* (F.) and *Agrotis* spp., (Lepidoptera: Noctuidae); *Aspavia armigera* (F.) and *Nezara viridula* (L.), (Hemiptera: Pentatomidae), *Liriomyza* spp. (Diptera: Agromyzidae), *Cletus* spp. (Hemiptera: Coreoidae), *Hypolixus nubilosus* (Coleoptera: Curculionidae), *Epilachna elaterii* (Rossi) (Coleoptera: Coccinellidae), *Hyphantria cunea* (Drury) (Lepidoptera: Arctiidae) and aphids (Homoptera: Aphididae) (Clarke-Harris *et al*., 2004; Sharma and Ramamurthy, 2009; James *et al*., 2010; Aderolu *et al*., 2013). *Spoladea* (*Hymenia*) *recurvalis* F. (Lepidoptera: Crambidae) and other Lepidopteran leaf webbers have been reported to be the most damaging pests of amaranth (Clarke-Harris *et al*., 2004; Sharma and Ramamurthy, 2009; Aderolu *et al*., 2013). These pests cause severe damage to the crop which sometimes leads to complete yield loss (James *et al*., 2010).

A number of these pests have also been reported to attack cultivated amaranths in Meru, Nairobi, Kiambu, Machakos, Narok, and Kakamega Counties of Kenya and cause significant losses (Kagali *et al*., 2013; Mureithi *et al*., 2015). The most common and economically important arthropod pests known to attack leaves and stems include webworms *Herpetogramma bipunctalis* (F.), *Spoladea (Hymenia) recurvalis* (F.), *Udea ferrugalis* (Hübner) (Lepidoptera: Crambidae), *Omoides indicata* and amaranth weevil (*Hypolixus nubilosus*) (Coleoptera: Curculionidae) (Kagali *et al*., 2013; De Prins and De

Prins, 2014; Mureithi *et al*., 2015). Coreid bugs (*Cletus* spp.) are notorious for causing damage to grains (Kagali *et al*., 2013; Mureithi *et al*., 2015).

Natural enemies in the Families Coccinelidae, Sphecidae, Ichneumonidae and Braconidae have been reported to be associated with these pests (Narayanan *et al*., 1957; James *et al*., 2010; Kahuthia-Gathu, 2013; Kagali *et al*., 2013). Among the parasitoids, *Apanteles* sp. (Hymenoptera: Braconidae) has been reported to cause parasitism of up to 62% on *S. recurvalis* (Narayanan *et al*., 1957) and therefore raising the need to explore its possible implementation in augmentative biological control in Kenya.

Spoladea recurvalis and other lepidopteran pests are mainly controlled using synthetic insecticides mainly organophosphates, organochlorides, pyrethroids and carbamates. These insecticides are usually hazardous and overuse by smallholder farmers impact negatively on the environment, increases resistance of pests and residues on the crop and destroys beneficial insects (Chahal *et al*., 1997; Losenge, 2005; Srinivasan, 2012). This therefore creates a need to explore alternative management practices within an Integrated Pest Management (IPM) framework which are efficient, sustainable and affordable.

Floral lures such as Phenylacetaldehyde (PAA), and cis-jasmone among other lures have been reported to attract *S. recurvalis* and other pests belonging to the families Crambidae and Noctuidae (Landolt *et al*., 2011). While the use of such lures in the management of lepidopteran pests have been shown to be effective in North America and Europe, such trials have never been conducted

in Kenya. These lures are used with traps of various designs and can also be modified to suit the smallholder farmers of amaranth in Kenya.

In Kenya the population dynamics of the lepidopteran defoliators of amaranth, occurrence of their associated indigenous natural enemies and parasitism rates have not been studied. Such studies are nevertheless crucial for development of sustainable and effective IPM strategies for lepidopteran pests attacking amaranths. The current study assessed the population dynamics of amaranth lepidopteran defoliators on amaranths and evaluated the role local parasitoids, and floral attractants play in their management.

1.2 Statement of the problem

Amaranth is grown by smallholder farmers in Kenya mainly for the domestic market. Its nutritive value and potential to alleviate poverty and improve food security has made it a popular vegetable crop in the country. In spite of these benefits, pest infestations limit its optimal production. Lepidopteran defoliators are considered to be among the most damaging pests of amaranth in most parts of the world but remain poorly documented in Kenya. Control of these pests using synthetic insecticides can cause health and environmental risks that could be avoided through designing, promoting and implementing attract-and-kill techniques as well as use of natural enemies among other Integrated Pest Management (IPM) strategies. Phenylacetaldehyde (PAA), a floral lure has been shown to attract certain lepidopteran defoliators of amaranth such as *S. recurvalis* and therefore has a potential to be used in the management of these pests. Several companies have also designed different

kinds of traps that could be used with the floral lures but the efficacy of these trap designs are yet to be studied. In order to come up with an efficient and sustainable IPM package, there is need to determine the seasonal abundance of these lepidopteran defoliators and their natural enemies in Kenya. The efficacy of PAA attractant when used with delta traps and the effect of various amaranth lines on the pest populations also need to be assessed as possible means of pest management. Performance of indigenous parasitoids should also be studied to indicate their potential as possible IPM components in the management of amaranth lepidopteran defoliators.

1.3 Justification of the study

The information generated from this study will be useful to farmers and researchers in establishing sustainable management strategies for the amaranth leaf webbers and increase production of amaranth in Kenya. Promotion of use and conservation of natural enemies in the management of amaranth webworms will also reduce pesticide usage, which is usually expensive and pose challenges of resistance, residual effects and risk to environment and human health. Floral attractants which also reduce levels of pesticide usage and are important in attracting both sexes of pests will be of great importance in an IPM strategy for managing pests of amaranths. Since most trap designs that have been used with Phenylacetaldehyde associate a toxicant as a killing agent, this study will focus on the efficacy of using delta traps with a sticky pad as a killing agent which might prove to be cheaper and sustainable to small holder farmers. Plant breeding programs will gain information regarding lines of amaranth that

possess pest resistant traits. Policy makers will also be guided through the outcomes of this study regarding economically important pests of amaranths and possible strategies of their management.

1.4 Research questions

1) How does seasonality affect the populations of amaranth lepidopteran defoliators and their associated parasitoids?
2) Does PAA attract amaranth lepidopteran defoliators under field conditions?
3) Do amaranth lines affect the populations of lepidopteran defoliators and their associated parasitoids?
4) Are the incidences and levels of damage by amaranth lepidopteran defoliators affected by either seasonality or amaranth lines?
5) How do the leaf webbers *Spoladea recurvalis* and *Udea ferrugalis* affect the performance of the indigenous endoparasitoid *Apanteles hemara*?

1.5 Hypotheses

1) The seasonal abundance of amaranth lepidopteran defoliators and their associated parasitoids remain the same throughout the year.
2) Phenylacetaldehyde has no attractive effect on amaranth lepidopteran defoliators.
3) Amaranth lines have no effect on abundance of either lepidopteran defoliators or their associated parasitoids.

4) Seasonality and amaranth lines have no effect on the incidence and levels of damage by amaranth lepidopteran defoliators.
5) *Spoladea recurvalis* and *Udea ferrugalis* are neither acceptable nor for the endoparasitoid *Apanteles hemara*.

1.6 Objectives of the study

1.6.1 General Objective

To evaluate the population dynamics of amaranth lepidopteran defoliators and the potential of Phenylacetaldehyde and indigenous parasitoids in their management in Nairobi County, Kenya.

1.6.2 Specific objectives

1) To assess the seasonal abundance of amaranth lepidopteran defoliators and their associated parasitoids in Nairobi County.
2) To evaluate the potential of Phenylacetaldehyde as attractant of amaranth lepidopteran defoliators attacking amaranth crops in Nairobi County.
3) To determine the effects of selected amaranth lines on the abundance of lepidopteran defoliators and their associated parasitoids.
4) To assess the effects of seasonality and amaranth lines on the incidence and levels of damage by amaranth lepidopteran defoliators
5) To evaluate the acceptability and suitability of *Spoladea recurvalis* and *Udea ferrugalis* to the endoparasitoid *Apanteles hemara*.

CHAPTER 2: LITERATURE REVIEW

2.1 Origin, distribution and uses of amaranth

Amaranth was already known and used as food and ornamental during the pre-Columbian civilizations in Mexico and Chile in the 1500s (O'Brien and Price, 1983; Myers, 2004; Amicarelli and Camaggio, 2012). It later spread and established in several parts of the world including Africa, Asia, and Europe where for many centuries, it was abandoned and neglected as a potential source of food (Amicarelli and Camaggio, 2012). Today amaranth is distributed in all the continents of the world and it occurs both as weed and cultivated crops (Infonet-biovision, 2012; Fatinah *et al*., 2013). In Africa, Nigeria is the largest producer and consumer of amaranth followed by Ghana, Benin, Senegal, Kenya, Uganda, Cameroon, Gabon, Tanzania, Ethiopia, South Africa, Zambia and Zimbabwe (Smith and Eyzaguirre, 2007). In East Africa, the documented cultivated species include *A. cruentus, A. dubius, A. blitum* and *A. tricolor* (Costea, 2003).

In Kenya, amaranth is known as terere (Kikuyu), muchicha (Kiswahili, Ngiriama), lidodo, (Luyha) and alika (Luo) (NAFIS, 2011). Amaranth is of high economic importance as a vegetable, grain, and ornamental. There are limited documented data on the economic production of amaranth in Kenya which also explain why AIVs and particularly amaranths have been neglected. This inadequacy however does not downplay the importance of amaranth and its potential in food security.

The leaves have a high energy value and are rich in protein, minerals like calcium, potassium, iron, ascorbic acid**,** lysine and vitamins A, B and C (Ouma, 2004; Amicarelli and Camaggio, 2012). The leaves can be consumed fresh as vegetable in salads or mixed with other vegetables, they can be purred to provide base for sauces or dried to be used as spice (O'Brien and Price, 1983; NRC, 1984; Amicarelli and Camaggio, 2012). Amaranth grains also possess unique chemical composition and are different from other cereals in that they contain high amounts of proteins, amino acids and fats. Absence of gluten in amaranth proteins make them most preferred in celiac diet for people suffering from celiac disease (gluten intolerance) (NRC, 1984; Mlakar *et al.*, 2010; Amicarelli and Camaggio, 2012).

Amaranth grain especially *Amaranthus cruentus* can be used to produce oil which has various health benefits. These benefits include improvement of circulatory system, increase in energy, lessening of pain, lessening wrinkles, control of chronic disease, arthritis, allergies, diabetes, asthma and candidiasis; healing of burns, healing of infections and skin lesions, reduction of various symptoms of cancer, increase in white blood cells, increase in the excretion of mercury and clearing of eczema (Kirby *et al*., 2010; Kumar *et al*., 2014). In addition, Squalene, a component of amaranth oil which is a terpenoid and a precursor of cholesterol biosynthesis has led to increased interest in amaranth by pharmaceutical industries because of its properties (Amicarelli and Camaggio, 2012). Naturalists and conservationists may also have interest in the crop so as to conserve sharks which are a major source of Squalene (Amicarelli and

Camaggio, 2012). Due to such growing interests from various sectors, amaranth farmers can have an advantage of increased demand and therefore better economic returns from amaranth.

Mature whole plants of *A. retroflexus* have been recommended as animal feed, providing 20 to 30% protein and over 40% soluble carbohydrates in above-ground tissue (Costea *et al*., 2004). Amaranth can also be used for phytoremediation and the wild species used as a source of genes for breeding programs with cultivated species of amaranth (Costea *et al*., 2004). Due to its qualities of being inexpensive, drought tolerant, early maturing, easy to harvest and highly nutritive (NAFIS, 2011), amaranth farming can be promoted in Kenya to supplement the unreliable supply of maize, the country's staple, that has aggravated food insecurity.

2.2 Growing conditions of amaranth

Amaranth species can grow from sea level to 2,400 m above sea level (ASL). They require temperatures ranging from 22 to 30°C with minimum temperatures of 15 to 17°C for seed germination. Amaranth can be grown during both wet and dry seasons, though irrigation is normally required during the dry season. It can however tolerate periods of drought after the plant has become established (O'Brien and Price, 1983; DAFF, 2010). It is adapted to low and medium humidity (Infonet-biovision, 2012). Amaranth grows best in loam or silty-loam soils with good water-holding capacity, but it can also grow on a wide range of soil types and soil moisture levels. It can tolerate a soil pH from 4.5 to 8 and requires thorough land preparation and a well-prepared seedbed for good

growth (AVRDC, 2004). It is planted either by direct seeding or transplanting depending on availability of seeds, labour and growing season (Infonet-biovision, 2012). This broad adaptability of amaranth is because it belongs to the C4 group of dicotyledonous plants whose pathways allow high photosynthetic and water use efficiency in a broad range of temperatures, moisture and water-stress environments (O'Brien and Price, 1983; Ebert *et al*., 2011; Amicarelli and Camaggio, 2012).

2.3 Varieties of amaranth

Of all the indigenous tropical leafy vegetables, amaranth has the largest number of species and varieties (AVRDC, 2004). Some of the most common commercial amaranths are selections of *Amaranthus tricolor* which come in various leaf colours such as white (light green), dark green, red, purple and variegated (AVRDC, 2004; Amicarelli and Camaggio, 2012). More than 20 species of amaranth are consumed as vegetable or grain and people have different preferences for the different amaranth species.

