INFLUENCE OF SORGHUM-LEGUME INTERCROP ON INSECT DIVERSITY, NATURAL ENEMIES AND DAMAGE ON SORGHUM BY SPOTTED STEMBORER (CHILO PARTELLUS SWINHOE) (LEPIDOPTERA, CRAMBIDAE)

MASTER OF SCIENCE IN CROP SCIENCE
(CROP PROTECTION)

BY

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A research Dissertation submitted to the University of Botswana in partial fulfillment of the requirements for the Degree of Master of Science in Crop Science (Crop Protection)

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This thesis has been examined and is approved as meeting the required standards of scholarship for partial fulfillment for the Degree of Master of Science in Crop Science- Crop Protection.

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STATEMENT OF ORIGINALITY

I hereby declare that the work contained in this thesis was carried out by the author at Botswana University of Agriculture and Natural Resources between January 2016 and June 2017. This study contains no results previously published by another person or any results which has been accepted by any other degree or certificate of any university except where due acknowledgement and reference has been made in text.

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DEDICATION

This Thesis is dedicated to my loving mother Mrs. Tefo Karabo who always encouraged me all my life and watched over me in my studies and Professor Motshwari Obopile who has been like a father to me. To all my colleagues who participated in my academic life and to God who is the leader of my life.

ABSTRACT

Stemborers are considered major pests of sorghum (*Sorghum bicolor* (L) Moench) in Botswana. An evaluation of the effect of intercropping sorghum with legumes on insect diversity, natural enemies and damage on sorghum by stemborers was conducted in the 2015/2016 cropping season at Botswana University of Agriculture and Natural Resources in Sebele, Gaborone. Sorghum was intercropped with four different legumes namely cowpea (*Vigna unguiculata* (L) Walp.), groundnut (*Arachis hypogea* L.), Bambara groundnut (*Vigna subterranean* (L.) Verdc.) and chickpea (*Cicer arietinum* L). The study showed that intercropping significantly increased insect species composition and diversity. There were more herbivores than predators and the predominant insect herbivore found infesting sorghum was *Melanaphis sacchari* (Zehntner) followed by *Chilo partellus* (Swinhoe). Principal component analysis and cluster analysis showed that the insect species were separated between the monocrop and intercrop systems. There was a significant difference ($P \leq 0.05$). in level of parasitism between the monocrop and intercropping systems. More parasitoids of the stemborer were found in the intercrops especially in the sorghum groundnut intercrop that had more species than the other intercrops and none were found on the sorghum monocrop. There was no significant difference ($P>0.05$) in the density of predatory Coccinellidae and Syrphidae but numerically they were predominant in the sorghum-legume intercrops. The predator prey relationship showed a pattern consistent with a functional response. The study also showed that intercropping significantly reduced stemborer infestation and damage compared to sorghum monocrop where high levels occurred. A significant ($P> 0.05$) reduction in the number of larvae per plant, number of stem tunnels and stem tunneling length occurred on intercrop than on monocrop system. Proportions of plants with deadhearts, whorl leaf damage and number of moth exit holes did not vary significantly between the sorghum intercrop and monocrop. Grain yield of sorghum increased significantly (P>0.05) where sorghum was intercropped with grain legumes than on monocrop. Multiple regression analysis using the best subsets procedures showed that the predictor model included number of larvae per plant, number of stem tunnels and stem tunneling length. The model indicated that a significant reduction in yield was related to the number of larvae per plant, number of tunnels and tunneling length, accounting for 72.4% of the variation in sorghum grain yield. The calculated Economic Injury Level (EIL) of sorghum intercrops ranged between 3.00-8.39 larvae per plant. Sorghum-Bambara groundnut intercrop had the highest cost to benefit ratio and lowest cost of intercropping indicating that this combination was the most cost effective system able to reduce stemborer damage below economic damage. These results show that intercropping sorghum with grain legumes reduces stemborer damage and consequently increases yield potential of sorghum.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 General Introduction

Worldwide, sorghum (*Sorghum bicolor* (L.) Moench) is ranked 5th among the cereal crops and is Africa's second most important cereal (Mace *et al.*, 2013). In 2012 the area estimated for sorghum was 23 142 595 ha which produced 23 350 064 tonnes of sorghum. It is the second most important cereal in Africa after maize with 22% of total cereal area followed by millet (Macauley and Ramadjita, 2015). Despite the importance of sorghum to millions of people in Africa, yields per area planted are low, unpredictable, variable and fluctuate largely (Van der Berg, 1994). The variability and continuous decline in yields in Africa where, sorghum is the staple food of the majority is of serious concern (FAO and ICRISAT, 1996). Rohrbach and Malaza, (1993) reported average yields of 800 kg ha^{-1} in low input farmers in Southern Africa which is significantly lower than in United States of America (USA) where it averages 3705 kg ha^{-1}.

Maize and sorghum are two major crops grown in Botswana and in terms of area planted, sorghum is the most important and best suited to Botswana agro- climatic conditions. The report by Statistics Botswana (2013) showed that subsistence farmers produced 5 946 metric tons of sorghum while commercial farmers produced 26 645 metric tons. Sorghum production in Botswana is based on rain-fed farming characterized by low erratic rainfall coupled with poor soils, making production risk with low productivity. This may be the reason why subsistence farmers tend to grow open pollinated, drought tolerant varieties with relatively short days to maturity (120- 125 days) (Chiduza, 2001).

In Botswana sorghum is milled and cooked as soft and hard porridge to provide carbohydrates to many people in rural and urban areas. It is used to produce malt for brewing traditional beer (Persaud *et al.*, 2007). Sorghum production practices in Botswana are considered as low input compared to those associated with modern, intensive commercial agricultural husbandry such as use of fertilizers, weed and pest control and rotations (Pule-Meulenberg and Batisani, 2003). According to Persaud *et al.* (2007), increasing crop yields per unit of land can be achieved through use of improved technologies, high yielding cereal varieties and improved production practices. The major constraints to sorghum production in Botswana, include among others, drought, poor soil and pests (Chipanshi *et al.*; 2003 Batisani, 2012).

Sorghum yield loss associated with pests in Asia and Africa ranged between 25 and 50% (Teetes, 1985). There are many pests that attack sorghum in Botswana and those that occur annually include shoot fly (*Atherigona soccata* Rondani), *Melanaphis sacchari* (Zehntner), various species of stem borers and termites (Davies, 1982). In many areas where sorghum is produced, cereal stemborers are considered the most destructive (Sheshu Reddy and Sum, 1991; Harris and Nwanze, 1992; Kfir *et al.*, 2002). A survey conducted by Mosinkie and Obopile (2001), showed that famers in Botswana considered stemborers as the most damaging group of insect pests. The species of stemborers occurring in Botswana are spotted stemborer, *Chilo partellus* Swinhoe, African maize stemborer, *Busseola fusca* Fuller, the pink stemborer, *Sesamia calamistis* Hampson and the sugarcane stemborer, *Eldana saccharina* Walker (Obopile and Mosinkie, 2001). An average stemborer infestation of up to 98 % on sorghum was reported, but yield loss was not determined in Botswana (Obopile and Mosinkie, 2001). The dominant lepidopteran stemborer in Botswana is *C. partellus* with a countrywide distribution, followed by *B. fusca* (Ingram, 1973; Obopile and Mosinkie, 2003). Roome, (1970), showed that yield loss of up to 10% per larva per plant due to damage caused by stemborers occurred in Botswana.

In Botswana, low input famers primarily grow sorghum with very limited use of pesticides and no other methods like cultural practices were reported (Mosinkie and Obopile, 2001). Since stemborers are considered the most destructive pest of cereal (Kfir, 2002), it is important that pest control methods be put in place to reduce yield losses associated with their damage on sorghum. The methods recommended for control of stemborers include chemical, biological control and cultural control. Chemical control is effective but there are difficulties associated with it like cost of pesticide (Van den Berg and Nur, 1998), pollution to the environment and development of resistance. These problems designate chemical control as a last resort in control of pests. Biological control involves the use of natural enemies (predators, parasitoids and pathogens) which reduce pest numbers but they seldom reduce them below the economic injury level (Bonhof, 2000; Kfir *et al.*, 2002; Obopile and Mosinkie, 2003;) and the environment has to favour their establishment. Cultural control methods have been used to control stemborer in areas where they are main pests of sorghum (Polaszek, 1998). Cultural methods comprise of removal of crop residues, manipulation of planting density and dates, trap cropping and intercropping (Kfir *et al.*, 2002).

According to Dent, (1991), cultural control methods are preventative and can be used strategically to control pests. Among the cultural methods used, intercropping stand out as one of the most researched cultural method (Sheshu Reddy and Masyanga, 1988; Dissemond and Hindorf, 1990; Oloo and Ogeda, 1990). Intercropping with legumes has the capacity to enrich soil with nitrogen because legumes are capable to fix atmospheric nitrogen through their association with rhizobium in root nodules (Caswell, 1984), which is adequate to meet nitrogen requirements (Pule-Meulenberg and Dakora, 2009).

Research has shown a significant reduction in stemborer population (Schulthess *et al.*, 2004; Chabi-Olaye *et al.*, 2005). The effectiveness of intercropping is explained by four hypotheses; natural enemy, resource-concentration, appropriate–inappropriate and host plant quality hypotheses.

Vandermeer (1989) proposed the natural enemy hypothesis, which states that intercropping patterns attracts more predators and parasitoids than the monocrop, as one of the mechanisms for reducing pest infestation. This hypothesis may be tested by comparing the parasitoids and predator species richness and impact on the monocrop and the intercrop. The resource-concentration hypothesis suggest that higher herbivore numbers in monocrop system are due to their ability to locate the host, higher feeding rates and ability to achieve higher reproduction rates than those herbivores with narrow host ranges (Root, 1973). To test this hypothesis the number of pests in a monocrop and intercrop are compared. According to the appropriate-inappropriate hypothesis, related plants closer to the host have the ability to interrupt the herbivore's behaviour to accept the host and the ability to find the host (Finch and Collier, 2000). This hypothesis is tested when two related crops are planted as monocrops and intercrops, then pest numbers between intercrop and monocrop are compared. The host-plant quality hypothesis stated that intercropping negatively affects the host quality and the chemical suitability of the plants for herbivores when compared to the monocultures (Bach, 1981; van Lenteren, 1998). The hypothesis can be verified by measuring the chemical contents of the plants sampled from the intercrop and monoculture and the weight of the grain at harvesting, which can be used to measure the quality.

The use of intercropping as a pest management tool requires the ability to collect information on pest density, crop condition, climate and other various related factors (Alston, 2011). This information can then be used in developing an economic injury level (EIL) which is a prerequisite in establishing an Integrated Pest Management (IPM) system (Pedigo, 1986). The economic injury level (EIL) and its derivative, economic threshold (ET) are decision tools that aid the famer in making economically sound decisions in pest management.