Across the world, varieties of *Amaranthus tricolor, A. blitum, A. spinosus, A. viridis* and *A. blitum* are consumed (Ebert *et al*., 2011). *Amaranthus cruentus, A. dubius* and *A. blitum* are the most common vegetable varieties in East Africa (Costea, 2003). The main varieties grown for grain in Kenya are *A. cruentus, A. hypochondriacus* and *A. caudatus* (Shroyer *et al*., 1990). Most of the other varieties found in Kenya are majorly weeds and are not grown for production purposes.

2.4 Lepidopteran defoliators of amaranth

The major group of arthropod pests that cause significant damage to amaranths are the lepidopterans whose larvae feed voraciously on leaves of the crop (Clarke-Harris *et al*., 2004). Two distinct groups of lepidopteran defoliators have been frequently reported to cause losses in amaranths in several countries around the world. The first group are the leafwebbers or webworms whose larvae fold, web or glue amaranth leaves using their silken webs as they feed within the leaves (Batra and Bhattacherjee, 1960; James *et al*., 2010). Leafwebbers attacking amaranths mostly belong to the family Crambidae and include major pests of amaranth like *S. recurvalis, U. ferrugalis, P. basalis, H. bipunctalis* and *A. rantalis* among others (Clarke-Harris *et al*., 2004; Arivudainambi *et al*., 2010;James *et al*., 2010; (Kahuthia-Gathu, 2013; Grovida, 2015).

The second group are the leafworms which usually occur as occasional pests of amaranth. Their larvae also feed on amaranth leaves but unlike webworms, they do not glue or fold amaranth leaves. Major leafworms attacking amaranths belong to the family Noctuidae and include *Spodoptera exigua*, *S. littoralis, S. furgiperda,* and *S. eradania* among others (Clarke-Harris and Fleischer, 2003; Clarke-Harris *et al*., 2004; Aderolu *et al*., 2013; Mureithi *et al*., 2015)

2.5 Ecology and distribution of amaranth lepidopteran defoliators

Both leafwebbers and leafworms of amaranth are widely distributed across the world and are found in the tropical and sub-tropical regions including

Africa, Asia, and Australia (Shirai, 2006; Bailey, 2007; De Prins and De Prins, 2014). They are also found in America and the Neotropics and have also been reported in the temperate regions including Belgium and Denmark (Bailey, 2007; Aderolu *et al*., 2013). In Africa, they have been reported in Cameroon, Democratic Republic of Congo, Equatorial Guinea, Ethiopia, Gambia, Kenya, La Reunion, Madagascar, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Ghana, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Togo, Tanzania, Zambia, Mauritius, Seychelles, Lesotho, Comoros and Zimbabwe ((Kahuthia-Gathu, 2013; De Prins and De Prins, 2014). This broad distribution therefore calls for well thought out strategies of managing these pests to enhance amaranth production.

2.6 Alternative host crops of amaranth leafwebbers (webworms)

Apart from the *Amaranthus* spp., the leafwebbers have been reported on other crops such as the adzuki beans *Vigna angularis* (Willd.), mung beans/ green grams *Vigna radiata* (L.), soy beans (*Glycine max* (L.), sugar beet *Beta vulgaris* (L.), silver beet (*B. Vulgaris* var. *cicla* (L.), spinach *Spinacia oleracea* (L.), purslane *Portulaca* spp., black pigweed *Trianthema portulacastrum* (L.), goosefoot *Chenopodium* sp., watermelon *Citrullus lanatus* var. *lanatus* (Thunb.) Matsum and Nakai), aubergine/ eggplant *Solanum melongena* (L.), peanut *Arachis hypogaea* (L.), cotton *Gossypium* sp., and maize *Zea mays* (L.) (Bailey, 2007; James *et al*., 2010; De Prins and De Prins, 2014). Kahuthia-Gathu (2013) observed yield losses of up to 100% on spinach *Spinacia oleracea* L. (family Amaranthaceae) from *Spoladea recurvalis* infestations.

The pests also infests wild hosts such as devils horse whip A*chyranthes aspera* L. (Amaranthaceae) (Kahuthia-Gathu, 2013). *Spoladea recurvalis* has been observed to feed veraciously on leaves of *Trianthema portulacastrum* (L.) leading to complete destruction of the weed and is therefore considered as a potential biological control agent of the weed (Martin *et al*., 2004; Baltazar, 2009; Kedar and Kumaranag, 2013).

2.7 Biology of amaranth leafwebbers

The amaranth leafwebbers lay their eggs singly or in small batches in grooves of leaf veins on both lower and upper surfaces of the leaf. The eggs differ in colour from white, cream to yellowish depending on the species (El-Gendi *et al*., 2006; Grovida, 2015). The female adults of *S. recuvalis* and *U. ferrugalis* can lay between 200 to 400 eggs during their lifespan (KiYeol *et al*., 2002; El-Gendi *et al*., 2006) and they usually have overlapping generations within a year. The eggs of *S. recurvalis* hatch after 5 - 7 days at 18.6 ± 2°C and 70 ± 5% RH (El- Gendi *et al*., 2006) and those of *U. ferrugalis* in 5 ± 0.35 days at 25°C (KiYeol *et al*., 2002) whereas those of *Herpetogramma bipunctalis* in 5.59 days (Diez-Rodríguez *et al.*,2013).

The first and second instar larvae feed on the epidermis of the leaves skeletonising the tissue and thereafter the entire leaf is consumed with the third instar being the most destructive in *S. recurvalis* (Aderolu *et al*., 2013). The larvae undergo five instars before they reach a pre-pupation stage and finally pupation, which mostly occurs in the soil (El-Gendi *et al*., 2006; Grovida, 2015). The larval period in *S. recurvalis*, *U. ferrugalis* and *H. bipunctalis* lasts 24 - 30,

10 - 25 and 26-37 days, respectively depending on temperature while the pupal period ranges between 15 - 18, 5 - 16 and 13 - 37 days, respectively (KiYeol *et al*., 2002; El-Gendi *et al*., 2006; Diez-Rodríguez *et al.*, 2013).

2.7.1 Description of *Spoladea (Hymenia) recurvalis*

It is also known as the Hawaiian beet webworm. It is largely restricted to plants in the family Chenopodiaceae (Grovida, 2015). The adult is a dark brown moth with two white translucent bands on the forewings and one on the hind wings; these bands form a continuous arch pattern when the wings are spread. The forewing also bears one elongate and two small white spots distally and the wing span is about 17-23 mm (Clarke-Harris *et al*., 1998; Grovida, 2015). The margin of the front is alternating dark and light and there are also narrow light bands on the abdomen. The eggs are elliptical, scale-like, shiny translucent yellow sacs, deposited singly or in rows of several eggs. The egg measures 0.6 mm long, 0.5 mm wide and 0.25 mm in height and are normally laid on the lower surface of leaves adjacent to leaf veins and sometimes on the upper leaf surface (Clarke-Harris *et al*., 1998; Grovida, 2015).

The larvae are a translucent green with the gut visible through the integument as a pulsating dark green band. There are two longitudinal white wavy lines sandwiching the green band formed by the gut (Clarke-Harris *et al*., 1998). The head capsule is light colored though a few dark spots are found on the head and thoracic plate (Grovida, 2015). Young larvae of *S. recurvalis* feed beneath the leaves and occasionally spin light webs in which they rest. The body bears numerous stout hairs over the length of its body but lacks the dark spots

found with such hairs on many webworms (Grovida, 2015). In the pre-pupal stage the larva changes color from green to creamish and then to bright pink. The pink pre-pupa often fall to the ground and pupate in the soil while in some cases it webs the leaves around itself using silken threads and pupates within the leaf shelter. Pupae are 8-10 mm long and straw colored (Clarke-Harris *et al*., 1998).

Figure 2.1: Life cycle of *Spoladea recurvalis* at 25 ± 2^{o}C and 60 ± 10% RH

Source: AIV Project, ICIPE, 2014.

2.7.2 Description and biology of *Udea ferrugalis*

The rusty-dot pearl, *Udea ferrugalis*, belongs to a group of moths known as the snout moths (Mally and Nuss, 2011). The adults are dark brown or yellow brown with an elongate triangular shape. The male body length is 8.3 mm and has a wing span of 16.6 mm whereas the female has a body length of 10.1 mm and wingspan of 18.5mm (KiYeol *et al*., 1999). The most distinctive features of the species *U. ferrugalis* are that the postmedial line on the forewing has a loop and that the coloration of the discoidal stigmata on the forewing is darker than the ground color of the wing (Mally and Nuss, 2011). The eggs are oval shaped

with a light-gray tint and are laid singly or in small batches beneath the leaves adjacent to the leaf veins. The larva undergoes five instars which vary in size and coloration with the first instar larva being milk white 1.5 - 1.9 mm long and the fifth instar light yellow 13.2 - 14.6 mm long (KiYeol *et al*., 1999). The total larval period ranges between 10-25 days. They also have a pre-pupal stage which is light pink and lasts about 3 days. At the pupation stage, they roll amaranth leaves to provide them with protection. The pupae are yellow/ brown and between 8.2 - 9.7 mm in length. The pupation period ranges between 7-11 days. Adult longevity of *U. ferrugalis* is between 4-15 days and is dependent upon prevailing temperatures (KiYeol *et al*., 1999).

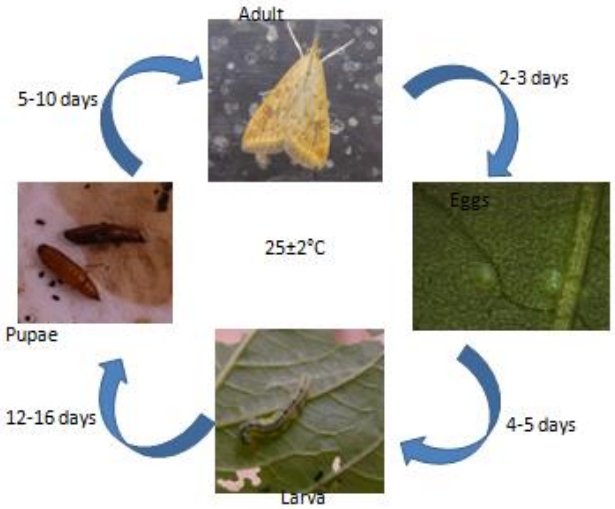

Figure 2.2: Life cycle of *Udea ferrugalis* at 25 ± 2°C and 60 ± 10 % RH

Source: AIV Project, ICIPE, 2014.

2.8 Webworm damage on amaranths

Webworms usually wrap young leaves in a loose web and feed within the protection of the web (Grovida, 2015). Young larvae of leaf webbers feed

only on the epidermis of the leaves skeletonising the tissues. After the second instar, they consume the entire leaf and eventually defoliate the plant (Grovida, 2015). For example, the larvae of *S. recurvalis* skeletonises the foliage leaving only the main leaf veins intact and rolls amaranth leaves into distinctive leaf shelters, form webbing on leaves and leave frass on the leaves (James *et al*., 2010; Grovida, 2015). The webbing and rolling of the leaves deprives the crops of essential physiological processes, mainly photosynthesis, and often leads to death of the plant. Larvae of *U. ferrugalis* glue together the leaves of host plants as they feed between, and they leave dark frass on the leaves. They also cause windowing of the leaves as they feed on them. As they near pupation, they roll the leaves to form a protective covering for their pupae. Larvae of *P. basalis* scrape epidermal and palisade tissues of leaves, web the leaves with silken threads resulting to drying of webbed leaves (Grovida, 2015). *Eretmocera impactella* web leaves with white silken threads and remain hidden in the folds while feeding from the inside.

Plate 1: Damage caused by *Spoladea recurvalis* on amaranths

Source: Kahuthia-Gathu, 2014; AIV Project ICIPE, 2014

2.9 Management of lepidopteran defoliators of amaranth

Pests of Amaranth are difficult to control because of their intrinsic biology and ecology. Control by only chemical or biological means is difficult to achieve and a combination of these and other tactics are often needed. Integrated pest management (IPM) is therefore an approach that can not only reduce pesticide application but also ensure adequate control is attained (Wheeler, 2002). To achieve adequate levels of control, growers also need to use microbial insecticides, cultural control, variety selection, parasitoids and adjusting planting schedules (Zehnder *et al*., 2006; James *et al*., 2007). The conservation and enhancement of populations of natural enemies are cornerstones of successful IPM programmes as they reduce populations of primary pests, limit pest damage and keep secondary pests below the economic threshold.

2.9.1 Cultural and physical/ mechanical control

Cultural practices such as crop rotation, farm sanitation, application of manure and adjusting of planting schedules go a long way in reducing populations of webworms (James *et al*., 2007). The webworms can also be controlled using different types of enhanced traps. Light traps have been used to trap these nocturnal moths which are later killed (Viqar and Ali, 2012). Various traps baited with chemical/floral lures have been used. They include the UniTraps, AgriSense and PontyPridd traps which consist of a white bucket covered by a yellow cone and a green lid and the lures placed within the traps in polypropylene vials with holes in the lids to provide release of volatized

chemicals at different rates (Landolt *et al.,* 2011). In addition, Vaportape® (2,2-Dichlorovinyl dimethyl phosphate) killing agent is incorporated within the trap.