Studies that incorporate EIL concept in testing effectiveness of intercropping are lacking. However, as reported by Stejskal (2003), the use of the EIL concept is limited: (i) in situations where an injury or damage cannot be quantified, (ii) when pest monitoring is difficult or EIL is very low, and (iii) with proactive methods like preventative measures of pests. Determination of EIL involves varying insect populations by exposing the pest to different levels of pest control interventions. The pest population or density is then related to yield via regression analyses. However, when preventive methods are used, they bring a challenge because of the assumption of zero population in such systems. EIL, as redefined by Southwood and Norton (1973) and Ramirez and Saunders (1999), relates the cost of protection to pest density so that control measures can be justified. This definition is consistent with the original proposal by Stern *et al.* (1959) and Mumford and Knight (1997). There is need, therefore, to investigate how preventive methods like intercropping can be incorporated into the formula that calculates EIL (Stejskal, 2002; Stejskal, 2003). The study therefore propose to develop EIL that incorporate intercropping as a pest management intervention for reducing stemborer damage and increasing sorghum yield potential. Stemborer density and damage can be varied by intercropping sorghum with different legume species and evaluating pest responses.

1.2 Justification of the study

Sorghum is considered a staple food in Botswana by both commercial and resource-poor small-scale farmers. However, insect pests are among the major constraints, in particular lepidopteran stemborers, which cause significant grain losses. The challenge faced by farmers is a lack of capacity to manage stemborers especially at subsistence level of production. In commercial production, pesticides are often used to control stemborers but in subsistence farming, most farmers seldom use chemical control methods against stemborer and other pests. They hardly use any form of control.

Pesticides often expose users to hazards and have raised environmental concerns such as pollution of water sources, reduced number of beneficial insects resulting in the imbalance of terrestrial and aquatic ecosystems (Zacharia, 2011). Alternative pest management options that are safe to the users and environmentally sound need to be developed to reduce yield loss associated with stemborer infestation. Most studies that have been done on the sorghum-cowpea intercrop were focused on attaining high yield, reduction in pest population and enhancement of natural activities but has not considered incorporating the decision making tools that would help the farmer make economically sound decisions and yet still attain the highest possible yields.

1.3 Objectives

The current study was aimed to determine the following objectives;

1. To determine the effects of sorghum-legume intercrop on insect diversity and abundance.
2. To assess population dynamics of natural enemies and predatory-prey relationship as influenced by different sorghum-legume intercropping systems.
3. To determine the most effective sorghum intercrops that will lower stem borer populations below EIL.

1.4 Hypotheses

The theories of the current study were based on the following;

1. There is no significant difference in insect biodiversity and abundance between various sorghum-legume intercrops.
2. The natural enemies, resource concentration and host plant quality hypothesis do not explain the effectiveness of intercropping in regulating pest densities in agroecosystems.
3. Sorghum intercrops will not lower stemborer populations below EIL.

CHAPTER 2: LITERATURE REVIEW

2.1 Distribution of stemborer species

There are three types of stemborers that attack sorghum; the spotted stemborer (*Chilo partellus*) (Swinhoe) (Lepidoptera: Crambidae), the African maize stalkborer (*Busseola fusca*) (Fuller) (Lepidoptera: Noctuidae) and African pink stemborer (*Sesamiae calamistis*) Hampson (Lepidoptera: Noctuidae) (Kfir *et al.*, 2002). *Chilo partellus* is an introduced species that invaded Africa sometime before 1930 when it was first recorded in Malawi but has since spread in many parts of Africa (Kfir and Bell, 1993; Kfir, 1997). It has now proved to be a highly competitive colonizer in many of the areas it has invaded in eastern and southern Africa often becoming the most injurious stem borer and displacing native species (Kfir and Bell, 1993). Displacement has been reported in the eastern Highveld region of South Africa where *C. partellus* partially displaced *B. fusca* and it was most evident in grain sorghum where the proportion of *C. partellus* in the total stemborer population increased from about 3% in 1986 to 91% in 1992 (Kfir *et al.*, 2002).

Busseola fusca is an indigenous species to Africa that is widely distributed in East and southern Africa (Van Den Berg *et al.*, 1991; Kfir, 1997). It does occur in lower altitudes in East Africa and it feeds on a few host plant species (Catalayud *et al.*, 2014).

Sesamia calamistis is one of the indigenous stemborer pests associated with maize and sorghum in Africa (Bowden, 1976). Its economic importance varies across Africa but remains a minor pest in eastern and southern Africa (Bosque-Pérez and Schulthess, 1998). Difference in pest status may be attributed to variations in diet breadth and ecological preferences among populations (Kfir, 1997; Sheshu Reddy, 1998). *Busseola fusca*, *S. calamistis* and *C. partellus* larvae were often observed in mixed populations in the same planting as well as individual plants (Van Den Berg *et al.*, 1991; Bate *et al.*, 1991; Ong'imo *et al.*, 2006; Calatayud *et al.*, 2014).

2.2 Biology and Ecology

The most damaging stage in the life cycle of these stem borers is the larval stage which enters the plant and feeds. Many cereal stem borers have a resting period toward the end of the cropping season, which they spend as fully-grown larvae in dry crop residues in the field (Ofomata *et al.*, 1999). In southern Africa, *B. fusca* and *C. partellus* pass winter in diapause which is the cold dry season (April- September), in the lower parts of the dry stalks where they are well protected from natural enemies and adverse climatic conditions (Kfir, 1991).

In regions where there is abundance of host plants and climate is warm, *C. partellus* normally develops continuously all year round (Kfir et al., 2002). Dry condition of host plant and the general deterioration of the nutritive environment induced diapause in larvae of *C. partellus* even when climatic conditions were favourable for development (Scheltes, 1978). The longer the time the larvae remained in diapause, the lighter in weight the emerging adults were, with fewer eggs and oocytes in the ovaries (Kfir, 1991). In the field, *C. partellus* starts to emerge from diapause in the second part of August and it continues until the first week of November a period of 12 weeks (Kfir, 2000).

Busseola fusca is capable of producing up to four generations per year (Kfir, 1998). At the end of the rainy season, the larvae of the last generation enter into diapause in maize and sorghum stubble or in wild grasses. They pupate a few months later just before the start of the following season (Cataluyd *et al.*, 2014). Crop losses estimates differ greatly in different regions and agro ecological zones. In Kenya alone, losses due to *B. fusca* damage on maize fluctuate around 14% on average (De Groote, 2003) while in humid forest zone of Cameroon losses of around 40% are common in monocropped maize fields (Cardwell *et al.*, 1997; Chabi-Olaye *et al.*, 2005).

The ability of stemborers to enter diapause stage makes them more persistent in the environment and hard to control them with only one method. The combination of methods (integrated pest management) and economic injury levels is ideal and can be used to tackle this problem.

2.3 Economic importance of cereal stemborers

Of the various insect pests attacking maize and grain sorghum in southern Africa, *B. fusca* and *C. partellus* are by far the most important (Sheshu, 1998). In South Africa, estimated yield losses from *B. fusca* damage ranges between 10% to total loss (Barrow, 1987) and the estimated yield losses due to *C. partellus* in maize and sorghum exceed 50% (Revington, 1986). In Tanzania, *B. fusca* can reduce maize and sorghum yields from 10-20%. Trials in separate and mixed populations using artificial infestation on sorghum indicated that *C. partellus* was more injurious than *B. fusca* (Van den Berg *et al.*, 1991). Yield loss between 16% and 49% by *S. calamistis* and *B. fusca* has been reported in the Guinea Savanna of Nigeria (Ajayi, 1991).

Berger, (1981), reported that in Mozambique, larvae of third generation *C. partellus*, the most important stemborer, was reported to infest 87% of cobs of late planted maize and to severely damage 70% of grain. Based on the fact that stemborers significant economic losses due to reduction in yield and difficult to control make, them one of the pests of economic importance. Different forms of management tactics have been developed towards the control of these notorious pests but by far no studies have combined intercropping with economic injury levels, making the current study a valuable contribution to science. Research done by Obopile and Mosinkie, (2003), showed that in Botswana *C. partellus* is the most established stem borer constituting to 92% of the collection from infested sorghum followed by *S. calamistis* and *B. fusca*.

2.4 Damage by stemborers

Stemborers can cause damage from seedling to maturity (Lynch, 1980; CAB, 2007). The destruction of meristematic tissues of seedlings causes dead heart symptoms that may result in total plant loss but some sorghum varieties are capable of compensating by producing additional tillers. Leaf feeding by stemborers results in the reduction of plant photosynthetic area (Polaszek, 1998). Stem tunnelling destroys the central pith or conductive tissues of plants causing a reduction in nutrient uptake and the consequent interruption of grain filling. Stem tunnelling also causes peduncle breakage, poor pollen production, interruption of fertilisation and stem breakage. Larval attack by different instars to different plants parts ultimately results in stunted plant growth and reduced yield (Bosque Pérez and Marek 1991; Polaszek, 1998). Severe infestation leads to physiological disruption of plant growth, panicle emergence and grain formation, resulting in reduction of kennel numbers and mass (Lynch, 1980). It is therefore evident that the damage caused by stemborers on sorghum can greatly affect the yield therefore affecting the farmers economically.

2.5 Management of stemborers

There are different methods used to manage stemborers. These can either be chemical, cultural and biological control.

2.5.1 Chemical control

Since stemborers can cause up to 100% yield loss, insecticides are often justified to use as a component of integrated pest management to lower pest outbreak below economic injury level (Van den Berg and van Rensburg, 1991). Chemical control is limited because complete control is very seldom achieved and are not normally used by the small scale farmers because of their cost (Midega *et al.*, 2005). They are mostly used by commercial farmers on their cash crops (Van Den Berg and Nur, 1998).

Chemical pesticides against stemborer may be applied in granular form or spray. Granular chemicals may be carbofuran, phorate and fipronil. Fipronil can also be used in spray form, endosulfan and acephate. Studies shows unavoidable losses always occur, since 100% efficacy can never be achieved with insecticidal control (Van den Berg and van Rensburg, 1991).

Khan and Amjad (2000), showed that the numbers of deadhearts were significantly less in chemically treated plants compared to untreated plots. Percentage infestation was less in all the treated plots compared to the check plots. Stalk weight per plot of maize was significantly more in all of the treated plots compared to untreated plots. Khan (1983), concluded that the systemic compounds applied in the furrow were more effective than the non-systemic compounds as foliar applications.

The use of insecticides in control of stemborers is not easy because the larvae feed internally on foliage, shoots and stems. The chemicals used to control stem borers need to penetrate deep inside the plant hence the use of systemic pesticides (Van Rensburg and van den Berg, 1992). Better understanding of the most susceptible stage of stem borers needs to be known to effectively control them. *Chilo partellus* feeds behind leaf sheaths of sorghum where they are not reached by insecticide application (Van Rensburg and van den Berg, 1992).

Pesticides have been successful in controlling stemborers but their negative effects on the environment and human health have led to them being used as the last resort in pest management. Some of the negative impacts of synthetic insecticides include environmental contamination, destruction of non-target organisms like natural predators, parasitoids and pollinators. In a study done by Deedat, (1994), it was found that when the pesticides were used against stemborers, the number of parasitoids was greatly reduced when compared to the numbers where pesticides were not used. There were also problems associated with resistance as continuous use of pesticides lead to pest developing resistance against them. Considering these negative impacts, the use of synthetic insecticides in stemborer management is being minimized and alternative safer methods are being sought (Ruiu *et al.*, 2013).

Chemical control of stemborers is uneconomical and impractical to many resource-poor, small scale farmers (Khan *et al.*, 2003). Due to lack of training and resource constraints, pesticides are not suitable for most African farmers. In Kenya, less than 30% of growers use pesticides to control cereal stemborers (Kipkoech *et al.*, 2006). If applied incorrectly and at sub-lethal dose, they may selectively kill the natural enemies of the pest, thereby aggravating pest infestation and increasing yield loss (Cugala *et al.*, 2006). The most appropriate pest control technology should focus on sustainability by minimizing the negative impacts to users and the environment and requiring farmers to only spend a fraction of their income, since for resource-poor farmers the marginal opportunity cost of any expenditures is high (Kipkoech *et al.*, 2010).

2.5.2 Biological control

Biological control is defined as the management of a pest by deliberate use of living organisms (natural or applied) to maintain pest population density at a lower level than would occur in the absence of the biological agent (DeBach, 1964). Natural enemies have always been present and they have an effect on pest numbers. The environment has to favour them so that they can successfully reduce the number of pests below the economic injury level. Natural enemies may be insects (predators, parasitoids) or other athropods, nematodes and pathogens.

2.5.2.1 Predators

Natural predators of stem borers are arthropods and most of these have not been investigated. Most studies that have been done were based on predation on the life stages of the stemborer.

The stages most researched are the eggs and the young larvae as these are the stages that are exposed and the older larvae are enclosed in the pupal case (Bonhof, 1998). The eggs are the most exposed as they are laid on the leaves or stem of plants and predators like earwigs and spiders feed on them (Bonhof *et al.*, 1997). The importance of predation was demonstrated by research done by Leslie (1982) who showed that when predators were excluded by insecticides, the percentage of eggs recovered was 77-88%, compared to 24-62% recovery when no exclusion was done.

Neonate larvae are vulnerable to predation especially while migrating from the egg batch to the leaf whorl. Late instar larvae feed in the protected environment of the stem and seem therefore less vulnerable to predation. When the larvae migrates to other plants that is when they become vulnerable to predation. Most studies have concluded that indigenous predators (ants, spiders and earwigs) are not able to keep stem borer populations below economic injury levels (Bonhof, 2000).

2.5.2.2 Parasitoids

Parasitoids play an important role in maintenance of equilibrium in nature and have been used successfully as biological control agents in cultivated crops (sorghum, maize and sugarcane). Parasitoid can be endoparasitoids, which are those that live inside another animal and ultimately kill it or ectoparasitoids that live externally on another animal and eventually kill it.

Cortesia flavipes Cameron (Hymenoptera: Braconidae), a larval parasitoid was released against the exotic stemborer *C. partellus* in Kenya, Uganda and Tanzania for 5 years between 1968 and 1972 by International Institute of Biological Control but it failed to establish (Overholt, 1998). It was reintroduced from Pakistan to Kenya in 1993 (Overholt *et al.*, 1994) and has become permanently established on *C. partellus* in maize fields of that country

(Songa *et al.*, 2001). Zhou *et al.*, (2001) demonstrated that the parasitoid caused a significant reduction in the density of *C. partellus*. In Northern part of Ethiopia 50% parasitism was recorded on *C. partellus* in sugarcane (Assefa, 2006). *Cortesia flavipes* attacks cartepillars of the spotted stemborer and *Xanthopimpla stemmator* Thunberg (Hymenoptera: Ichneumonidae), a wasp, attacks the pupa of stemborer. *C. flavipes* has caused a 32-55% decrease in stemborer densities (Kfir *et al.*, 2002).

Tachnid larval parasitoid *Sturmiopsis parasitica* Curran (Diptera: Tachinidae) has a wide distribution in Eastern, Southern and West Africa where it attacks several species of cereal stemborers (*C. partellus, B. fusca* and *S. calamistis*) (Chawanda *et al.*, 2014). Gravid females deposit mobile first instar maggots (planidia) on moist frass stemborer tunnel entrances. Planidia then use the moist frass to traverse the tunnel until they reach a borer larva which they then penetrate to feed internally (Smith *et al.*, 1993).

Investigations on the removal or partial removal of parasitoids from stemborer infested crops by applying insecticides showed that borer populations doubled in the same crop (Kfir *et al.*, 2002). Research on biological control in Botswana is limited except for the survey done by Obopile and Mosinkie, (2003). The survey showed that local stemborer populations were parasitized by an array of larval and pupal parasitoids. The larval parasitoids reported in the survey include *Cortesia sesamiae* Cameron, *Stenobracon rufus* Szepligeti (Hymenoptera: Braconidae) and *Phanerotoma* species amongst others. The pupal parasitoids recorded were *Pediobius furvus* Gahan (Hymenoptera: Eulophide) and *Psilochalis soudanensis* Steffan (Hymenoptera: Chalcididae) amongst others. Kfir (1995) reported 90% parasitism of *B. fusca* by *C. sesamiae* and up to 100% parasitism of pupae by *Dentichasmias busseolae* Heinr. (Hymenoptera: Ichneumonidae) and *P. furvus* in South Africa.

While significant level of stemborer parasitism occurs in most areas where stemborers are found, parasitoids do not reduce the stem borer population to below economic injury levels in Botswana (Obopile and Mosinkie, 2003). It is therefore important to work on cropping systems that will enhance parasitism thus reducing stemborer damage to sorghum and other cereal crops.

2.5.2.3 Pathogens and nematodes

Fungi, bacteria, viruses and nematodes have been found to infect the larval stages of stemborers. Nematodes of the genera *Hexamermis* and *Steinernema* enter the larval stage by penetrating the cuticle (Poinar and Polaszek, 1998). Entomopathogenic nematodes (EPNS) cooperate with insect-pathogenic bacteria to kill the insects as they have adapted specific mechanisms to associate and transmit bacteria to insect hosts (Dillman *et al.*, 2012).

The fungi of the genera, *Aspergillus*, *Beauveria* and *Metarrhizum* reportedly play an important role in regulating populations of stemborer (Harris, 1962). Pathogens *Beauveria bassiana* and *Metarrhizium anisopliae* infect stemborers (Tefera and Pringle, 2003). Bacteria associated with killing of stem borers are *Baccilus thungiensis* which has been developed into insecticides. It has been concluded that nematodes and pathogens are of not great importance in regulating stem borer numbers (Kfir *et al.*, 2002). In Amhara, Ethiopia, Emana *et al.* (2001), reported higher nematode densities (*Steinernema intermedia*) on *B. fusca*. Nematodes were observed during the wet months in the cool wet Amhara (Wale *et al.*, 2006). Wet habitats are essential for nematode survival (Poinar Jr and Polaszek, 1998).

Since establishment of extensive sugarcane plantations, some stemborer species such as *Eldana sacchariana* Walker (Lepidoptera: Pyralidae), have become serious pests in the cultivated crops due to lack of natural enemies and the high quality food source (Conlong, 1990; Le Rui *et al.*, 2006). The predators, parasitoids and pathogens are effective against stem borers but alone they are not able to reduce the pest population below the economic injury level. They are not harmful to the environment as they occur naturally making them a better choice than chemical control. The manipulation of the environment can improve their habitat condition thus increasing their numbers making them effective in greatly reducing stemborer numbers. They can be combined with other methods of control in an integrated pest management.

2.5.3 Host plant resistance

Use of plant resistant varieties is environmentally safe, economically feasible and socially acceptable as a tactic of pest management (Muhammed and Muhammed, 2009). Resistant crop varieties are generally compatible with other insect control methods (Kfir *et al.*, 2002). Morphological characters have been known to contribute a lot towards the host plant resistance (Rebe *et al.*, 2004). There is also biochemical factors associated with resistance like the content of amino acids or silica content which are associated with resistance to stemborer (Sharma and Nwanze, 1997). An experiment done by Saxena (1990), in cages, revealed that oviposition was high on susceptible cultivars but significantly lower on resistant cultivars. Resistant varieties are able to control low pest density unlike chemical control which is justifiable only when the density reaches the economic injury level (Kfir *et al.*, 2002). Lines of sorghum and maize resistant to *C. partellus* have been identified (Sheshu Reddy, 1998) and in South Africa some hybrid sorghums showed great tolerance to stem borer damage therefore suffering low yield loss (Van Den Berg and van Rensburg, 1993). In Botswana most research on sorghum has been based on drought tolerance and less on tolerance to stemborers, therefore resistant varieties are not available for management of stemborers.

2.5.4 Fertilizer application

Research has shown that amount of nutrition available to plants influence stemborer herbivory on cereal crops (Van den Berg *et al.*, 1998). An increase in nitrogen content of plants can increase infestation and survival of borers (Van Den Berg *et al.*, 1998). Van den Berg and Van Rensburg (1991), indicated that sorghum plants which did not receive fertilizer or irrigation were less preferred by *C. partellus* for oviposition. Nitrogen enhances borer development as well as plant tolerance to stem borer attack (Setamou *et al.*, 1995) so it has to be applied at a rate that will make the plant less susceptible to stem borer. Manipulation of fertilizer rate for pest control in subsistence farming is largely impractical as most farmers do not have access to fertilizers (Van den Berg *et al.*, 1998). Ajayi, (1990), suggested that the manipulation of time of nitrogen application may achieve a compromise between using low levels of nitrogen for stemborer infestation and using high levels for better yields.

2.5.5 Planting density and dates

Planting density has been found to affect the stemborer numbers and their behaviour when searching for food and oviposition site (Lawani, 1982). Studies in Nigeria found that increasing maize density resulted in higher borer incidence (Ogunwolo *et al.*, 1981). *Busseola fusca* larvae migrated up to 2.4 m (Harris, 1962) so increasing the inter-row spacing reduced stemborer damage. Manipulation of the planting date can be effective if the seasonal patterns of stemborer cycles are known. If the crop is grown when the pest is less abundant and the crop susceptible stage does not occur at the same time as the periods when the moth activity is at its peak there would be less damage (Sheshu Reddy, 1990). In South Africa, it is recommended that sorghum be planted in mid-October to mid-December to avoid infestation from the first moth peak (Van Hamburg, 1979; Sorghum production guideline, 2010). Manipulation of planting dates is recommended in South Africa and Zimbabwe since the borer has a different moth flight pattern with moths being absent for a period of 2-4 weeks between the first and second generation moth flight (Sithole, 1989). The drawback of using planting date in Africa is unreliability of rainfall that does not allow farmers to manipulate planting date to evade pests at their highest population peak (Van den Berg *et al.*, 1998).