2.9.2 Use of synthetic pesticides

Growers of amaranth mostly rely on synthetic insecticides to control pest that attack the crop (Clarke-Harris *et al*., 2004; Losenge, 2005; Arivudainambi *et al*., 2010). Organochlorides, organophosphates, pyrethroids and carbamates including Lambda-cyhalothrin, Dimethoate, Endosulfan, Abamectin, Chlorpyriphos, Spinosad and Carbaryl are widely used across the world and in Kenya in the management of agricultural pests including pests of amaranth such as *S. recurvalis* and other leaf webbers (Losenge, 2005; Aderolu *et al*., 2013 and Kagali *et al*., 2013).

Application of these insecticides is usually done frequently resulting to unwarranted use of such chemicals (Clarke-Harris *et al*., 2004). Indiscriminate use of these pesticides has thus brought about environmental pollution. Moreover, health concerns due to residue levels in vegetables and economic concerns have often been raised concerning these pesticides, thus the need for development of effective, safe and sustainable IPM approaches (Chahal *et al*., 1997; Losenge, 2005; Arivudainambi *et al*., 2010; Srinivasan, 2012). The use of synthetic insecticides also leads to elimination of natural enemies. Natural enemies foraging for pests within farms sprayed with pesticides often risk coming into contact with the pesticide which may lead to death or cause an indirect effect by impairing the performance of the natural enemy (Srinivasan, 2012).

2.9.3 Botanical pesticides

Botanical pesticides act as a synergistic component in several IPM strategies (Srinivasan, 2012). Evidence of this synergistic action has been reported between neem and microbial pesticides such as nucleopolyhedroviruses (NPVs) against common army worm (Nathan and Kalaivani, 2006), and between neem and entomopathogenic fungi (*B. bassiana*) against common army worm (Mohan *et al.*, 2007). The use of neem extracts from *Azadirachta indica* A. Juss has been reported to reduce the pest populations and also increase the yields of amaranth in Nigeria (Aderolu *et al*., 2013). Neem contains the active ingredient Azadiractin which acts as an antifeedant and a repellent.

Herbal extracts from Karra *Cleistanthus collinus* (Roxb.), Asian spider flower *Cleome viscosa* L., cat's whiskers *Gynandropsis pentaphylla* DC., and Creat *Andrographis paniculata* Nees., have also been used in the management of *S. recurvalis* (Arivudainambi *et al*., 2010). China berry (*Melia azedarach*) has also been reported to enhance the attraction of the parasitoid *Cotesia plutellae* (Hymenoptera: Braconidae) when sprayed to control diamondback moth in cabbage (Srinivasan, 2012).

2.9.4 Microbial control agents

Entomopathogenic fungi (EPF) play a vital role in managing insect pests in humid tropics (Srinivasan, 2012). Several reports have confirmed the effectiveness of entomopathogenic fungi against various pests on vegetables. For instance, ovicidal and pupicidal effects have been reported in some lepidopteran pests (Srinivasan, 2012). *Paecilomyces farinosus* (Holmsk) have also been

shown to infect and kill larvae of leaf webbers like *Psara basalis* Walker and *S. recurvalis* on amaranth (Kuruvilla and Jacob, 1980; James *et al*., 2007). Microbial pesticides based on the soil borne bacterium *Bacillus thuringiensis* (Berliner) (*Bt*) are among the most widely used groups of biopesticides (Srinivasan, 2012). *Bacillus thuringiensis* formulations have also been found to be effective against several lepidopteran pests when used solely or in combination with other biological control agents (Srinivasan, 2012). According to the same author, *Bt* preparations are a promising alternative to conventional insecticides because of their high toxicity to certain pests and their compatibility with IPM strategies due to their narrow host specificity, high amenability to genetic engineering and being harmless to non-target organisms (Tabashnik, 1994). Delplanque and Gruner (1975) reported that *Bt* preparations are also used in the management of leaf webbers and have been effective against *S. recurvalis* and *Herpertogramma bipunctalis* (F) (Lepidoptera; Crambidae).

2.9.5 Plant volatiles for pest management

Certain secondary metabolites in plants act as deterrents for generalist feeders, or attractants for specialist feeders (Srinivasan, 2012). Phenylacetaldehyde (PAA), a flower volatile and attractant for many nectar-seeking moths is the most effective biochemical lure for moths (Landolt *et al*., 2011). In addition, PAA lure was observed to attract both sexes of moths unlike the sex pheromones which normally attract a particular sex (Landolt *et al.,* 2011). By itself, PAA attracts many noctuid species and thus appears to be the main attractant volatile in some flowers. Various field trials with PAA and other floral

lures such as linalool, *cis*-jasmone, methyl-2-methoxybenzoate, isobutanol, β-myrcene (BM) and methyl salicylate (MS), have shown that they were effective in attracting *Spoladea recurvalis*, *Udea ferrugalis, Achyra rantalis* (Guenee), *Udea profundalis* (Packard), *Ostrinia nubilalis* (Hb.) and *Pyrausta orphisalis* (Walker) among other Crambidae (Maini and Burgio, 1990; Landolt *et al.*, 2011; Landolt et al., 2014). Other than Crambidae, these floral lures also attract Noctuidae such as *Chrysodeixis eriosoma* (Doubleday), *Autographa biloba* (Doubleday), *Mythimna unipuncta* (Haworth), *Mamestra brassicae* L., *Agrotis exclamationis* L., *Amphipyra pyramidea* L., (Tóth *et al*., 2010; Landolt *et al.*, 2011).

2.9.6 Parasitoids of leaf webbers

Natural enemies play a very important role in keeping pest population under check and are composed of both predators and parasitoids. A number of parasitoids have been reported to be associated with webworms. These include the egg parasitoids *Trichogramma* species (Hymenoptera: Trichogrammatidae); larval parasitoids including *Apanteles* spp. *Cardiochiles* spp., and *Phanerotoma* spp., *Cotesia marginiventris* Cresson (Hymenoptera: Braconidae), *Campoletis* spp., *Venturia infesta* Cresson (Hymenoptera: Ichneumonidae), and *Prosopodopsis* spp. (Diptera: Tachinidae) have been reported on *S. recurvalis* (James *et al*., 2010; Kedar and Kumaranag, 2013; Grovida, 2015). Bhattacherjee and Ramdas-Menon (1964) reported parasitism of 11.46% on *S. recurvalis* by *Apanteles delhiensis* Mues and Subba-Rao. Narayanan *et al*. (1957) also reported parasitism of up to 62% by *Apanteles* sp. on *S. recurvalis*. In Kenya, certain

natural enemies such as *Dentichasmias busseolae* Heinr (Hymenoptera: Ichneumonidae) and *Iphiulax varipalpis* (Hymenoptera: Braconidae) have been associated with pests of amaranths but information relating the natural enemies to specific pests is still lacking (Kagali *et al*., 2013).

2.9.6.1 Biology of *Apanteles* sp.

Apanteles sp. is a solitary endoparasitoid of lepidopteran larvae. The eggs are laid in the larva of a lepidopteran host by inserting its ovipositor through the caterpillar's integument. The eggs usually float on the body cavity of the host before they hatch into larvae (Cardona and Oatman, 1975). According to the same author, once the eggs hatch, the parasitoid larvae feed on the haemolymph of the host, secondary metabolites and lastly on the vital organs of the host.

The larval period of *Apanteles subandinus* and *A. myeloenta* takes 8-10 days and 7-10 days, while the pupal period takes 4-6 days and 11-19 days respectively (Figure 2.3). Development time depends on temperature and relative humidity (RH) (Cardona and Oatman, 1975; Farahani *et al.*, 2012). Before pupation, the larva cuts its way along the lateral line of the host and exits from the host body and spins a white silken cocoon just next to the killed host (Cardona and Oatman, 1975). The adult emerges from the pupal cocoon and mates after feeding. The females do not have a pre-oviposition period and can even lay eggs without mating though such eggs will only develop into males (Cardona and Oatman, 1975). *Apanteles* sp. has oviposition preference for the second instar larvae though other instars can also be parasitized (Cardona and

Oatman, 1975; Farahani *et al*., 2012; Tunca *et al*., 2014). The adult longevity depends on the diet and environmental conditions.

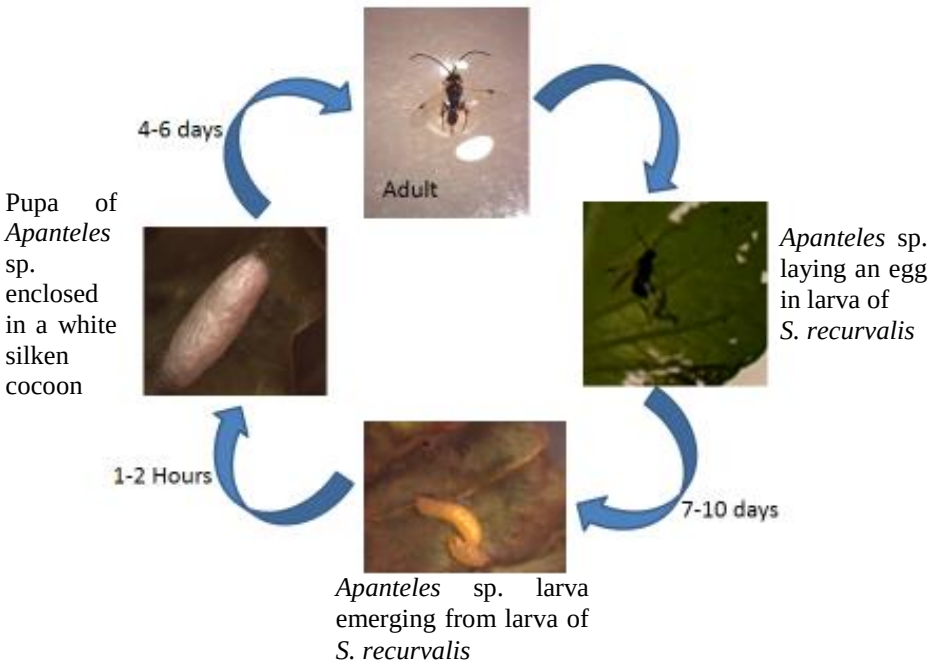

Figure 2.3: Life cycle of *Apanteles* sp. at 25 ± 2^{o}C and 60 ± 10 % RH

Source: AIV Project, ICIPE, 2014.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study sites

Kenyatta University (KU) main campus farm and ICIPE, Duduville campus, were selected for the studies on the pests and natural enemies' incidence and abundance and assessment of the efficacy of Phenylacetaldehyde (PAA) attractant. KU is about 20 km from the Nairobi's city centre along the Nairobi-Thika road highway. It is located at 1° 10′ 51.81″ S, 36° 55′ 38.02″ E, at 1552 m A.S.L (Figure 3.1). The area experiences temperatures of between 12.8°C and 24.6°C, has bimodal rainfall regime, with the long rains falling between March and May and short rains October to December, with an average of 989 mm annually. The ICIPE Duduville campus is about 10 km from the Nairobi city off the Nairobi-Thika road highway. It lies at 1° 13′ 21.44″ S, 36° 53′ 44.37″ E at 1599 m A.S.L (Figure 3.1). It experiences mean temperatures of between 10°C and 24°C. The area has bimodal rainfall with an average of 1000 mm annually. The two sites are within the same agro-ecological zone, mid altitude (Hassan, 1998).

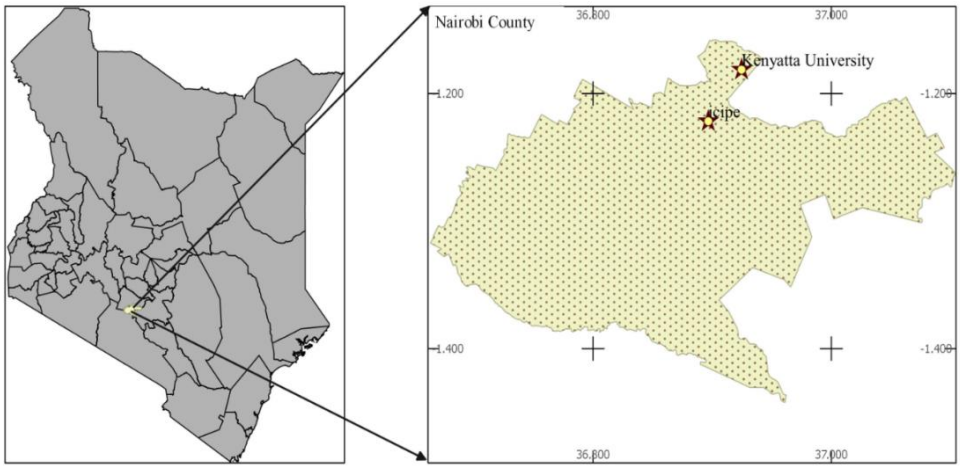

Figure 3.1: Map of Kenya and Nairobi County showing the location of the study area

Source: AIV Project ICIPE, 2014

3.2 General methodology

A Randomized Complete Block Design (RCBD) with six replicates per treatment was used for the field trials. Each block was measuring 2 m by 16.6 m. At each site, two experimental plots measuring 16.6 m by 14 m and 100 m – 150 m apart were set up. Each plot was laid out into 18 beds of 5 m long and 2 m wide with spacing of 0.8 m along beds and 0.4 m across the beds. Three lines of amaranth: Var. Abuku amaranth 1 (Abuk1), Var. Abuku amaranth 2 (Abuk2) (vegetable amaranths) and Var. Abuku amaranth 8 (Abuk8) (vegetable and grain amaranth) were randomly assigned to 18 beds in each experimental plot, and every amaranth line was replicated six times within each plot (Appendix 1).