2.5.6 Cultural control

2.5.6.1 Removal of crop residues

Farmers have been advised to destroy crop residues as the stemborer larvae overwinter in them and if they are not destroyed they infest the crop in the following season. Stalks of sorghum or maize can be buried 10-15 cm in the soil because at this depth there is no emergence of adults (Mohyuddin and Greathead, 1970). Burning of the stalks after harvest leads to 100% eradication of the overwintering larvae of stemborers (Duerdin, 1953). In many parts of Africa stalks of cereals are not destroyed but rather used for thatching and fencing and livestock bedding (Unnithan and Sheshu Reddy, 1989). Basing on these cultural practices, Amlak (1988), conducted an experiment where stalks were cut post-harvest and placed horizontally on the ground and showed that cutting stems and for a period of four weeks resulted in 97% mortality of *B. fusca* larvae in maize and 100% in sorghum.

2.5.6.2 Intercropping

In management of stemborers, major emphasis has been given to the development of habitat management techniques such as intercropping, soil fertility measures, and chemical control. Among the above intercropping has drawn attention to several studies because it has been shown to decrease pest densities in diversified cropping systems (Oloo and Ogeda, 1990; Ampong-Nyarko *et al.*, 1994; Kruess and Tscharntke, 2000). In Africa, small-scale farmers traditionally practice intercropping in order to obtain a greater total land productivity to insure against failures associated with single crop and unpredictable markets (Vandermeer, 1989). Research has demonstrated that intercropping maize with non-host plants like legumes reduced stemborer infestations by up to 80% (Schulthess *et al.*, 2004). Intercropping also increase diversity of natural enemies and consequently reduce stemborer populations (Cardinale *et al.*, 2003).

Growing two or more crops at the same time on a single field is an ancient practice still used in much of the developing world. There is mixed intercropping which has no distinct row arrangement and row intercropping: where at least one crop is planted in rows. Strip intercropping comprises of growing crops in strips wide enough to separate them yet narrow enough to allow interaction between them (Smith and Carter, 1998). There is also relay intercropping which consists of growing two or more crops during differing parts of their life cycle (Machado, 2009). Research has shown that the major advantage of intercropping to a crop is reduced damage from insects and infection by plant pathogens. In intercropping system, one crop can serve as a deterrent whereby it alters the quality of the other crop making it a less attractive host for a predator or a parasite (Sullivan, 2003). Smith and McSorley (2000) reported that intercropping increases crop species diversity and that offers advantages at reducing pest densities resulting in significantly less damage from insects compared to monocrop (Altieri and Letourneau, 1999).

When using maize/lablab intercrop, Maluleke *et al.* (2005) established that relationship between two crops can be negative, thus resulting in grain yield reduction of another crop. Crop combinations with non-host lowers the spread of pests within crops by emitting chemicals or odours that negatively affect pests (Smith and Liburd, 2015). Intercropping system is ideal to African smallholder farmers as it provides total land productivity and insurance against failure or unsure market value of single crop (Rische *et al.*, 1983), so intercropping is an economic sound decision to small-scale farmers. Most studies on intercropping as a management strategy for stemborers have been directed towards reducing pest numbers and enhancing efficiency of natural enemies (Songa *et al.*, 2007).

Many field studies have been conducted in Africa during the past two decades in an effort to identify the best crop combinations for reducing stem borer populations on cereal crops (Kfir, *et al.*, 2002). Many of these intercropping studies did not seek to determine the underlying mechanisms behind the effect of intercropping on stem borer population levels (Pats *et al.*, 1997). The finding that intercropping maize with cowpea is an effective way of reducing damage by *C. partellus* was confirmed by reports that 30% of *C. partellus* oviposition in maize/sorghum/cowpea-intercropping system on cowpea and the number of larvae reaching host plants from cowpea decreased with distance (Ampong-Nyarko *et al.*, 1994). In another study done by Chayi-olaye *et al.* (2005) in West Africa, a considerable reduction in number of eggs laid by *S. calamistis* and *B.fusca* was related to reduce host quality by the ovipositing adults moths in maize intercropped with grain legumes or cassava than those in monocrop. Studies have also shown that an increase of parasitoids population was associated with intercropping cereals like pearl millet with groundnuts (Degri *et al.*, 2014). The mechanism underlying the effectiveness of intercropping in reducing pest damage is explained by evidence that plants in the system emit phytochemicals that adversely affect the pests, thereby conferring some level of protection to the host plant (Reddy, 2012). Adoption of effective intercrop practices for natural regulation of insect pests including stem borers remains crucial (Verma and Singh, 1989), especially by resource-poor farmers that lack the capacity of input-intensive plant protection measures.

2.6 Adopting decision-making tools to intercropping system

Decision-making tools entails economic injury levels (EILs)and economic thresholds (ETs). EIL's are the lowest pest population density that would cause sufficient economic loss to justify the cost of control, which are a fundamental component of Integrated Pest Management (IPM) programs (Pedigo *et al.*, 1986). It depends on the pest, time necessary to obtain pest population information, population dynamics and predictability of the pest behaviour. The knowledge of ET helps determine whether an insect can be classified as a pest or not. ET is when action should be taken to control the pest and it depends on the insect species.

IPM programs have contributed to the economics of pest control (Headley, 1972), depending on the development and application of EIL and ET (Damos and Savopoulou-Soultani, 2010). It involves coordinated use of multiple tactics for optimising the control of all classes of pests (insects, pathogens, vertebrates and weeds) in an ecologically and economically sound manner (Dent, 1994; Agra CEAS, 2002; Damos and Savopoulou-Soultani, 2010). Its major goal is not to eradicate pest populations but to accept the presence of a tolerable pest density, conserve environmental quality and improve user profits (Boller *et al.*, 2004). Attention given to environmental protection, food safety and human health has caused the IPM concepts to be included in the determination of EIL. IPM can substitute pesticides application, recognizes the cost of pest control beyond the direct chemical and application costs and requires consideration of management options to reduce the necessity for chemical treatment. IPM increases the EIL density of pests necessary to apply treatments. The type of pest management actions, as related to productivity and price commodity, significantly affects the cost of crop production and thus defines the adoption of IPM and sustainable crop production systems at local or international level (Altieri and Nicholls, 2000). EIL has mostly been used in cases where chemical control was used and not for preventive methods like intercropping. Entomologists were one of the first to attempt to include the cost of pest control practices in management decision-making. Their goal was to develop some decision-making tools that would aid the pest manager in making economically sound decisions (Alston, 2011). Economic decisions emerged as an encouragement for more rational use of insecticides (Pedigo and Rice, 2006). Decision-making involves allocating scarce resources judiciously to meet human needs by considering that treating a pest needlessly is not cost-effective especially after incorporating expenditures into crop protection activities (Alston, 2011).

According to Pedigo and Rice (2006), economic decision levels are the keystone of insect pest management programs. They indicate the course of action to be taken at any given pest situation and without such knowledge there are risks in making wrong economic decisions like spending more to supress an insect than the value of the commodity the pest could destroy. These economic decisions can increase producer profits and conserve environmental quality (Pedigo and Rice, 2006).

Economic Injury Level (EIL) is the lowest population density of a pest that will cause economic damage (Stern *et al.*, 1959). Although the economic injury level was founded on economic considerations, it has been expanded to embrace concerns about environmental, social and resource concerns and sustainability (Pedigo and Higley, 1992). The EIL concept has mostly been calculated for chemical control, which is applied when the pest is already established but not for preventive control methods like intercropping. The literature cited here shows that intercropping reduce pest numbers and consequently reduce yield loss but the concept of EIL has never been used to show the most economic population or damage that can be prevented by using intercropping. Such lack of information has prompted the current study which will focus on coming up with an EIL for preventive method (intercropping). According to Stejskal (2003), establishing EILs for preventively controlled pests can help re-evaluate their pest status and reduce the use of chemical control.

CHAPTER 3: MATERIALS AND METHODS

3.1 Planting and experimental layout

This study was done under field conditions at Botswana University of Agriculture and Natural Resources fields. Sorghum, variety phofu was intercropped with four different legumes namely cowpea (*Vigna unguiculata* (L) Walp) variety ER7, groundnut (*Arachis hypogaea* L.) variety nakwana , Bambara groundnut (*Vigna subterranean* L.) and chickpea (*Cicer arietinum* L.). Sorghum mono-crop was used as a control. Hand planting of all crop combinations was done on 14 January 2016 following the intercropping ratio 1 row of sorghum to 2 rows of legume crop as it has been found as the best crop ratio in controlling stemborer (Degri et al. 2014). The land was prepared using a tractor mounted disc harrow. The experiment was laid out in randomized complete block design, with four replications making a total to 20 experimental units. The individual plots were 5m long with spacing between the rows of 0.75 m and between plants 0.30m. The spacing between each block was 1 m and plots were labeled using pegs. Two seeds were placed per planting station and after germination the crops were thinned to one plant a station. During the course of the experiment, weeding was done using a hoe to allow the crops to have optimal growth.

3.2 Insect data collection

The crops were exposed to natural infestation by diversity of insects including two major pests being sugarcane aphid and stemborers. Insect monitoring and data collection were done daily to establish population dynamic of insect herbivores and natural enemies for 12 weeks. Sampling of insect was done through *in situ* counts and to reduce effects of sampling on natural insect population dynamics spatially and temporarily. Insect species richness (number of species) and abundance (number of individuals) were used to determine insect diversity among different crop combinations. The athropods were caught on the field to be later identified in the laboratory. They were stored in glass vials containing 99.9% alcohol. Arthropods were identified morphologically using a microscope (Nikon SMZ800) observing the head (antennae, eyes, mandibles and shape of head), thorax and abdomen (number of abdominal segments, number tarsi on the legs). The coccinellidae were identified based on the distinctive colour of the elytra and the shape. An insect key was used to further identify into family, genus and species level. A handbook of field guide to insects of South Africa was further used to help in the identification.

Species richness, abundance and diversity index were used to characterize insect assemblages between various intercrops. The Shannon-Weaver index (H') (Shannon and Weaver, 1949) was used to determine arthropod diversity using the formula:

$$H' = -\sum_{i=1}^{s} \frac{n_i}{n} \log \frac{n_i}{n} \qquad (1)$$

where; s is the number of s species in a sample; n_i is the number of individuals belonging to species i and n is the number of individuals in a sample from a population.

Assessment of foliar stemborer during seedling stage was done by counting the number of sorghum plants showing windowpane feeding, shot holes on whorl leaves and deadhearts on five randomly selected plants. The plants were selected by tossing. The foliar damage was expressed as percentage of plants showing whorl leaf and dead-hearts.

The determination of damage to sorghum stems by larvae was done by splitting stalks after physiological maturity and measuring tunnel length (cm). Stalks of five plants were taken from each plot by excising the plants at the base with knives. The whole stalks were brought to the laboratory where they were dissected longitudinally then, the cumulative lengths of larval tunnels in the stalks, number of tunnels per stalk, number of live borers and moth exit holes were recorded.