The amaranth seeds were first sown in a nursery and 3 weeks later transplanted to the beds. Transplanting onto the beds was done at a spacing of 40 cm between rows and 25 cm within row to give 100 plants per bed. Cattle

manure was applied to the soil at a rate of 5 t/ha before transplanting during both cropping seasons. Watering was done daily when the crops were in the nursery and for the first two weeks after transplanting and afterwards at intervals of two days. Weeding was done using a hand hoe every four weeks during both planting seasons. No insecticides or fungicides were used during the growing seasons. The experiments were conducted during the cold dry season between July and September, 2014 (dry season) and the short rainy season between November, 2014 and January, 2015 (wet season).

3.3 Assessing the seasonal abundance of lepidopteran defoliators attacking amaranths at the field

Scouting for pests and natural enemies was done once every two weeks from the second week after transplanting until harvest. Sampling was conducted using the quadrant technique by dividing each bed into four quadrants. Ten plants were randomly sampled per quadrant from each experimental unit (bed) using both destructive and non-destructive sampling methods. Destructive sampling involved plucking leaves that contained eggs and larvae folded within the leaves of the randomly selected plants. Non-destructive sampling involved the use of beating trays in which the plants were shaken and the insects allowed to fall on a tray and by hand-picking the insect pests. The specimens that were collected during the sampling process included eggs, larvae and adults of the pests.

The collected plant parts, eggs, larvae and adults were placed in labelled plastic lunch boxes (15 cm × 7 cm × 5 cm) lined with paper towel to absorb

excess moisture and the lid fixed with fine netting material for ventilation and taken to the laboratory for processing. The immature stages of the insect samples were incubated in the laboratory at 25 ± 2°C, 50-70% RH and photoperiod of 12:12 hours (Light: Darkness) until adult emergence. During the incubation period, the larvae were fed daily on fresh amaranth leaves until pupation. This also allowed for the development of any associated parasitoids until their emergence. Data on developmental stage, part of the plant affected, and insect numbers were recorded on a datasheet from which abundance of pests was calculated and further statistical analysis conducted.

All adult insects were identified and specimens sent to the National Museums of Kenya (NMK) for confirmation.

3.4 Assessing the effect of Phenylacetaldehyde as an attractant of lepidopteran defoliators of amaranth

Three delta traps made from strong corrugated plastic applied with ultra-violet (UV) resistant coating supplied by Russell IPM (Russell IPM, 2010) were assembled and set up in each of the plots. The traps were separated by a distance of 7.5 m and suspended at a height of 1 m above the ground level. A sticky insert, to trap and kill the attracted moths was placed at the base of the traps. In one plot at each site, 4 ml of PAA lure soaked in cotton plugs was incorporated at the centre of the sticky insert to provide slow release of the volatile chemical attractant. The cotton plug soaked in PAA was replaced every four weeks while the sticky insert was replaced bi-weekly. The second plot at each site which acted as a control had the same design of delta traps but no PAA lure was incorporated

in the traps. The insects trapped in both PAA incorporated and control traps were counted and recorded every two weeks during which the sticky insert was replaced.

Plate 2: Delta trap hung in one of the experimental plots

Source: AIV Project ICIPE, 2014

3.5 Effect of amaranth lines on the abundance of lepidopteran defoliators and their associated parasitoids

The three amaranth lines, Abuk1, Abuk2 and Abuk8 were sown in nurseries and transplanted into beds as described in section 3.2. Scouting for pests was done on the three amaranth lines every two weeks using the same procedure described in 3.3. From each of the three amaranth lines, the number of lepidopteran pests collected was recorded and the pests transported to the laboratory for incubation and later identification.

3.6 Assessing the incidence and levels of damage caused by lepidopteran defoliators on amaranths

The incidence of damage by lepidopterans either leaf worms or webworms on the leaves was assessed visually by observing their webbing, scrapping, frass deposits and windowing characteristics on the leaves. The levels of damage on the leaves were assessed visually in the field and scored using a modified assessment scale described by Gilbert and Gregoire (2003) where scale 0= 0%; 1= 0-5%; 2= 6-25%; 3= 26-50%; 4= 51-75% and 5= 76-100% of damage.

3.7 Evaluation of the acceptability and suitability of *Spoladea recurvalis* and *Udea ferrugalis* to *Apanteles hemara*

Laboratory experiments on acceptability and suitability of *S. recurvalis* and *U. ferrugalis* to *Apanteles hemara* were conducted at ICIPE, Duduville campus insectaries. Both acceptability and suitability assessment studies were conducted at 25 ± 2°C, 60 ± 10% RH and 12:12 L: D photoperiod.

3.7.1 Host plants

Amaranthus dubius, a vegetable variety of amaranth, was used in the laboratory experiments at the International Centre of Insect Physiology and Ecology (ICIPE), Nairobi, Kenya. Selection of this variety was based on its widespread consumption in Kenya, rapid growth rate and broad leaves it produces. The seedlings were raised in trays in the greenhouse from seeds obtained from Simlaw seed company, Nairobi, Kenya. A mixture of red soil and

compost (4:1) was used as the medium for growth. They were then transplanted into 10 cm diameter plastic pots (628 cm^3) two weeks after germination and watered daily. The plants were then used for experiments 6-7 weeks after transplanting.

3.7.2 Leaf webber colonies

Colonies of *S. recurvalis* and *U. ferrugalis* were established and maintained in the insectary at ICIPE on *A. dubius*. The adults and larvae of *S. recurvalis* and *U. ferrugalis* were originally collected from a field survey on amaranth lepidopteran pests in Narok county, Transmara (0° 35’ 32.892”N 3° 0’ 49.14”E) and Yatta, Machakos County (01° 08.295’S 037° 25.892’ E) in 2014. The moths were placed in transparent perspex rearing cages (40 cm × 40 cm × 45 cm) with a sleeve and a netting material at the back for ventilation. The moths were fed on 10% honey solution soaked in cotton wool and provided with potted amaranth plants for oviposition.

The plants were removed after every 24 hours and placed in separate holding cages (50 cm ×50 cm × 60 cm) made from wooden material with ventilations on the sides and at the top for the eggs to hatch. Hatched larvae were left to feed on the live plants for three days then placed into plastic lunch boxes (15 cm × 7 cm × 5 cm) lined with paper towel to absorb excess moisture and fine netting material on the lid for ventilation where they were supplied with fresh amaranth leaves as food until they pupated. The pupae were harvested and placed in individual glass vials until the adult emergence.

3.7.3 *Apanteles hemara* colony

A colony of the parasitoid *Apanteles hemara* was established at the ICIPE insectary from pupal samples collected during a survey conducted in Yatta, Machakos County (01° 07.878'S 037° 33.274'E) in 2014. The emerged adults were placed in a perspex cage (40 cm × 40 cm × 45 cm) with a sleeve on one side and fed on undiluted honey smeared on strips of paper. Potted plants containing three days old larvae of *S. recurvalis* or *U. ferrugalis* were then introduced into the cage for the parasitoids to oviposit. After 24 hours, the exposed larvae were removed and placed in ventilated plastic lunch boxes (15 cm × 7 cm × 5 cm) lined with paper towel to absorb excess moisture. Fresh amaranth leaves were added into the lunch boxes as required until pupation. The parasitoid pupae were harvested, put in clean petri dishes and placed in a perspex cage for adult emergence. These parasitoids were reared until the fifth generation to ensure adaptability before they were used for experiments.

3.7.4 Host acceptability

One potted amaranth plant (6-7 weeks old) infested with five second instar (3 days old) larvae of *S. recurvalis* or *U. ferrugalis* for 24 hours were exposed separately to a single two days old mated female of *Apanteles hemara* reared on either *S. recurvalis* or *U. ferrugalis* from the stock culture. The plant was placed in a clear perspex cage (20cm × 20cm × 30cm) with a netting material at the top for ventilation. Acceptance of *A. hemara* was determined by its searching ability, occurrence of oviposition attempts and successful ovipositions which were observed and recorded during the two hours exposure regime.

Searching ability was determined as the time (minutes) taken by the parasitoid to locate the host. Any attempt made by the parasitoid to oviposit on its host was recorded as oviposition attempt. Two hours after the exposure, the larvae were removed and incubated in a lunch box where fresh amaranth leaves were supplied daily until host and parasitoid pupation. Successful ovipositions were determined by the occurrence of at least one parasitoid pupa from each exposure. This experiment was repeated 20 times with each host species.

3.7.5 Host suitability

Five potted amaranth plants were infested with 50 second instar larvae of *S. recurvalis* or *U. ferrugalis* and left to feed for 24 hours in separate perspex cages (40cm × 40cm × 45cm). Two days old of five mated females and two males of *Apanteles hemara* reared on *S. recurvalis* were released in each of the cages and allowed to oviposit in the larvae of *S. recurvalis* or *U. ferrugalis* for 24 hours. The larvae were then removed from the cages after 24 hours of exposure and incubated in lunch boxes where they were supplied with fresh amaranth leaves and monitored daily until parasitoid or host pupation. A control of each host was set up with five potted plants infested with 50 larvae but not exposed to parasitoid to assess natural mortality of both *S. recurvalis* and *U. ferrugalis.* This experiment was repeated 10 times with each host species.

The data parameters to assess host suitability were drawn from Chabi-Olaye *et al* (2013) and included: number of *A. hemara* pupae, number of parasitoids emerging from incubated larvae (successful parasitism), number of adult parasitoids that emerge, development time of the parasitoid, F1 sex-ratio

and lengths of adult hind tibia and forewing (as indices of body size) of 20 randomly chosen parasitoids of each sex. *Spoladea recurvalis* and *Udea ferrugalis* larvae that died before pupation by either parasitoid presence or host natural mortality were inspected visually for signs of parasitism including retarded growth, color changing from green to cream-white and reduced feeding rate before death and their number recorded. This was then used to correct the actual parasitism rates.

3.8 Data analyses

Data on seasonal abundance of leaf webbers and natural enemies, and the number of moths attracted by PAA were compared using Chi-Square goodness of fit test. Effect of amaranth lines and phenological stages of the crop on abundance of leaf webbers and other lepidopteran defoliators, as well as searching time and oviposition attempts were determined using one-way Analysis of Variance (ANOVA) in general linear model (GLM). Incidence and levels of damage by leaf webbers were analysed using Logistic and ordered logistic regression models respectively in GLM.

Parasitism was calculated as the percentage of the corrected number of parasitized larvae divided by the total number of larvae exposed. Pupal mortality was calculated as the difference between the total number of pupae and the total number of emerged adults divided by the total pupae x 100.

Successful oviposition, development time of parasitoid, number of pupae and adults of *Apanteles hemara,* and F1 sex ratios when exposed to the two hosts

were compared using Chi-square. Parasitism rates and mortalities of larvae and pupae of the hosts and parasitoid, fore wing and hind tibia lengths of parasitoids from each host were compared using independent samples t-test. Where significant differences occurred, the means were separated using Tukey's test. Abbott formula was used to correct mortality in both hosts (Abbott, 1925). The level of significance was set at $P<0.05$. All data were analysed in R version 3.0.2 statistical software (R Development Core Team, 2013).

CHAPTER 4: RESULTS

4.1 Assessing the seasonal abundance of lepidopteran defoliators attacking amaranths and their associated parasitoids at the field

Lepidopteran defoliators were recovered from amaranth crops during both dry and wet seasons with no significant difference in their abundance during the two seasons (χ^2 = 0.20; P = 0.659) (Table 4.1). The abundance of leaf webbers (χ^2 = 0.38, P = 0.537) and leaf worms (χ^2 = 0.0, P = 1.0) also showed no significant difference during the two seasons. Parasitism was observed in some of the lepidopteran larvae during both seasons with the number of parasitoids recovered from both seasons showing no significant differences (χ^2 = 3.0; P = 0.083).

Table 4.1: Mean (± SE) of leaf webbers, leaf worms and parasitoids during the wet and dry seasons

	Effect of season			
	All lepidopteran defoliators	Parasitoids	Leaf webbers	Leaf worms
Dry season	0.61 ± 0.17a	0.14 ± 0.09a	0.33 ± 0.09a	0.28 ± 0.11a
Wet season	0.53 ± 0.19a	0.03 ± 0.03a	0.25 ± 0.09a	0.28 ± 0.12a
χ^2	0.20	3.0	0.38	0.0
P	0.659	0.083	0.537	1.0

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

Leaf webbers mean numbers did not differ significantly between the two sites (χ^2 = 0.38; P = 0.537) while leaf worms were more abundant at ICIPE than

KU (χ^2 = 8.1; *P* = 0.004). The number of parasitoids at either of the study sites was not significantly different (χ^2 = 0.33; *P* = 0.564) (Table 4.2).