To determine the level of parasitism, live stemborer larvae from five dissected plants from each crop combination were individually collected and placed in glass vials containing clean stalk of sorghum (not infested by stemborers) from the field and allowed to feed until moth or parasitoid emergence or death of larvae. The glass vials were closed on top with cotton wool to avoid escape off parasitoids after hatching. The number of parasitized larvae was expressed as a percentage of the total larvae recorded per the number of sampled plants to determine the level of parasitism.

3.4 Nitrogen analysis

Sorghum plants were analyzed for nitrogen to determine host plant quality among the different intercrops and sorghum mono-crop. Three plants were randomly selected from each experimental unit and oven dried at a temperature of 75°C for two days. The dried plants (stem and leaves) were then grounded to powder using a grinder (Fritsh, Industriestr. 8 D-55743 Idar-Oberstein Germany, Serial number: 15.302/1070). After grinding, 0.3g of the plant sample was then mixed with 3ml of hydrogen peroxide and 9ml nitric acid for digestion. The digested samples were then transferred in 20ml volumetric flasks which were filled to the mark with dionized water. Titration was used to help in calculation of nitrogen. 20ml of the sample from the volumetric flask was mixed with 25ml of sodium hydroxide and then distilled. The distilled sample was mixed with 50ml of boric acid in a 250ml conical flask. The sample was than titrated using 0.01M hydrochloric acid (HCl). As soon as there was colour change the amount of HCl used was recorded. Before the samples were titrated a blank was used to determine the amount of HCl used when there was no sample.

Percentage nitrogen was calculated using the following equation:

$$\%N = \frac{(a-b)}{s} * M * 1.4 * mcf \tag{2}$$

where; a = ml of HCl required for titration sample, b=ml of HCl required for titration blank, s = air-dry sample weight in grams, M = molarity of HCl, 1.4 $=14*10^{-3}*100\%$ (14 = atomic unit of N), mcf = moisture correlation factor.

3.5 Grain yield

After the sorghum crop reached physiological maturity by observing the panicle when the seeds were in milk to dough stage, sorghum grain yield and yield components (harvest index, seed weight and panicle weight) were measured randomly by harvesting grain from ten plants per row and weighing threshed grain and then converting to kg/ha. The panicle weight was measured using a scale and expressed in Kg. The seeds were counted using a seed counter machine to determine the 1 000 seed weight. For harvest index, the plants were oven dried at a temperature of 75°C for 2 days. These were then weighed and harvest index was determined using the following formula:

Harvest Index = Grain yield (kg/ha)/Total Biomass Yield (Stover+Grain yield)

3.6 Assessment of yield loss caused by stemborer damage

The sorghum-legume intercrops and mono-crop treatment were used to vary larval density of stem borer which was then related to yield by regression analysis. The relationship between yield (Y) and larval density, yield loss and larval density were determined by fitting a linear curve;

$$y = a-bx \tag{3}$$

where a = expected yield loss at zero stemborer infestation, b = regression coefficient or yield loss in tonnes caused by stemborer damage, x= number of larvae per plant. A linear relationship between stem tunnelling and yield and between stem tunnelling and yield loss was also determined through regression analysis. Yield loss was calculated as *(1- yield as proportion of the maximum yield) * 100* (Catangul *et al.*, 2009). Maximum yield obtained from sorghum groundnut intercrop was used in the calculation of yield losses of different crop combinations.

3.7 Determination of Economic Injury Level

Results from regression analysis of larval counts and sorghum grain yield was used in calculating EIL. EIL was calculated using the equation from Pedigo and Rice (2006);

$$EIL = C/VIDK \qquad (4)$$

where; C= cost of management per area (intercropping cost i.e. labour and cost of seed of legume); V= market value per unit of produce; I = injury units per insect per production unit; D= damage per unit injury; K= proportionate reduction in potential injury or damage (k =1). The IxD product which is difficult to separate when dealing with most insects (Pedigo *et al.*, 1986) was substituted with coefficient b after regressing yield loss against number of larve per plant. Therefore EIL was calculated as, $EIL= C/VbK$. Gain threshold (GT) which estimate the yield increase needed to compensate for pest management costs was calculated as *GT= cost of protection/ market value*. The market value of sorghum sourced from Botswana Agricultural Marketing Board was P185.00 per 50kg in 2016. The cost of intercropping which represent cost of protection was determined by adding the labour cost for planting and the cost of seed in kgha^{-1} The price of groundnut and cowpea was BWP700. 00, Bambara groundnut groundnuts was BWP 600.00 and chickpea was BWP700.00. Benefit to cost ratio and gross monetary profit were analyzed to determine the most cost-effective crop combinations that can lower stemborer damage to sorghum below economic injury levels.

3.8 Data analyses

The pattern and structure of data on species richness, diversity and composition was detected using multivariate analysis. Species composition of the insects collected from different intercrops was examined using cluster analysis. The within the group clustering method based on the Euclidean distances was used in the cluster analysis. Principal Component Analysis was used to investigate relationship in species composition between intercrops,.

Data on weekly counts of insects were analyzed as repeated measure designs using a repeated statement in a mixed model procedure (PROC MIXED) (SAS Institute, 2003). The procedure was adjusted for the serial autocorrelation among the repeated samples on each sampling time (weeks) (Littell *et al.*, 1996). The Akaike's Information Criterion (AIC) (Akaike, 1974) was used to select the covariance structures which best model the insect data.

The response of predatory coccinellid beetles to aphid density was tested by fitting a polynomial function. The dependent variable was density of prey predated and independent variable was density of prey per predator. A significant positive correlation indicated that an increase in prey density consumed resulted in an increase in predator density.

The relationship between sorghum grain yield and stemborer damage on sorghum was determined using multiple regression analysis, with yield as the dependent variable deadhearts, foliar damage, length of tunneling, number of tunnels and number of moth exit hole and number of larvae per plants as independent (predictor) variables. The multiple linear regression model used to fit the data is;

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon. \qquad (5)$$

Where; Y is potential yield, x is the predictor variable, β_0 is the intercept, β_1 slope of equation, ε is the error term. The best-fit models were selected based on stepwise procedures and the best subsets regression in Minitab® Release 17 (Minitab Inc., 2017). The selection criteria were based on coefficient of determination (R^2), mean square error (MSE), and Mallow's Cp (Quinn and Keough, 2002). The selection was based on small mean square error (MSE), highest adjusted r^2 values, and a smallest Cp values (Fry, 1993). Multicollinearity was diagnosed by assessing the bivariate correlations and the variance inflation factor (VIF) to identify predictor variables that could be correlated.

Data on species richness diversity, abundance, percentage nitrogen, stemborer damage to sorghum and yield and yield components were analyzed using the mixed model procedures to generated restricted maximum likelihood (REML) variance estimates. Multiple comparisons were made on least square means. All comparisons were based on least significance level (LSD) at $P \leq 0.05$.

CHAPTER 4: RESULTS

4.1 Arthropod abundance and diversity

Insect diversity and abundance data showed that a total of 6632 individuals from six insect Orders of Coleoptera, Hymenoptera, Orthoptera, Hemiptera, Diptera and Lepidoptera were collected from the four different crop combinations and sorghum-monocrop (Table 1). The crop combination that had the highest number of individual species was sorghum- cowpea intercrop (n=1904). Sorghum mono-crop had the lowest number of total individual species (n=852). The most collected species across the crop combination was *Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae) (n= 2495) followed Aphididae sp. 1 (n = 1982) then *Chilo partellus* (n = 650) and the least (n=1) were *Harmonia vigintiduomaculata* F. (Coleoptera: Coccinellidae), *Parachilus capensis* Saussure (Hymenoptera: Eumenidae), *Stenobracon rufus* Szepligeti (Hymenoptera: Braconidae) and *Temelucha* species (Hymenoptera: Ichneumonidae). There was a significant difference in the number of individuals between the crop combinations ($F_{4,12}$= 3.70, P = 0.0350) (Table 2). The lowest mean number of individuals was recorded on sorghum monocrop while the highest was obtained from sorghum-cowpea intercrop.

The Order Coleoptera was presented by two families namely Coccinellidae and Staphylinidae. The highest number of individual coleopteran species was collected from sorghum-cowpea intercrop (n= 27) while sorghum-chickpea intercrop had the lowest numbers (n=19). The most commonly collected Coleopteran species was *Cheilomenes lunata* Fabricius (Coleoptera: Coccinellidae) which appeared in all crop combinations (n=72). Cocinellidae sp.1 was the least collected Coleopteran species (n=1). From the Order Orthoptera only two well-known pest species were recorded namely *Zonocerus elegans* Thunberg (Orthoptera: Pyromorphidae) and *Acanthoplus discoidalis* Walker (Orthoptera: Bradyporidae) (Table 1).

Table 1. Abundance of arthropods collected from sorghum and companion crops

Arthropod species	Abundance (Number of individuals collected)				
	Sorghum monocrop	Sorghum-cowpea	Sorghum-groundnut	Sorghum-Bambara groundnut groundnut	Sorghum-chickpea
COLEOPTERA					
Coccinellidae					
Cheilomenes lunata (Fabricius)	14	20	13	17	8
Exochomus flavipes (Thunberg)	2	3	1	2	2
Hippodamia variegata (Goeze)	2	0	6	2	0
Harmonia vigintiduomaculata (F.)	0	0	3	2	1
Coccinellidae sp. 1	0	0	0	1	0
Oenopia cintella (Mulsant.)	9	4	3	5	6
Coccinellidae sp. 2	1	0	0	0	1
Chrysomelidae sp.1	0	0	0	1	1
Staphylinidae sp. 1	0	0	3	0	0
ORTHOPTERA					
Pyrgomorphidae					
Zonocerus elegans (Thunberg)	0	7	2	3	4
Bradyporidae					
Acanthoplus discoidalis (Walker)	0	0	0	1	0
DIPTERA					
Syphidae					
Syphidae larvae sp. 1	11	8	10	5	6
Syphidae larvae sp. 2	2	8	7	6	3
Syphidae larvae sp. 3	2	3	6	0	0

Syrphid fly adult	1	4	2	3	6
Tachnidae sp. 1	0	0	0	0	2
HEMIPTERA					
Alydidae					
Mirperus jaculus (Thunberg)	0	10	0	9	3
Pentatomidae					
Nezara viridula L.	2	0	1	1	0
Lygaidae					
Spilosthethus pandurus (Scopoli)	2	3	3	5	0
Oncopeltus famelicus F.	1	0	0	2	0
Aphididae					
Melanaphis sacchari (Zehntner)	321	820	303	514	537
Aphididae sp. 1	129	508	326	458	561
HYMENOPTERA					
Eumenidae					
Parachilus capensis (Saussure)	1	0	0	0	0
Apidae	0	0	0	0	0
Apis mellifera capensis					
(Eschscholtz)	0	23	0	0	0
Formicidae					
Formicidae sp.1	0	0	11	5	2
Formicidae sp. 2	0	41	0	0	0
Formicidae sp. 3	0	28	0	6	0
Formicidae sp. 4	0	0	1	0	0
Formicidae sp. 5	5	12	1	3	2
Formicidae sp. 6	0	35	20	28	10
Formicidae sp. 7	197	209	152	190	175
Braconidae					
Iphiaulax species	0	1	0	0	0

Stenobracon rufus (Szepligeti)	0	0	1	0	0
Cortesia sesamiae (Cameron)	0	4	19	0	7
Braconidae1	0	0	1	0	0
Chalcididae					
Psilochalis sondanensis (Steffan)	0	1	1	1	0
Ichneumonidae					
Temelucha spp	0	0	1	0	0
Eulophidae					
Pediobius furvus (Gahan)	0	0	3	0	0
LEPIDOPTERA					
Noctuidae					
Helicoverpa amigera (Hübner)	1	4	0	2	2
Chilo partellus (Swinhoe)	146	142	137	94	131
Non-Insect Arthropods					
Chilopoda	0	1	1	0	1
Arachnid	3	5	0	0	1
Total No. individuals (*N*)	**852**	**1904**	**1038**	**1366**	**1472**
Total No. of species (*S*)	**20**	**24**	**28**	**26**	**23**

The highest number of individuals of *Z. elegans* was collected from sorghum- cowpea intercrop (n= 7) and the lowest numbers came from sorghum-groundnut (n = 2).