Table 4.2: Number (Mean ± SE) of leaf webbers, leafworms and parasitoids at ICIPE and KU

	Effect of sites			
	ICIPE	KU	χ^2	*P*
Leaf webbers	0.33 ± 0.10a	0.25 ± 0.08a	0.38	0.537
Leaf worms	0.42 ± 0.15a	0.14 ± 0.06b	8.10	0.004
Parasitoids	0.11 ± 0.07a	0.06 ± 0.04a	0.33	0.564

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

At KU, there was no significant difference in the abundance of leaf webbers, leaf worms and parasitoids between the wet and the dry seasons (Table 4.3). Similarly there was no significant difference in the abundance of leafwebbers, leafworms and parasitoids between the wet and dry seasons at ICIPE (Table 4.4)

Table 4.3: Abundance of leafwebbers, leaf worms and parasitoids at KU

	Parasitoids	Leaf webbers	Leaf worms
Dry season	0.06 ± 0.1a	0.33 ± 0.1a	0.11 ± 0.1a
Wet season	0.0 ± 0.0a	0.17 ± 0.1a	0.17 ± 0.1a
χ^2	0.0	0.89	0.0
P	1.0	0.346	1.0

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

Table 4.4: Abundance of leafwebbers, leaf worms and parasitoids at ICIPE

	Parasitoids	Leaf webbers	Leaf worms
Dry season	0.22 ± 0.2a	0.33 ± 0.1a	0.44 ± 0.2a
Wet season	0.06 ± 0.1a	0.33 ± 0.2a	0.39 ± 0.2a
χ^2	1.6	0.0	0.0
p-value	0.206	1.0	1.0

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

Total field parasitism of 9.5% on leaf webbers caused by *Leurus* sp. and a gregarious *Apanteles* sp. and 20% on leaf worms caused by *Cotesia* sp. and an Ichneumonidae was recorded during the two seasons (Table 4.5). The total field parasitism on all lepidopteran defoliators was 14.6%.

Table 4.5: Field parasitism (%) on leaf webbers and leaf worms caused by different parasitoids.

Pests	% collected (n = 42)	Parasitoids	% recovered (n = 6)	% Parasitism
Leaf webbers	51.22	*Leurus* sp.	16.67	9.5
		Apanteles sp.	16.67	
Leaf worms	48.78	*Cotesia* sp.	50.0	20
		Ichneumonidae	16.67	
Total				14.6

4.2 Investigating the potential of Phenylacetaldehyde as attractant of amaranth lepidopteran defoliators attacking amaranth crops

There were no significant differences in the number of leaf webber larvae in the plots which had PAA treatment compared to the control plots at both ICIPE ($\chi^2 = 1.5$; $P = 0.221$) and KU ($\chi^2 = 3.56$; $P = 0.059$) (Tables 4.6 and Table 4.7). The number of leaf worms also did not differ significantly between the PAA treatment and the control at both ICIPE ($\chi^2 = 0.53$; $P = 0.465$) and KU ($\chi^2 = 0$; $P = 1$). Similarly, the number of parasitoids recovered from either ICIPE ($\chi^2 = 1.6$; $P = 0.206$) or KU ($\chi^2 = 0$; $P = 1$) did not differ significantly between the PAA and the control plots.

Table 4.6: Number (Mean ± SE) of leaf webbers, leafworms and parasitoids in the PAA and control plots at ICIPE

Treatment	Leaf webbers	Leaf worms	Parasitoids
PAA	0.44 ± 0.17a	0.5 ± 0.25a	0.06 ± 0.06a
Control	0.22 ± 0.10a	0.33 ± 0.18a	0.22 ± 0.17a
χ^2	1.5	0.53	1.6
p-value	0.221	0.465	0.206

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

Table 4.7: Number (Mean ± SE) of leaf webbers, leafworms and parasitoids in the PAA and control plots at KU

Treatment	Leaf webbers	Leaf worms	Parasitoids
PAA	0.39 ± 0.14a	0.17 ± 0.09a	0 ± 0a
Control	0.11 ± 0.08a	0.11 ± 0.08a	0.06 ± 0.06a
χ^2	3.56	0	0
p-value	0.059	1	1

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$

There were significant differences in the number of moths caught in the traps during the two seasons at ICIPE ($\chi^2 = 35.82$; $P < 0.001$) and KU ($\chi^2 = 22.02$; $P < 0.001$) with a higher number of moths being trapped during the wet season (Table 4.8 and Table 4.9). The PAA incorporated traps attracted significantly higher number of moths during the wet season than the dry season at both ICIPE ($\chi^2 = 40.65$; $P < 0.001$) and KU ($\chi^2 = 46.51$; $P < 0.001$). Whereas there was no significant difference ($\chi^2 = 0.07$; $P = 0.789$) (Table 4.8) in the number of moths caught in the control traps at ICIPE between the wet and dry seasons, the control traps at KU attracted significantly higher number of moths during the dry season than the wet season ($\chi^2 = 17.29$; $P < 0.001$) (Table 4.9).

The PAA incorporated traps attracted significantly higher number of moths than the control traps during both dry ($\chi^2 = 19.76$; $P < 0.001$) and wet ($\chi^2 = 98.84$; $P < 0.001$) seasons at ICIPE (Table 4.8). At KU, the number of moths in the PAA and control traps did not differ significantly during the dry season ($\chi^2 = 3.66$; $P = 0.056$). However, during the wet season, PAA traps had significantly higher number of moths than control traps ($\chi^2 = 128.26$; $P < 0.001$)

(Table 4.9). Out of 214 moths caught in the traps during the two seasons in the PAA traps, one moth of *S. recurvalis* was recovered which represents 0.005%.

Table 4.8: Number **(**Mean± SE) of moths caught in the PAA and control traps during the dry and wet seasons at ICIPE.

	Traps Combined	PAA traps	Control traps	χ^2	*p*-value
Dry season	2.72 ± 0.77a	4.0 ± 1.33aA	1.44 ± 0.6aB	19.76	< 0.001
Wet season	5.67 ± 1.28b	9.67 ± 1.51bA	1.67 ± 0.82aB	98.84	< 0.001
χ^2	35.82	40.65	0.07		
p-value	< 0.001	< 0.001	0.789		

Means followed by the same lower case letters in the same column and same upper case in the same row do not differ significantly at $P < 0.05$

Table 4.9: Number **(**Mean± SE) of moths caught in the PAA and control traps during the dry and wet seasons at KU

	Traps Combined	PAA traps	Control traps	χ^2	*p*-value
Dry season	1.94 ± 0.53a	2.44 ± 0.73aA	1.44 ± 0.77aA	3.66	0.056
Wet season	3.89 ± 1.01b	7.67 ± 0.88bA	0.11 ± 0.11aB	128.26	< 0.001
χ^2	22.02	46.51	17.29		
p-value	< 0.001	< 0.001	< 0.001		

Means followed by the same lower case letters in the same column and same upper case in the same row do not differ significantly at $P < 0.05$

The number of moths attracted to the PAA traps did not differ significantly across the growth stages of the crop from the vegetative phase to the fruiting stage during both dry ($F_{2,6}$ = 0.72, P = 0.526) and wet ($F_{2,6}$ = 4.46, P = 0.065) seasons at ICIPE (Table 4.10). Similarly, there was no significant difference in the number of moths caught in the PAA traps during the dry ($F_{2,6}$ = 0.58, P = 0.587) and wet ($F_{2,6}$ = 0.04, P = 0.965) seasons at KU (Table 4.11). The control traps however showed significant difference in both dry ($F_{2,6}$ = 20.6, P = 0.002) and wet ($F_{2,6}$ = 6.4, P = 0.033) seasons at ICIPE (Table 4.10) with the fruiting stage recording higher number of moths than either the vegetative or the flowering stages in the dry season. At KU, the control traps did not show significant difference in the number of moths across the phenological stages during both dry ($F_{2,6}$ = 3.55, P = 0.096) and wet ($F_{2,6}$ = 1.0, P = 0.442) seasons (Table 4.11).

Table 4.10: The mean (± SE) of moths caught in the PAA and control traps at ICIPE during the dry and wet seasons across the phenological stages of amaranth

	Dry season		Wet season	
	PAA	Control plots	PAA plot	Control plot
Vegetative	2.67 ± 2.6a	0.0 ± 0.0a	14.0 ± 2.3a	4.33 ± 1.5b
Flowering	6.33 ± 2.4a	0.67 ± 0.3a	6.0 ± 2.3a	0.67 ± 0.7ab
Fruiting phase	3.0 ± 2.1a	3.67 ± 0.9b	9.0 ± 0.6a	0.0 ± 0.0a
$F_{2,6}$	0.72	20.6	4.5	6.4
p-value	0.526	0.002	0.065	0.033

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

Table 4.11: The mean (± SE) of moths caught in the PAA and control traps at KU during the dry and wet seasons across the phenological stages of amaranth

	Dry season		Wet season	
	PAA	Control plots	PAA plot	Control plot
Vegetative	1.33 ± 1.3a	0.0 ± 0.0a	7.67 ± 1.7a	0.0 ± 0.0a
Flowering	2.67 ± 0.7a	0.67 ± 0.3a	7.33 ± 1.5a	0.0 ± 0.0a
Fruiting phase	3.33 ± 1.8a	3.67 ± 1.8a	8.0 ± 2.1a	0.33 ± 0.3a
$F_{2,6}$	0.58	3.55	0.04	1.0
p-value	0.587	0.096	0.965	0.422

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

4.3 Determining the effects of selected amaranth lines on the abundance of lepidopteran defoliators

During the dry season, Abuk8 had significantly higher number of leafwebbers than Abuk2 but did not differ significantly from Abuk1 ($F_{2,15} = 4.77$; $P = 0.025$) at KU (Table 4.12). During the same season at ICIPE, Abuk1 had significantly higher number of leaf webbers than Abuk2 but did not differ from Abuk8 ($F_{2,15} = 3.75$; $P = 0.048$) (Table 4.13). There was no significant difference in the number of leaf worms across the three lines of amaranth at both sites and during both dry and wet seasons (Table 4.12 and 4.13). The number of leaf webbers did not differ significantly across the three lines of amaranth during the wet season at KU ($F_{2,15} = 1.15$; $P = 0.342$) and ICIPE ($F_{2,15} = 3.09$; $P = 0.075$) (Table 4.12 and 4.13).

Table 4.12: Abundance (Mean ± SE) of leaf webbers and leafworms across the three lines of amaranth at KU

	Dry season		Wet season	
Amaranth line	Leaf webbers	Leaf worms	Leaf webbers	Leaf worms
Abuk1	0.17 ± 0.2ab	0.0 ± 0.0a	0.17 ± 0.2a	0.0 ± 0.0a
Abuk2	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.17 ± 0.2a
Abuk8	0.83 ± 0.3b	0.33 ± 0.2a	0.33 ± 0.2a	0.33 ± 0.2a
$F_{2,6}$	4.77	2.5	1.15	1.15
p-value	0.025	0.116	0.342	0.342

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

Table 4.13: Abundance (Mean ± SE) of leaf webbers and leafworms across the three lines of amaranth at ICIPE

	Dry season		Wet season	
Amaranth line	Leaf webbers	Leaf worms	Leaf webbers	Leaf worms
Abuk1	0.67 ± 0.2b	1.0 ± 0.5a	0.17 ± 0.2a	0.17 ± 0.2a
Abuk2	0.0 ± 0.0a	0.0 ± 0.0a	0.0 ± 0.0a	0.17 ± 0.2a
Abuk8	0.33 ± 0.2ab	0.33 ± 0.2a	0.83 ± 0.4a	0.83 ± 0.7a
$F_{2,15}$	3.75	2.5	3.09	0.92
p-value	0.048	0.116	0.075	0.42

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

In both the PAA and control plots at KU, there was no significant difference in the abundance of lepidopteran defoliators across the three lines of amaranth in either the wet or dry seasons (Table 4.14). Similar observations were

made at ICIPE where no significant difference was recorded in the number on lepidopteran defoliators in the PAA and control plots during the wet and dry seasons (Table 4.15).

Table 4.14: Abundance (Mean ± SE) of lepidopteran defoliators in the PAA and control plots across the three lines of amaranth at KU.

	Dry season		Wet season	
Amaranth line	PAA	Control	PAA	Control
Abuk1	0.33 ± 0.3a	0.0 ± 0.0a	0.33 ± 0.3a	0.0 ± 0.0a
Abuk2	0.0 ± 0.0a	0.0 ± 0.0a	0.33 ± 0.3a	0.0 ± 0.0a
Abuk8	1.33 ± 0.9a	1.0 ± 0.6a	1.0 ± 0.6a	0.33 ± 0.3a
$F_{2,15}$	1.63	3.0	0.8	1.0
p-value	0.273	0.125	0.492	0.422

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

Table 4.15: Abundance (Mean ± SE) of lepidopteran defoliators in the PAA and control plots across the three lines of amaranth at ICIPE

	Dry season		Wet season	
Amaranth line	PAA	Control	PAA	Control
Abuk1	1.67 ± 0.7a	1.67 ± 1.2a	0.33 ± 0.3a	0.33 ± 0.3a
Abuk2	0.0 ± 0.0a	0.0 ± 0.0a	0.33 ± 0.3a	0.0 ± 0.0a
Abuk8	0.33 ± 0.3a	1.0 ± 0.0a	3.0 ± 1.7a	0.33 ± 0.3a
$F_{2,15}$	4.2	1.46	2.21	0.5
p-value	0.072	0.304	0.191	0.63

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test)

4.4 Assessing the effect of seasonality and amaranth lines on the incidence and levels of damage by amaranth lepidopteran defoliators

Higher incidences of damage by lepidopterans was recorded during the wet season than dry season (odds ratio (OR) = 1.41; P = 0.001). During both seasons, there were no significant differences in the incidences of damage at both ICIPE (OR = 1.20; P = 0.232) and KU (OR = 0.81; P = 0.104) (Table 4.16). The PAA and the control plots had no significant differences in the incidences of damage during the dry season (OR = 0.91; P = 0.55) whereas the control plots had significantly higher incidences of damage than the PAA plots during the wet season (OR = 1.51; P = 0.002). During the dry season, Abuk8 amaranth had significantly higher incidences of damage than either Abuk2 (OR = 2.64; P < 0.001) or Abuk1 (OR = 1.51; P = 0.016) while Abuk1 amaranth had higher incidences of damage than Abuk2 (OR = 0.57; P = 0.008). Similarly, during the wet season, Abuk8 had significantly higher incidences of damage than either Abuk2 (OR = 2.64; P < 0.001) or Abuk1 (OR = 1.47; P = 0.009) whereas Abuk1 had higher incidences of damage than Abuk2 (OR = 0.55; P = 0.001) (Table 4.16) (Appendix 2).

Table 4.16: Incidence of damage by lepidopteran defoliators between seasons, sites, plots and amaranth lines

Incidence of damage by amaranth lepidopteran defoliators						
Factors	Odds ratio	Confidence Interval	*P*	Odds ratio	Confidence Interval	*P*
Wet vs. Dry Season	1.41	1.16-1.71	0.001*	-	-	-
	Dry season			**wet season**		
KU vs. ICIPE	1.2	0.89-1.61	0.232	0.81	0.62-1.04	0.104
Control vs. PAA	0.91	0.68-1.23	0.55	1.52	1.18-1.98	0.002*
Abuk2 vs. Abuk1	0.57	0.37-0.86	0.008*	0.55	0.39-0.79	0.001*
Abuk8 vs. Abuk1	1.51	1.08-2.11	0.016*	1.47	1.10-1.97	0.009*
Abuk8 vs. Abuk2	2.64	1.8-3.96	< 0.001*	2.64	1.89-3.74	< 0.001*

* Incidence of damage is significantly difference at $P < 0.05$

Severity of damage by lepidopteran defoliators was greater during the wet season compared to the dry season (OR = 3.81; $P = 0.003$). Levels of damage however did not differ significantly between the two sites during both dry (OR = 1.18; $P = 0.773$) and wet (OR = 0.66; $P = 0.439$) seasons (Table 4.17). Similarly, lepidopteran defoliators did not show significant difference in their levels of damage between the PAA and control plots during both dry (OR = 1.16; $P= 0.792$) and wet (OR = 1.15; $P = 0.796$) seasons (Table 4.17). Levels of damage did not differ significantly between amaranth lines Abuk8 and Abuk1 during the dry (OR = 2.35; P = 0.29) and wet (OR = 2.92; P = 0.102) seasons and between Abuk1 and Abuk2 during the dry (OR = 0.23; $P = 0.06$) and wet (OR = 0.4; $P = 0.252$) seasons. However, Abuk8 had significantly higher levels of damage compared to Abuk2 in both dry (OR = 10.42; $P = 0.007$) and wet (OR = 7.2; $P = 0.009$) seasons (Table 4.17) (Appendix 3).

Table 4.17: Levels of damage by lepidopteran defoliators between seasons, sites, plots and amaranth lines

Level of damage lepidopteran defoliators						
Factors	Odds ratio	Confidence Interval	*P*	Odds ratio	Confidence Interval	*P*
Wet vs. Dry Season	3.81	1.65-9.63	0.003*	-	-	-
	Dry season			**Wet season**		
KU vs. ICIPE	1.18	0.38-3.76	0.773	0.66	0.22-1.88	0.439
Control vs. PAA	1.16	0.37-3.71	0.792	1.15	0.40-3.32	0.796
Abuk2 vs. Abuk1	0.23	0.04-0.98	0.060	0.4	0.08-1.81	0.252
Abuk8 vs. Abuk1	2.35	0.51-13.08	0.290	2.92	0.84-11.20	0.102
Abuk8 vs. Abuk2	10.42	0.51-13.08	0.007*	7.2	0.84-11.20	0.009*

* Levels of damage are significantly different at $P < 0.05$.

4.5 Evaluation of the acceptability and suitability of *Spoladea recurvalis* and *Udea ferrugalis* to the endoparasitoid *Apanteles hemara*

There were no significant differences in the searching time of the parasitoid regardless of the rearing host (when reared on *S. recurvalis* or *U. ferrugalis*) and the testing host (when tested on *S. recurvalis* or *U. ferrugalis*) ($P = 0.262$) (Table 4.18). Same trend was observed for the number of oviposition attempts regardless of the rearing and testing hosts and ranged between 2.2 – 3.4 attempts within a period of 40.8 – 66.3 minutes ($P = 0.722$) .

Table 4.18: Searching time, oviposition attempts and time to make the 2nd oviposition (Mean ± SE) of *Apanteles hemara*

Variable		Searching time (min)	Oviposition attempts	Time to make 2nd Oviposition (min)
Rearing host	Test host			
S. recurvalis	*S. recurvalis*	66.3 ± 9.2a	3.1 ± 0.5a	13.8 ± 5.2a
U. ferrugalis	*S. recurvalis*	40.8 ± 8.8a	2.9 ± 0.6a	11.5 ± 4.6a
S. recurvalis	*U. ferrugalis*	62.1 ± 12.3a	2.2 ± 0.5a	10.5 ± 4.5a
U. ferrugalis	*U. ferrugalis*	53.6 ± 10.2a	3.4 ± 0.8a	10.3 ± 3.5a
		$F_{3,67}$= 1.36 P = 0.262	$F_{3,67}$= 0.44 P = 0.722	$F_{3,67}$= 0.13 P = 0.941

Mean followed by the same letter in the same column do not differ significantly at $P < 0.05$ (Tukey's test).

Successful oviposition was significantly higher ($\chi^2 = 5.57$; $P = 0.018$) when *Apanteles hemara* was reared on *S. recurvalis* and exposed to the same host than when reared on *U. ferrugalis* and exposed to *S. recurvalis*. Rearing host did not however significantly affect successful oviposition ($\chi^2 = 0.08$; $P = 0.782$) when tested on *U. ferrugalis* (Table 4.19). There were however no significant effects brought about by the testing host on successful oviposition when *Apanteles hemara* was tested on *S. recurvalis* ($\chi^2 = 0.07$; $P = 0.796$) or *U. ferrugalis* ($\chi^2 = 1.68$; $P = 0.194$).

Table 4.19: Successful oviposition (%) by *Apanteles hemara* when reared and tested on *Spoladea recurvalis* or *Udea ferrugalis*

		Rearing hosts			
		S. recurvalis	*U. ferrugalis*	χ^2	*P*
Testing hosts	*S. recurvalis*	80aA	35bA	5.57	0.018
	U. ferrugalis	70aA	60aA	0.08	0.782
	χ^2	0.07	1.68		
	P	0.796	0.194		

Percentages within the same column followed by the same upper case letter and % followed by same lower case letter across a row do not differ significantly at $P < 0.05$

The time taken by *Apanteles hemara* to make the first oviposition attempt was significantly longer ($t = 2.67$; $P = 0.015$) when the parasitoid was reared and tested on *S. recurvalis* than when reared on *U. ferrugalis* and tested on *S. recurvalis* . There was no significant difference in the time taken to make the first oviposition attempt when the rearing host was *U. ferrugalis* ($t = 1.31$; $P = 0.221$) (Figure 4.1). Irrespective of the rearing host, the testing host did not have any significant effect on the time taken to make the first oviposition. The time taken to make the second oviposition attempt was however not affected by either the rearing host or the testing host ($F_{3,67} = 0.13$; $P = 0.941$) and was significantly shorter than the time taken to make the first oviposition ($t = 3.48$; $P = 0.001$) (Figure 4.1 and Table 4.18).

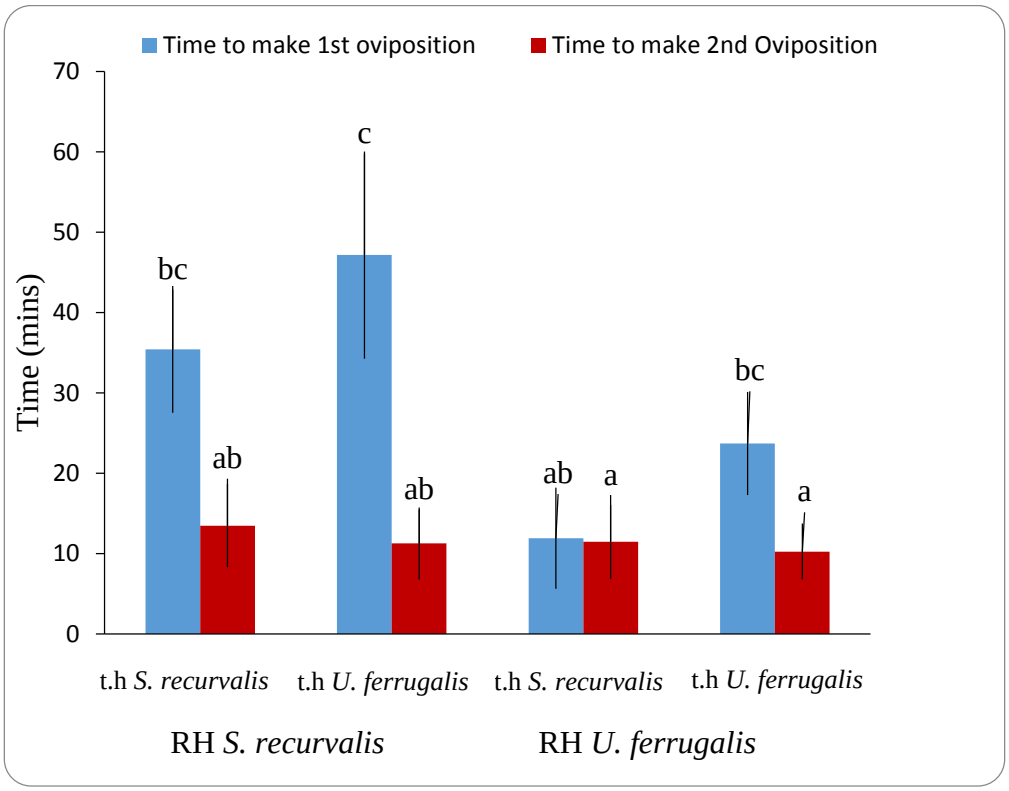

Figure 4.1: Time taken by *Apanteles hemara* to make the first and second ovipositions when rearing and testing hosts were *S. recurvalis* or *U. ferrugalis*. (t.h - Testing host, RH- Rearing host)

The number of *Apanteles hemara* pupae obtained from *S. recurvalis* was significantly higher than those obtained from *U. ferrugalis* (χ^2 = 15.26; P < 0.001) (Table 4.20 and Figure 4.2). There was also significant difference in the number of *Apanteles* sp. pupae that gave rise to adults (viable pupae) (χ^2 = 80.64; P < 0.001) with *U. ferrugalis* producing more viable pupae (75.85%) than *S. recurvalis* (36.54%) (Figure 4.2). The parasitoid's pupal mortality was therefore higher in *S. recurvalis* (64.51%) than in *U. ferrugalis* (25.51%) (t = 5.78; P < 0.001). The number of adults obtained from *U. ferrugalis* were however significantly higher than those obtained from *S. recurvalis* (χ^2 = 32; P < 0.001).

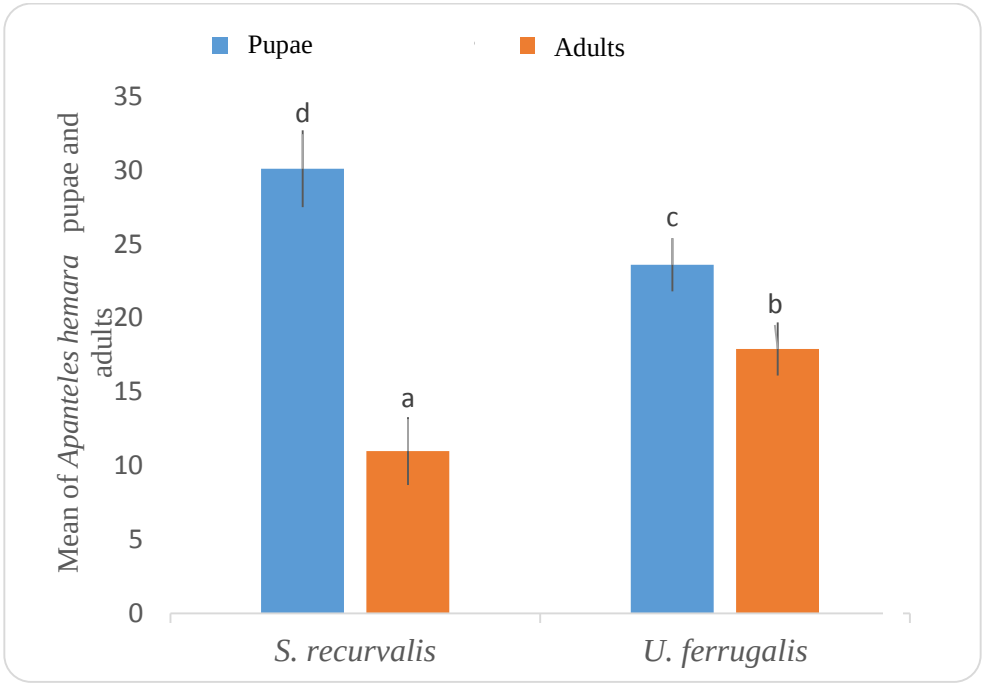

Figure 4.2: Mean ± SE of pupae and emerged adults of *Apanteles hemara* obtained from *Spoladea recurvalis* and *Udea ferrugalis*

The parasitism rate obtained on *S. recurvalis* (64.4) was significantly higher than the one obtained on *U. ferrugalis* (48.6) (t = 2.45; *P* = 0.025) (Table 4.20). There was no significant difference in the development time of the parasitoid from egg to pupation and from pupa to adult between *S. recurvalis* and *U. ferrugalis.* The total developmental time of the parasitoid from egg to adult did not differ significantly between *S. recurvalis* and *U. ferrugalis*.