In the order Diptera, sorghum-groundnut intercrop had the highest total number of individuals (n=25) and sorghum-Bambara groundnut intercrop had the lowest (n=14). The most collected Dipteran species was Sryphid larvae sp.1 (n=40) and least collected was Tachnidae sp 1. Sorghum-cowpea intercrop had the highest number of individual species from the order Hemiptera (n=1 341) while sorghum mono-crop had the lowest number (n=455). *Melanaphis sacchari* was the most abundant Hemipteran species (n=2 495) and the least abundant species was *Oncopelus famelicus* (n=3).

From the order Hymenoptera, sorghum-chickpea intercrop had the lowest number individual species (n=196) and sorghum mono-crop had the second lowest number (n=203). The most collected species was Formicidae sp. 7 (n=923). Sorghum-cowpea intercrop had the highest number of total Hymenopteran individuals (n=354) followed by sorghum-Bambara groundnut intercrop (n=233). Sorghum-Bambara groundnut intercrop had the lowest number of individual lepidopteran species (n=96) and sorghum-cowpea intercrop had the highest number of individual species (n=151). The most abundant lepidopteran species was cereal stemborer, *Chilo partellus* (n= 655) and highest numbers was collected from sorghum mono-crop (Table 1). The non-insect Orders Chilopoda and Arachnida were recorded on sorghum-groundnut and sorghum- chickpea intercrops.

The data on species richness (*S*) is shown in Table 1. There was a significant difference in the number of species among the crop combinations ($F_{4, 12}$=2.71; P= 0.05) (Table 2). A significantly lower number of species occurred in sorghum mono-crop and highest species richness was recorded on sorghum-groundnut intercrop (Table 1). The same trend was shown by the Shannon's diversity indices, which were significantly different among crop combinations ($F_{4, 12}$ = 25.41; P=0.0001). A significant reduction in species diversity was observed on sorghum mono-crop compared to other intercrops (Table 2). Sorghum-cowpea intercrop had the highest mean number of species and sorghum-groundnut intercrop had the lowest mean number of species (Table 2).

The species composition of arthropods collected from different crop combinations is shown in Fig. 1. The insect Order that had the highest number of species was Hymenoptera (S=16) and the least was Orthoptera (S=2) and Lepidoptera (S=2). Sorghum-groundnut intercrop had the highest number of total species (S=28) with sorghum mono-crop having the lowest number (S=20) (Table 1).

For the order Coleoptera, sorghum-Bambara groundnut intercrop had the highest number of coleopteran species, which were seven followed by sorghum-groundnut and sorghum-chickpea intercrops. *Cheilomenes lunata, Harmonia vigintiduomaculata, Exochomus flavipes* Thunberg (Coleoptera: Coccinelidae), and *Oenopia cintella* (Coleoptera: Coccinellidae), were common in all the crop combinations. There were two families of Orthoptera that were collected, Pyrgomorphidae and Bradyporidae. For the order Diptera, sorghum-Bambara groundnut intercrop had the lowest number of Dipteran species (S=3) while all the other treatments had a total number of four dipteran species.

Insect pest species recorded included Hemipterans namely *Nezara viridula* L., *Mirperus jaculus* (Thunberg) which appeared in all the intercrops *Spilosthethus pandrurus* (Scopoli), *Oncopeltus famelicus* F., *Melanaphis sacchari* (Zehtner) and Aphidae sp.1. In the order Hymenoptera, six families were collected and the Formicidae family had the most species collected. Formicidae sp.7 was collected across all treatments. *Apis mellifera* (Eschoholtz) only appeared in sorghum- cowpea intercrop. Parasitoids from familes Braconidae, Chalcididae, Ichneumonidae and Eulophidae were collected but absent in sorghum mono-crop. *Stenobracon rufus*, *Temelucha sp* and *Pediobius furvus* were only present in sorghum-groundnut intercrop while *Iphiaulax species* were only present in sorghum-cowpea intercrop.

Table 2. Mean insect abundance, species richness and diversity from five crop combinations ±SE.

Crop combinations	**Abundance**	**Species richness**	**Species diversity index**
Sorghum monocrop	176.50±37.79b	9.25±1.25c	0.24±0.01c
Sorghum- cowpea	438.00±102.52a	14.00 ±1.87b	0.54 ±0.02a
Sorghum- groundnut	218.75± 69.91b	10.0±1.47bc	0.47±0.05ab
Sorghum-Bambara groundnut	317.75 ± 43.78ab	13.00±1.08ab	0.52± 0.02ab
Sorghum- chickpea	333.50±110.88ab	11.50±1.55abc	0.45±0.01b

The means with the same letter are not significantly different (P≤0.05).

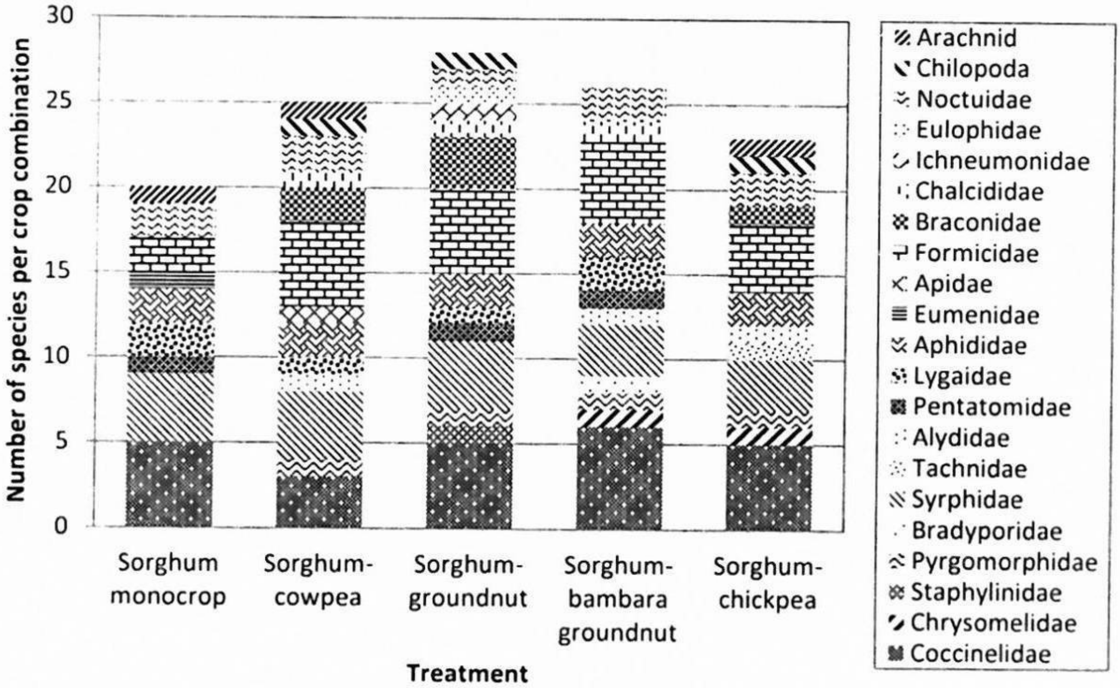


Fig. 1. Mean number of arthropod species of families collected from different crop combinations.

The most dissimilar treatment in terms of species composition was sorghum mono-crop which was only closer to sorghum-chickpea intercrop. Sorghum-Bambara groundnut intercrop had less similarities compared to the rest of intercrops. Similar trend was shown by Principal Component analysis (PCA) (Fig 2 and Table 3). Cluster analysis of species composition showed that sorghum- cowpea and sorghum-groundnut intercrops were clustered together therefore showing similarities in species composition (Fig. 3). Results from analysis of eigenvalues generated by PCA showed that more than 85% of the total variation was explained by the first two components. Plot of eigenvectors of the first component, which came from attribute loadings generated by variables were correlated with the intercrops. Apart from sorghum-Bambara groundnut the second component was correlated with the sorghum mono-crop.

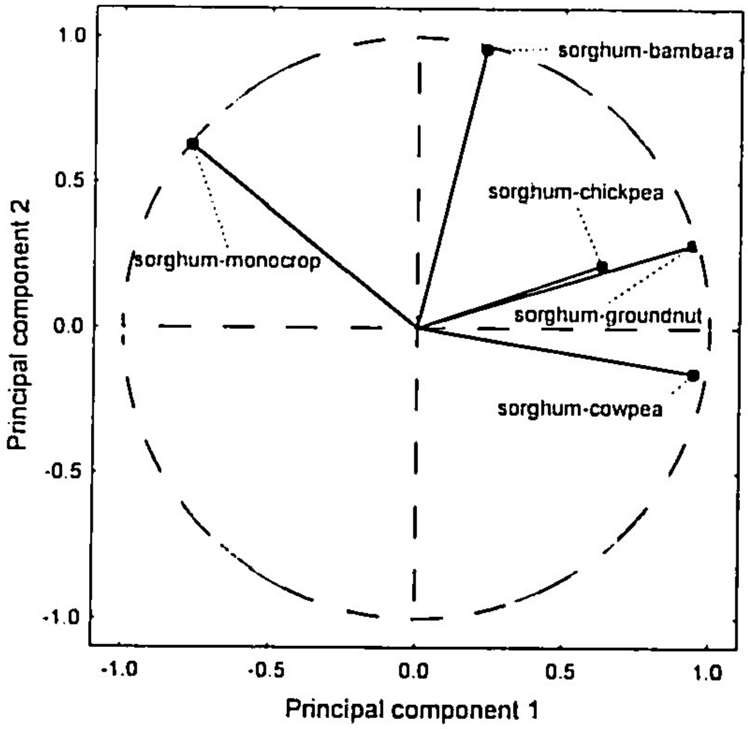


Fig. 2. Principal component and classification analysis of species composition from five different crop combinations.

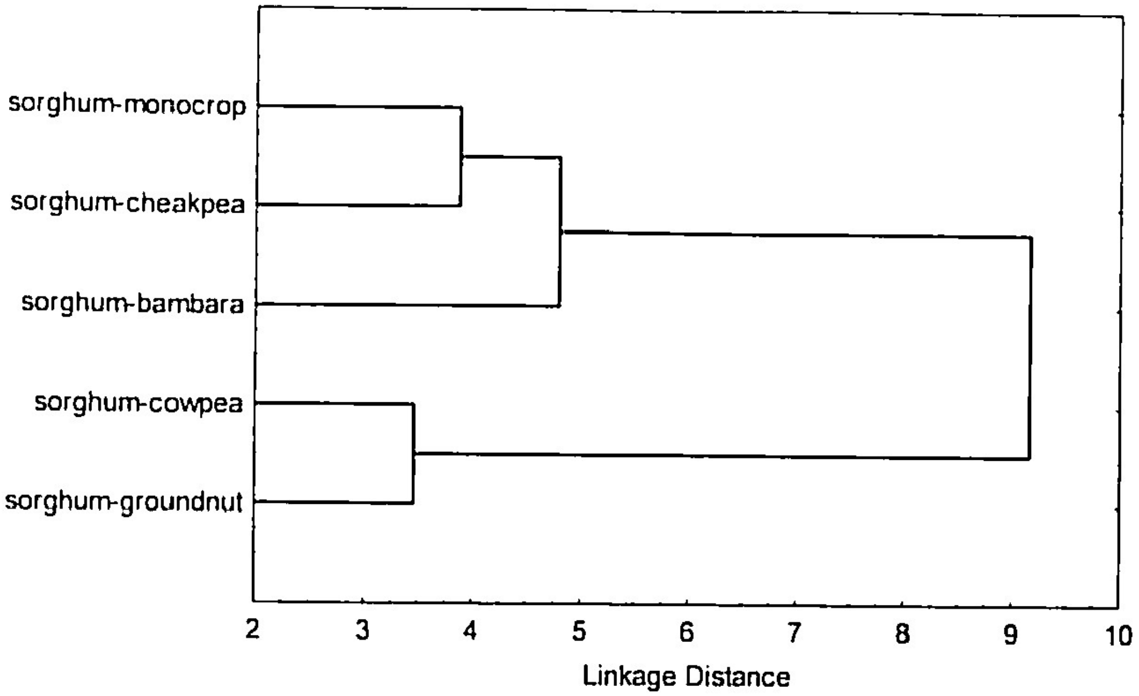


Fig. 3. Dendogramme of hierarchical analysis of cluster analysis of crop combinations showing similarities between the insect species combinations.

Table 3. Eigen analysis results of the correlation matrix for species composition of intercrops

Component	Eigenvalue	Variation explained (%)	Cumulative variation (%)
1	2.82	56.35	56.35
2	1.47	29.36	85.71
3	0.69	13.84	99.55
4	0.02	0.45	100.00

Attribute loading for eigenvectors[a]

Variable	Factor 1	Factor 2
sorghum monocrop	-0.460353	0.518218
sorghum cowpea	0.562398	-0.127068
sorghum groundnut	0.559444	0.239134
sorghum Bambara groundnut	0.137942	0.791135
sorghum chickpea	0.373869	0.179510

[a] Only eigenvectors for components 1 and 2 are shown.

These two components account for 85.70% of the total variation in the data set

4.2 Predation and parasitism

Population dynamics of the most predominant predatory coccinellids (*C. lunata, O. cintella, H. vigintiduomaculata, E. flavipes and H. variegate)* are shown in Fig.4-9. The density, of *C. lunata* was not significantly influenced by crop combination ($F_{4,\ 144}$=1.03, P=0.3955) but by time of sampling ($F_{11,144}$=10.17, P=0.0001). However, the mean density was lowest on sorghum-monocrop. *Cheilomenes lunata* was present in high numbers on the first week but then declined in the second week except on sorghum-cowpea intercrop where on the second week the numbers increased (Fig. 4). For sorghum- groundnut intercrop, after the first week the numbers reached zero but then peaked again on the third week where the numbers declined again. On the fifth week, *C. lunata* disappeared but then it reappeared on week 10. The population peaked again on week 12 with sorghum- Bambara groundnut intercrop having the highest numbers. Sorghum mono-crop had the lowest numbers compared to the intercrop on week 12.

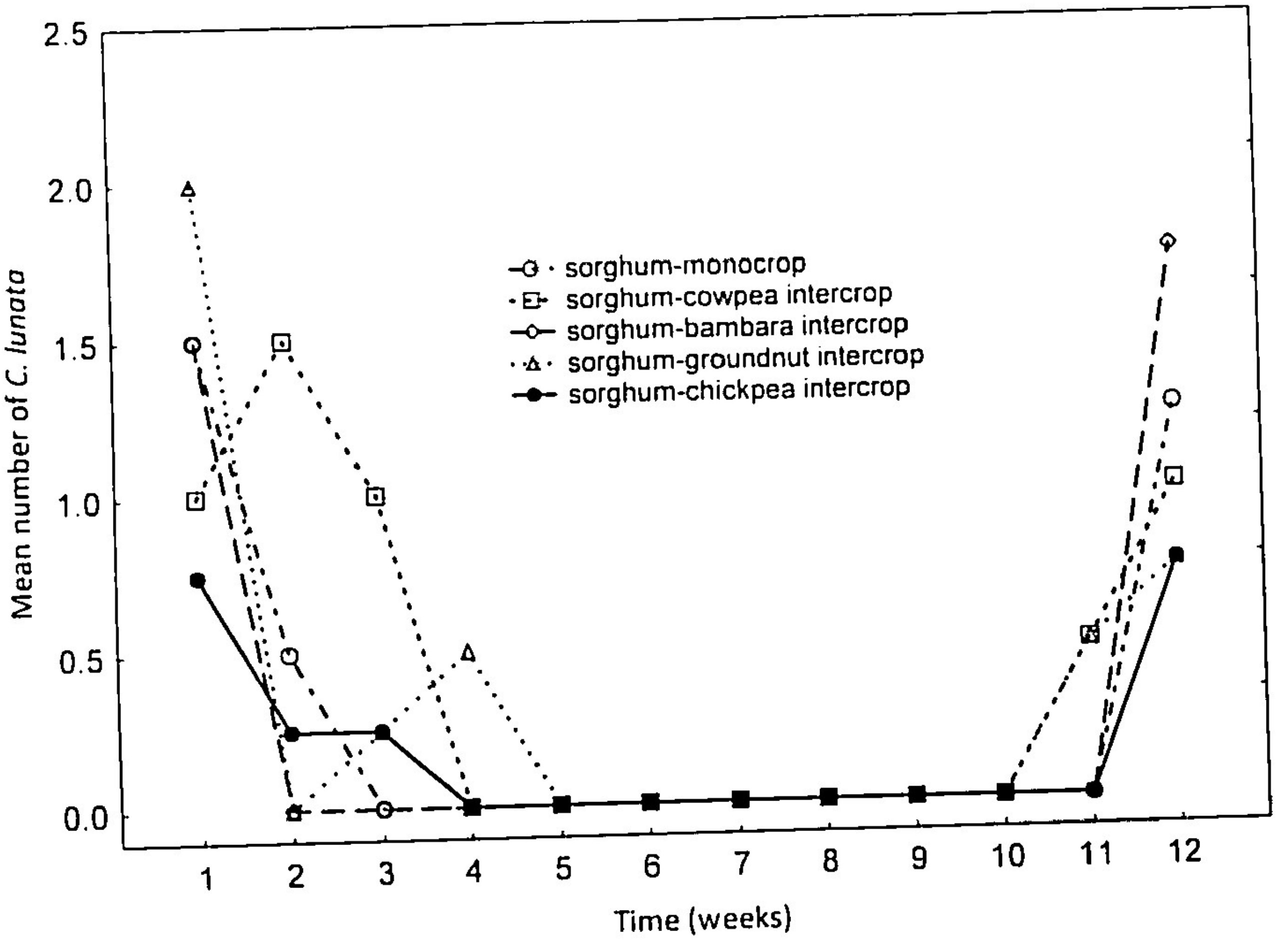


Fig. 4: Mean number of *Cheiolomenes lunata* over time (weeks) collected from different crop combinations.

The density of *O. cintella* did not vary significantly between crop combinations ($F_{4,144}$=1.30, P=0.2730) but was significantly affected by time of sampling ($F_{11,144}$=2.59, P=0.0045). *Oenopia cintella* first appeared on the second week and continued to increase to the third week (Fig. 5). Its numbers remained the same for sorghum mono-crop but gradually declined on week 6. On week five, it reached its highest peak for sorghum- cowpea and sorghum-chickpea, where the numbers kept fluctuating until week 10. At week 11, the highest peak was observed on sorghum-groundnut intercrop but then declined in week 12.