Table 4.20: Number of pupae, parasitism rates and development time of *Apanteles hemara* (Mean ± SE) on *S. recurvalis* and *U. ferrugalis*

Variable Host	*Apanteles hemara* pupae	Parasitism rates (%)	Development time (Eggs-larvae) (days)	Pupal period (days)	Total development time (days)
S. recurvalis	30.1 ± 2.61a	64.4 ± 5.19a	6.0 ± 0 a	4.6 ± 0.16 a	10.6 ± 0.16a
U. ferrugalis	23.6 ± 1.81b	48.6 ± 3.91b	7.3 ± 0.21a	3.7 ± 0.21 a	11.0 ± 0a
	$\chi^2 = 15.26$ $P < 0.001$	$t = 2.45$ $P = 0.023$	$\chi^2 = 2.17$ $P = 0.141$	$\chi^2 = 1.54$ $P = 0.214$	$\chi^2 = 0.08$ $P = 0.773$

Mean followed by the same letter within the same column do not differ significantly ($P < 0.05$)

The sex ratios of F1 parasitoid progenies that emerged from the two hosts also differed significantly with parasitoids obtained from *S. recurvalis* being female biased ($\chi^2 = 6.56$; $P = 0.01$) while those obtained from *U. ferrugalis* were male biased ($\chi^2 = 8.76$; $P = 0.003$).

Females obtained from both *S. recurvalis* and *U. ferrugalis* had significantly longer hind tibia and larger forewings compared to those of their male counterparts (Table 4.21).

Table 4.21: Length (µm) (mean ± SE) of hind tibia and forewing of F1 male and female *Apanteles hemara* exposed to *Spoladea recurvalis* and *Udea ferrugalis*

Host	Parameter	Male	Female	t	*p*-value
S. recurvalis	Hind tibia	10.33 ± 0.16a	11.81 ± 0.22b	5.48	< 0.001
	Fore wing	38.03 ± 0.19a	40.20 ± 0.24b	6.96	< 0.001
U. ferrugalis	Hind tibia	11.52 ± 0.18a	12.7 ± 0.18b	4.68	<0.001
	Fore wing	40.12 ± 0.37a	41.98 ± 0.35b	3.61	0.001

Mean followed by the same letter within the same column are not significantly different ($P < 0.05$)

The F1 progenies recovered from *U. ferrugalis* had significantly longer hind tibia and forewings compared to those recovered from *S. recurvalis* of either sex (Table 4.22)

Table 4.22: Mean (± SE) length (µm) of hind tibia and forewing of F1 male and female *Apanteles hemara* exposed to *Spoladea recurvalis* and *Udea ferrugalis*

	Parameter	***S. recurvalis***	***U. ferrugalis***	t	*p*-value
Male	Hind tibia	10.33 ± 0.16a	11.52 ± 0.18b	5.02	< 0.001
	Fore wing	38.03 ± 0.19a	40.12 ± 0.37b	4.9	< 0.001
Female	Hind tibia	11.81 ± 0.22a	12.7 ± 0.18b	3.12	0.003
	Fore wing	40.20 ± 0.24a	41.98 ± 0.35b	4.17	< 0.001

Mean followed by the same letter within the same column are not significantly different (P < 0.05)

The non-reproductive mortalities in larvae as well as pupae of *S. recurvalis* and *U. ferrugalis* were however not significantly different from the natural larval and pupal mortalities recorded in the controls (Table 4.23)

Table 4.23: Non-reproductive mortality in *Spoladea recurvalis* and *Udea ferrugalis* in the presence and absence of *Apanteles hemara*

		Absence of parasitoid (%)	Presence of parasitoid (%)	χ^2	*p*-value
S. recurvalis	Larval	25.27±3.04a	28.8±3.13a	0.08	0.782
	Pupal	33.23±5.64a	32.65±9.49a	0.00	1
U. ferrugalis	Larval	36.81±2.52a	21.9±4.59a	2.48	0.115
	Pupal	37.61±4.27a	34.2±11.26a	0.06	0.814

Mean followed by the same small letter within the same column are not significantly different at ($P < 0.05$)

CHAPTER 5: DISCUSSION

Studies about the different pests attacking amaranths have often reported that lepidopteran defoliators are the most important pests of amaranths (Narayanan, 1957; Bhattacherjee and Ramdas-Menon, 1964; Clarke-Harris *et al*., 1998; Sharma and Ramamurthy, 2009; Aderolu *et al*. 2013; Kagali *et al.*, 201 Mureithi *et al*., 2015). Management of these pests through an IPM approach therefore requires an understanding of their seasonal changes in abundance throughout the cropping seasons. The results of this study showed that, the most important pests of amaranths are the lepidopteran defoliators including the leaf webbers and leaf worms whose occurrence were observed during both the wet and dry cropping seasons. These results confirm the findings of Aderolu *et al*. (2013), who reported that populations of *S. recurvalis* did not differ between the wet and dry seasons in Nigeria. This is mainly attributed to the adaptability of the pests especially *S. recurvalis* to a wide range of climatic conditions mainly temperature and relative humidity (Aderolu *et al*., 2013). According to Shirai (2006) and El-Gendi *et al*. (2006), biological activities such as flight, longevity and developmental thresholds are greatly affected by temperatures which alternate with seasons.

The abundance of leaf webbers was not different from that of leaf worms in both seasons corroborating the findings of Aderolu *et al*. (2013) that lepidopterous pests of amaranth occur in a complex array. Clarke-Harris *et al*. (1998) also reported a complex set of insect pests attacking amaranths in Jamaica including *Spodoptera* spp, *Spoladea recurvalis* and *Herpetogramma bipunctalis*

which are among the most important lepidopteran defoliators. This implies that any of these pests have a potential of becoming a serious or primary pest of amaranths in Kenya as they could out-compete each other for food and space if not adequately managed (Aderolu *et al*., 2013).

Most lepidopteran defoliators have overlapping generations such that their occurrence in the field is always noted. These pests are also polyphagous and thus understanding the role of alternative hosts including weeds and vegetable crops in their occurrence and natural enemies' conservation is vital (Bailey, 2007; James *et al*., 2010; Kahuthia-Gathu, 2013). Alternative hosts, surrounding vegetation and weeds provide a source of nectar for the adult pests which in turn enhance their longevity and fecundity and also provide food for the larvae which is vital for their development (Shirai, 2006). The high number of leaf worms at ICIPE could therefore be attributed to the presence of alternative host crops such as spinach within the surrounding area which acted as pest reservoirs.

Larval parasitoids including *Cotesia* sp., a gregarious *Apanteles* sp., *Leurus* sp. and an Ichneumonidae were also observed to be associated with these pests during both dry and wet season causing parasitism of 9.5% on leaf webbers and 20% on leaf worms during both seasons. Aderolu *et al.* (2013), reported parasitism by *Apanteles hymeniae* and *Pogonomyrmex barbatus* among other indigenous parasitoids in Nigeria. This is a good potential component for the management of the pests by understanding the performance and interactions of these parasitoids. As observed by Kagali *et al*. (2013), these indigenous natural

enemies have a potential to keep the lepidopterous pests of amaranth under check and therefore should be exploited for conservative and augmentative biological control of these pests.

Significantly higher numbers of moths were caught in the traps during the wet season than the dry season. The high number of moths during the wet season implies possible outbreaks of pests during this time which may lead to serious loss of yields if not controlled. Phenylacetaldehyde lure has been demonstrated to attract different families of moths including Crambidae such as *S. recurvalis*, *Achyra rantalis* Guenee and *Udea* sp., and Noctuidae such as *Spodoptera* spp. from which some of the most lethal pests of amaranths belong (Clarke-Harris *et al*., 1998; Landolt *et al*., 2011, Aderolu *et al*., 2013). This study also found several families of moths attracted by PAA traps which confirms reports by Landolt *et al*. (2011). However, unlike Landolt *et al*. (2011) who reported that PAA is an effective lure for *S. recurvalis*, this study showed that PAA alone was not effective in attracting *S. recurvalis* as only 0.005% of the moths attracted were *S. recurvalis*. There is therefore a need to explore several combinations of floral lures like Linalool (LIN), methyl-2-methoxy benzoate (MMB), cis jasmine (CJ) and β-myrcene (BM) with PAA, since they have been shown to enhance attraction of moths (Maini and Burgio, 1990; Landolt *et al*., 2011).

There was no significant difference in the number of moths caught in the traps across the phenological stages of the crop in the PAA traps. This is evidence that the pests were always present and could cause damage to the

amaranth crops throughout their developmental stages. High number of moths during the fruiting and vegetative stages at ICIPE suggest that lepidopteran pests of amaranth are seasonal and their outbreaks could occur at any stage of plant growth. Successful control strategies have to then target all the stages of the plants when planning for and implementing pest management.

Leaf morphology including features like petiole length, breath, thickness and presence of trichomes have been reported to affect insect pest preference in several crops including amaranths and can be used to screen for pest resistance in breeding programs (Jiang *et al.*, 2000; Akaneme and Ani, 2013; Jared *et al*., 2015). Abuk8 and Abuk1 were the more preferred lines by leaf webbers than Abuk2 during both seasons and were more susceptible to the moths' attacks. Feeding non-preference in certain plants has be shown to be due to the plants biochemical characteristics especially plant volatiles which guide the pest's oviposition and feeding preferences (Gatehouse, 2002; Kumar *et al*., 2009; Jared *et al*., 2015). Biochemical characteristics of these lines could thus have played an important role in determining pest preference for a particular amaranth line. Based on phenotypic performance, breeding programs should therefore target lines which are not preferred by insect pests or resistant lines, to come up with superior genotypes that will evade pest outbreaks on amaranths and reduce or substitute the use of synthetic chemicals in management of these pests (Akaneme and Ani, 2013).

Incidences of damage by lepidopteran pests were higher during the wet season than the dry season which translated to greater severity in terms of

damage during the wet season. This is indicative of conducive environmental conditions during the wet season which facilitated adult oviposition and larval feeding. A need to have special focus on the wet season for efficient management of these pests is therefore a necessity. Abuk8 also had higher incidences of damage than either Abuk1 or Abuk2 exhibiting that Abuk8 was still the most preferred by pests for food and for oviposition. Pigmentation in different plants is often indicative of the chemical composition of that plant which at times are useful in plant defence against insect herbivores (War *et al.*, 2012). The low incidence and severity of damage on Abuk2 indicates that this line contains certain biochemical properties which inhibit pests from feeding on it. Abuk2 leaves also had purple pigmentation unlike the green pigmentation in Abuk1 and Abuk8 which could be speculated to be a reason for non-preference as food for the lepidopteran defoliators. Akamene and Ani (2013) also noted that pigmentation of amaranth leaves could affect pest preference but this should however be substantiated experimentally.

The results obtained from the laboratory host acceptance experiments demonstrated that females of *Apanteles hemara* were attracted to and accepted *S. recurvalis* and *U. ferrugalis* larvae with no significant differences in the time taken to search for and locate the two lepidopterous host species. Host location by a parasitoid is usually aided by chemical stimulus emitted/ produced by the host or plant secondary volatile chemicals associated with the host food plant (Godfray, 1994). The host seeking activity of *A. hemara* is also stimulated by presence of larval frass on the damaged crop as reported in various studies

(Shami, 1990; Hailemichael *et al*., 1994; Ngi-Song *et al*., 1999). The same observation was made in this study where *A. hemara* was first attracted to the area of the plant where larval frass was deposited mostly around a damaged section of the leaf before it could proceed to locate the host. It is therefore probable that there is synergistic action between the chemical stimuli produced by the damaged plant and the larval frass that attract *A. hemara* to its host. Irrespective of the host used in rearing *A. hemara*, no significant differences were recorded in the number of oviposition attempts on either of the two hosts; an indication that the morphological and physical characteristics of the host such as size, shape, texture and movement (Vinson 1991; Godfray, 1994) responses elicited by both *S. recurvalis* and *U. ferrugalis* are similar and the parasitoid has the same level of preference or acceptance to both hosts. According to Godfray (1994), profitability of a prey can be determined by the handling time by the parasitoid such that a parasitoid will take shorter time to handle a profitable prey. Both *S. recurvalis* and *U. ferrugalis* were therefore equally profitable to *A. hemara* with regards to searching time and host acceptance.

There was significant difference in the number of pupae obtained from *S. recurvalis* and *U. ferrugalis*, with *S. recurvalis* producing more pupae. Godfray (1994) reported that a parasitoid's choice to lay eggs depends on the profitability of the host such that more eggs are laid on the more profitable host. These findings are thus an indication that *S. recurvalis* was more profitable and suitable for *A. hemara* and therefore chose to lay more eggs on it. The proportion of adult parasitoids that emerged from pupae recovered from *U. ferrugalis* larvae

was significantly higher than those obtained from *S. recurvalis* larvae. According to Desneux *et al*. (2009), on a study conducted on aphid parasitoids, this kind of mortality observed in the parasitoid could be due to toxins produced by the host as a result of the plant fed on or low nutritional quality of the host. In the current study however, *S. recurvalis* appeared to be the most preferred host and therefore eliminating the possibility of having low nutritional quality and since both hosts were fed on the same host plant, toxins emanating from host plant may also not explain this result. This could be probable that there are certain intrinsic host factors that led to this mortality which require further investigations.

The parasitoid's larval and pupal developmental period was comparable in both *S. recurvalis* and *U. ferrugalis.* Developmental time of parasitoids largely depend on the availability of the necessary nutritional demands within their hosts (Harvey, 2000). These results therefore suggest that the second instar larvae of both *S. recurvalis* and *U. ferrugalis* are nutritionally similar and equally beneficial for the development of *A. hemara.* Although most studies present nutritional richness in terms of host size and age, it is probable that other intrinsic qualities of the host also play a big role (Godfray, 1994; Harvey 2000).

The total developmental time of the parasitoid was also the same in either *S. recurvalis* or *U. ferrugalis*. However, when compared to most species of *Apanteles* on different hosts, the total developmental time appears to be shorter (Cardona and Oatman, 1975; Shami, 1990; Ngi-Song *et al*., 1999; Farahani *et al*., 2012; Tunca *et al*., 2014) but concurrent with findings of Peter and David,

(1990) on *Apanteles machaeralis* Wilkinson (Hymenoptera: Braconidae). The quality of these two hosts as rearing hosts of *A. hemara* is therefore more desirable.

The sex ratios of the F1 progeny of *A. hemara* exposed to *S. recurvalis* showed that they were female biased while the progeny obtained from *U. ferrugalis* were male biased. This result showed that *S. recurvalis* is a better host for mass production of *A. hemara* than *U. ferrugalis* since more females parasitoids were obtained on *S. recurvalis*. Most species of *Apanteles* have been shown to be male biased on different hosts although with varying proportions of females (Cardona and Oatman, 1975; Shami, 1990; Ngi-Song *et al*., 1999; Farahani *et al*., 2012; Tunca *et al*., 2014). This desirable difference in sex ratio observed in *S. recurvalis* is similar to findings of Peter and David (1990) in *A. machaeralis* and suggests that *S. recurvalis* can be used as a good host for rearing *A. hemara* for biological control of leaf webbers. It is true that biological control programs largely desire female biased sex-ratios because the females are the ones that are responsible for attacking the host pests through host feeding or oviposition and not the males and also it is the females which are greatly responsible for building up populations (Chow and Heinz, 2005; Ode and Hardy, 2008).

In many parasitoids, host size is normally attributed to host quality such that the larger host is assumed to have better quality and therefore will be preferred by the parasitoid for laying female eggs and the resultant progeny also expected to be more fit and larger in size (Godfray 1994; Vinson 1998; Chau and

Mackauer, 2001; van Emden and Kifle, 2002; Sampaio *et al*., 2008). The results of this study indicated that this kind of relationship is non-linear and is not applicable to all koinobiontic parasitoids given that more females were obtained from progeny that were smaller in size and confirms findings reported in *Aphidius colemani* Vier. (Hymenoptera: Aphidiidae) by Sampaio *et al*. (2008). In both cases however, the females were larger than males and therefore desirable for purposes of biological control (Godfray, 1994; Vinson, 1998). Sexual size dimorphism has been reported in several insects with particular interests on parasitoid wasps because it is argued that parasitoid size is correlated with measures of fitness like fecundity and longevity (Harvey and Strand, 2003). Both *S. recurvalis* and *U. ferrugalis* can thus be used in rearing parasitoids that will be deemed fit, but *S. recurvalis* would be the preferred mass rearing host due to females dominant progenies.

Levels of parasitism can often indicate preference of a parasitoid for a given host whereby the most parasitized host becomes the most preferred (Rodrigues and Bueno, 2001). Levels of parasitism were significantly higher in *S. recurvalis* (64.4%) than in *U. ferrugalis* (48.6%). These results are concurrent with findings of Narayanan *et al.* (1957) who reported parasitism of 62% by *Apanteles* sp. on *S. recurvalis* but way above the one reported by Bhattacherjee and Ramdas-Menon (1964) of 11.46% on *S. recurvalis* by *Apanteles delhiensis* Mues and Subba-Rao. The results of this study reveal that *S. recurvalis* is a more preferred host and therefore more suitable host for *A. hemara* compared to *U. ferrugalis*.

Non-reproductive mortalities are usually associated with host feeding or host stinging (Akutse *et al*., 2015; Foba *et al*., 2015). The parasitoid induced non-reproductive mortality in the larvae of *S. recurvalis* and *U. ferrugalis* were not significantly different from the natural non-reproductive mortalities. Non-reproductive mortalities in *A. hemara* therefore cannot be used in the evaluation of the parasitoid's performance.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

i. Lepidopteran defoliators of amaranths occur during both dry and wet seasons and throughout the phenological stages of the crop therefore successful control strategies should target all the stages of the crop.

ii. Phenylacetaldehyde attractant was not effective in the management of leaf webbers including *S. recurvalis*. It can however be used by farmers as a monitoring tool for lepidopteran pests to indicate what kind of pests are present and even their densities.

iii. Different lines of amaranth exhibit varying levels of resistance to lepidopteran pests. Abuk2 exhibited greater levels of non-preference by lepidopteran defoliators compared to either Abuk1 or Abuk8.

iv. Damage incidences and severity were greater during the wet season which call for greater vigilance in terms of pest monitoring and management during the season. Low damage incidence and severity on Abuk2 thus makes it commendable to farmers who are experiencing losses due to lepidopteran defoliators.

v. Both *S. recurvalis* and *U. ferrugalis* are acceptable and suitable hosts for rearing of *A. hemara*. Due to the female biased sex ratio of progenies exhibited by *A. hemara* when reared on *S. recurvalis*, and the high levels of parasitism on *S. recurvalis*, *S. recurvalis* was the most preferred host for mass rearing of *A. hemara*.

6.2 Recommendations

i. Pest management in amaranths should be put in place throughout the growing seasons and critically during the wet season when there appears to be an influx.

ii. Further studies are recommended to show the efficacy of PAA when combined with other floral lures such as Linalool, methyl-2-methoxy benzoate, cis jasmine and β-myrcene in addition to exploring different designs of traps for the management of leaf webbers in Kenya.

iii. Breeding programs should target lines which are not preferred by insects/ resistant lines in order to develop superior genotypes of amaranth that will evade pest outbreaks, reduce the losses caused by lepidopteran defoliators and will also go a long way in reducing the use of synthetic chemicals on cultivated amaranths. The biochemical and molecular characteristics of the amaranth lines should also be investigated as this will play an important role in explaining pest preference.

iv. *A. hemara* was found to be a potential biological control agent for *S. recurvalis* and *U. ferrugalis*, therefore could be incorporated in IPM package for the management of *S. recurvalis* and other leaf webber pests of amaranth and other AIVs.

6.3 Suggestions for further studies

i. Different varieties/ accessions/ lines of amaranth should be screened to identify their sources and mechanisms of resistance to lepidopteran

defoliators with a special focus on their volatiles and biochemical properties.

ii. Further research should be conducted to identify and possibly harness the chemical volatiles in larval frass and damaged leaves that orient the parasitoid in host searching and location for enhancing the control of these leaf webbers on amaranths.

iii. It is also important to examine the effect of rearing host in the suitability experiments to establish the levels of parasitism on the two pests.

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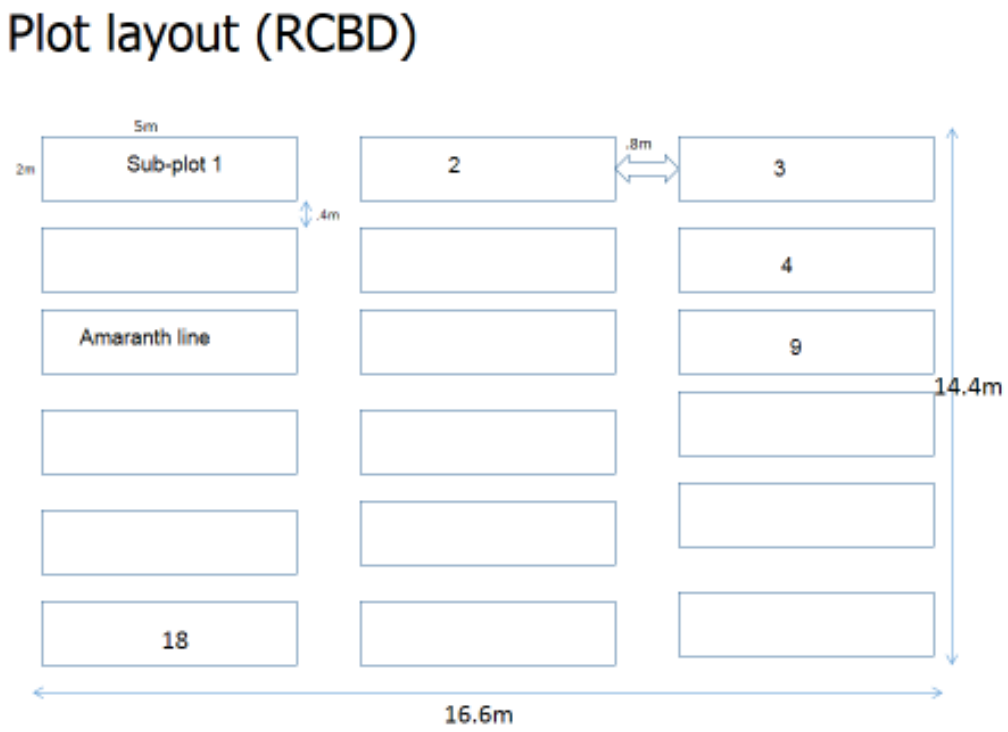
APPENDICES

Appendix 1: Randomized complete block design layout in each plot



Appendix 2: Logistic regression model for incidences of damage

Coefficients:

	Estimate	Std. Error	z value	Pr (>|z|)
(Intercept)	-2.4193	0.1487	-16.275	< 2e-16 ***
Line [T.2]	-0.5892	0.1826	-3.227	0.00125 **
Line [T.8]	0.3872	0.1479	2.617	0.00887 **
Site [T.KU]	-0.2131	0.1309	-1.628	0.10361
Plot [T.2]	0.4198	0.1323	3.173	0.00151 **

(Intercept)	Line [T.2]	Line [T.8]	Site [T.KU]	Plot [T.2]
0.08898354	0.55478381	1.47279525	0.80808895	1.

	2.5 %	97.5 %
(Intercept)	0.06601994	0.1182812
Line [T.2]	0.38567779	0.7901974
Line [T.8]	1.10376748	1.9726540
Site [T.KU]	0.62450836	1.0438616
Plot [T.2]	1.17572802	1.9759278

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-2.8805	0.1439	-20.017	< 2e-16 ***
re-Line [T.1]	0.5871	0.1823	3.221	0.00128 **
re-Line [T.8]	0.9722	0.1731	5.616	1.96e-08 ***

(Intercept)	reordervarty[T.1]	reordervarty[T.8]
0.05610561	1.79870480	2.64368140

	2.5 %	97.5 %
(Intercept)	0.04179284	0.07355222
re-Line [T.1]	1.26363460	2.58581063
re-Line [T.8]	1.89464509	3.73981086

Appendix 3: Ordered logistic regression model for levels of damage

	Value	Std. Error	t value	p value
Factor (Line) [T.2]	-1.1378217	0.5567016	-2.043863	4.096711e-02
Factor (Line) [T.8]	0.9332273	0.4913712	1.899231	5.753416e-02
0|1	-2.8675013	0.4981676	-5.756097	8.608093e-09
1|2	1.8169214	0.3911665	4.644879	3.402753e-06

	OR	2.5 %	97.5 %
Factor (Line) [T.2]	0.3205164	0.1008230	0.9193997
Factor (Line) [T.8]	2.5427021	0.9886267	6.8738371

	Value	Std. Error	t value	p value
Factor (re-line) [T.1]	1.137323	0.5565963	2.043353	4.101746e-02
Factor (re-line) [T.8]	2.070450	0.5662479	3.656438	2.557447e-04
0|1	-1.729293	0.3717902	-4.651260	3.299129e-06
1|2	2.954229	0.4963398	5.952030	2.648375e-09

	OR	2.5 %	97.5 %
Factor (re-line) [T.1]	3.118409	0.1008230	0.9193997
Factor (reline) [T.8]	7.928390	0.9886267	6.8738371

Appendix 4: Research authorization

KENYATTA UNIVERSITY
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E-mail: dean-graduate@ku.ac.ke
Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 8710901 Ext. 57530

OUR REF: A146/23316/12

DATE: 14th February, 2015

The Principal Secretary,
Higher Education, Science & Technology,
P.O. Box 30040,
NAIROBI

Dear Sir/Madam,

RE: RESEARCH AUTHORIZATION FOR MR. OMBURO S. TARMOGIN REG. NO.A146/23316/12

I write to introduce Mr. **Tarmogin** who is a Postgraduate Student of this University. **He** is registered for M.Sc. Degree programme in the **Department of Agricultural & Science Technology in the School of Agriculture & Enterprise Development.**

Mr. **Tarmogin** intends to conduct research for a proposal entitled, **"Population Dynamics of Amaranth Lepidopteran Leaf Webbers in Central Kenya and the Role of Local Parasitoids in their Control".**

Any assistance given will be highly appreciated.

Yours faithfully,

MRS. LUCY N. MBAABU
FOR: DEAN, GRADUATE SCHOOL

DN/cao

Committed to Creativity, Excellence & Self-Reliance