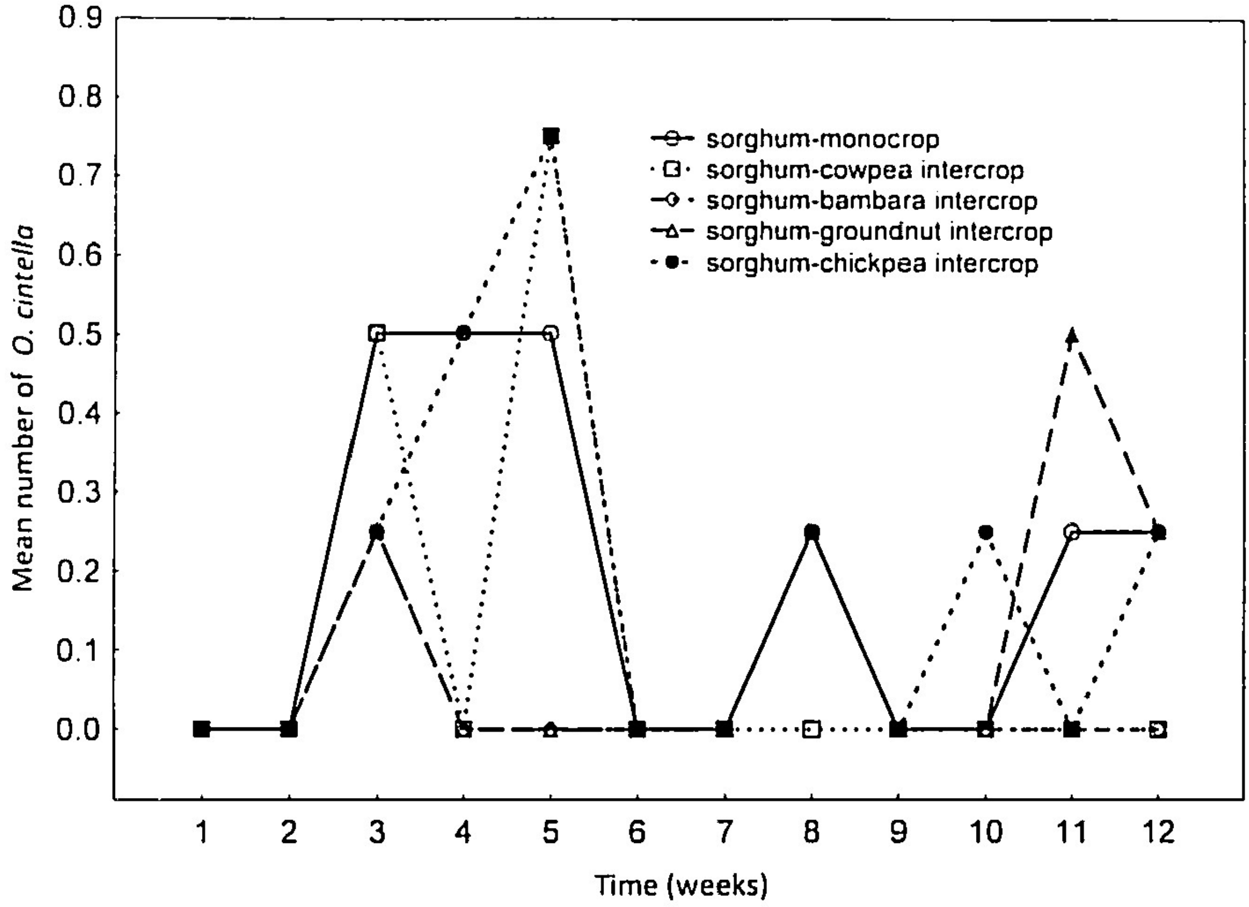


Fig. 5. Mean number of *Oenopia cintella* over time (weeks) collected from different crop combinations.

Harmonia vigintiduomaculata density did not vary significantly between crop combinations ($F_{4,144}$=0.55, P=0.6991) but varied between time ($F_{11,144}$=2.80, P=0.0022). Its first appearance was on week 11 and had the highest peak on week 12 when the experiment was discontinued (Fig. 6). Its density changed significantly overtime but did no vary among crop combinations. The highest density was observed on sorghum-groundnut intercrop and the lowest was on sorghum monocrop.

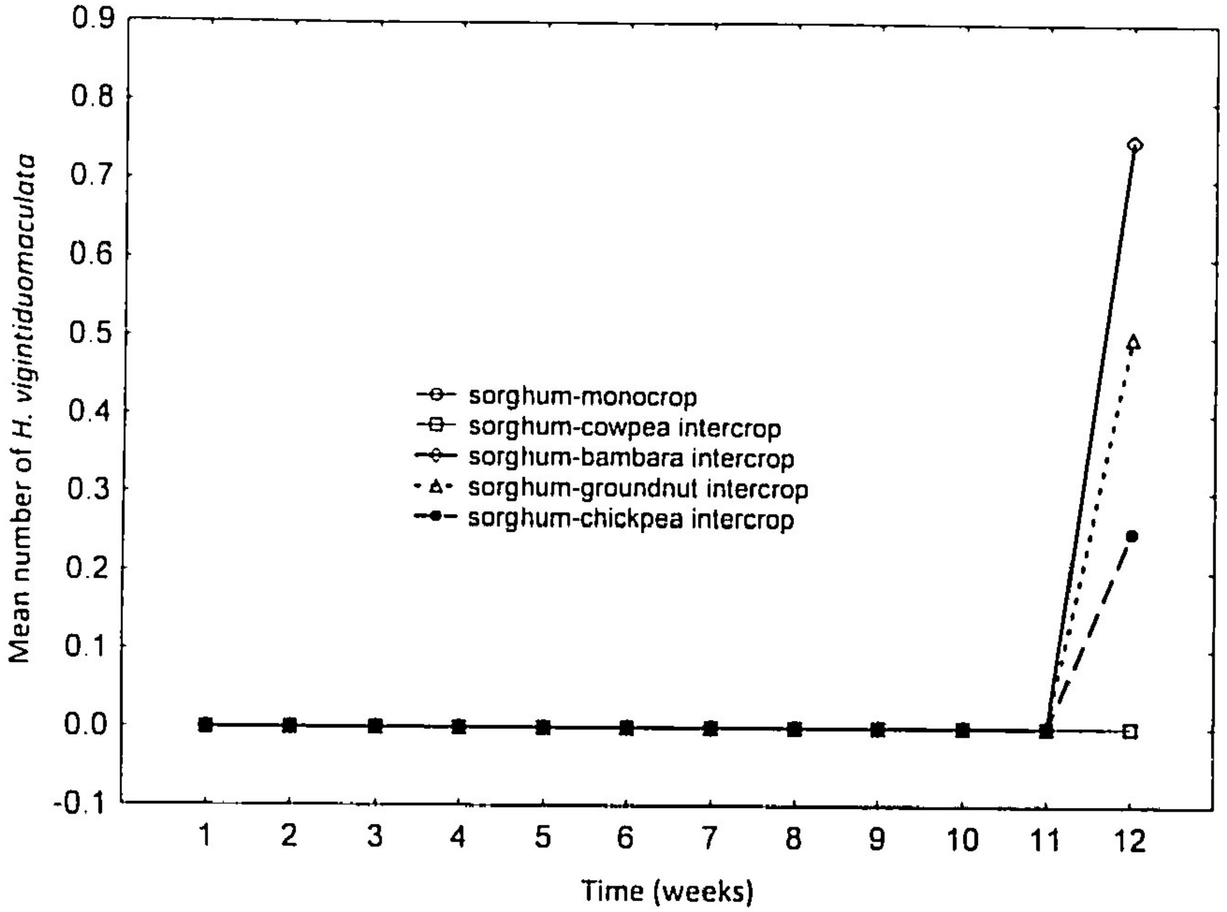


Fig. 6. Mean number of *H. vigintiduomaculata* over time (weeks) collected from different crop combinations.

The mean number of *E. flavipes* did not vary significantly between crop combinations but significance occurred over time ($F_{11,144}$=2.17, P=0.0178). No significant crop combination x time interaction was detected ($F_{44,144}$=0.58, P=0.9811). The peak of *E. flavipes* was highest on week 1 in sorghum- cowpea intercrop but reached 0 in week 2, when it appeared in sorghum-chickpea intercrop (Fig. 7). It remained constant until week 4 when its density declining. In sorghum- Bambara groundnut intercrop it was at the same density as sorghum-chickpea intercrop at week 3 but its density gradually decreased and reached 0 at week 4. The following weeks it was absent until week 9 when it appeared in sorghum-groundnut intercrop and remained constant until week 11. At week 12, its density was zero in all crop combinations.

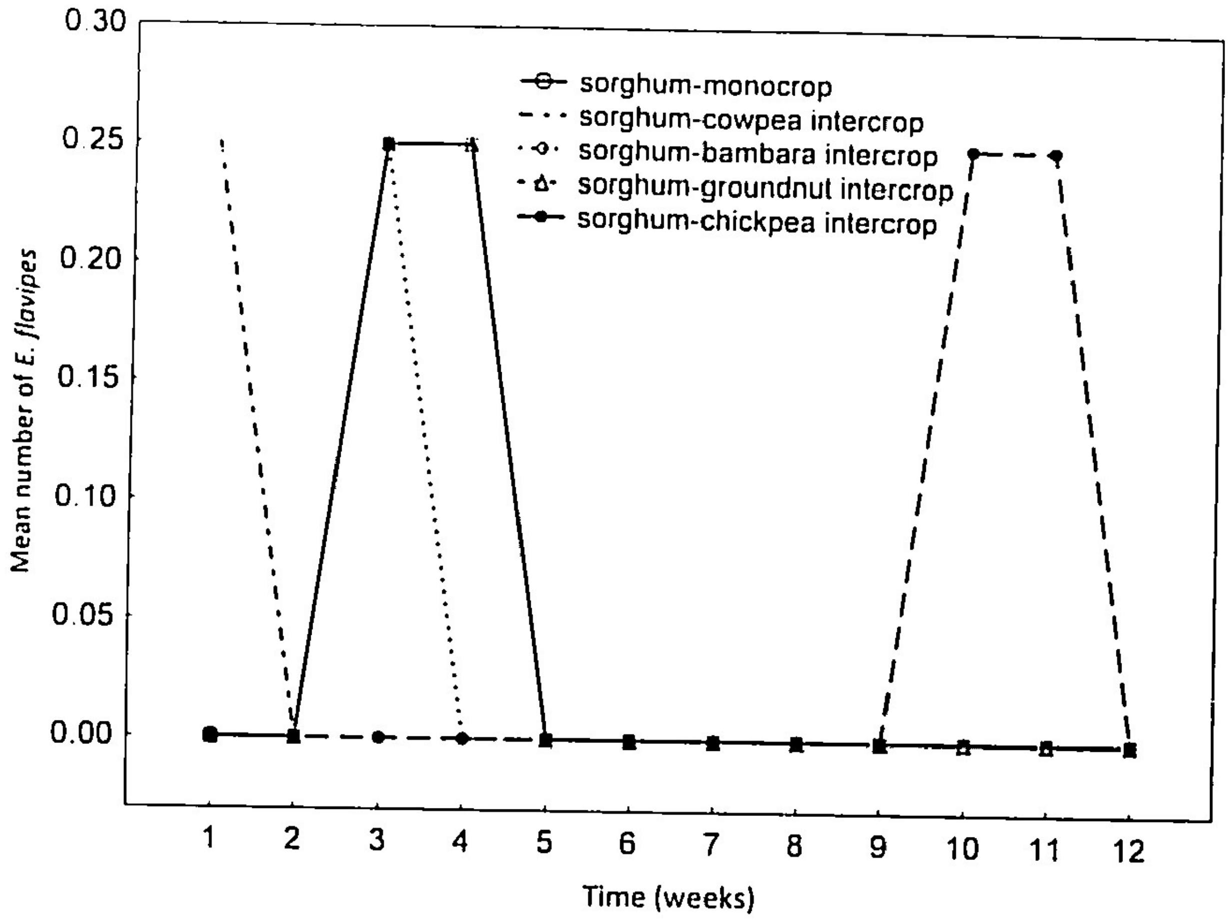


Fig. 7. Mean number of *E. flavipes* over time (weeks) collected from different crop combinations.

The density of *H. variegeta* did not vary significantly over crop combinations ($F_{4,144}$=0.70, P=0.5962) or time ($F_{11,144}$=1.43, P=0.1613). It first established in sorghum-groundnut intercrop at week 2 and reached its peak on week 3 where it was at the same density as in sorghum mono-crop (Fig 8). Its density started declining but it remained constant in sorghum mono-crop and reached zero at week 5. After week five it was absent in all the crop combinations then at week 11 it appeared in sorghum-Bambara groundnut and sorghum-groundnut intercrop. At week 12, it was at its highest on sorghum-Bambara groundnut intercrop followed by sorghum-groundnut and it did not appear on the other crop combinations.

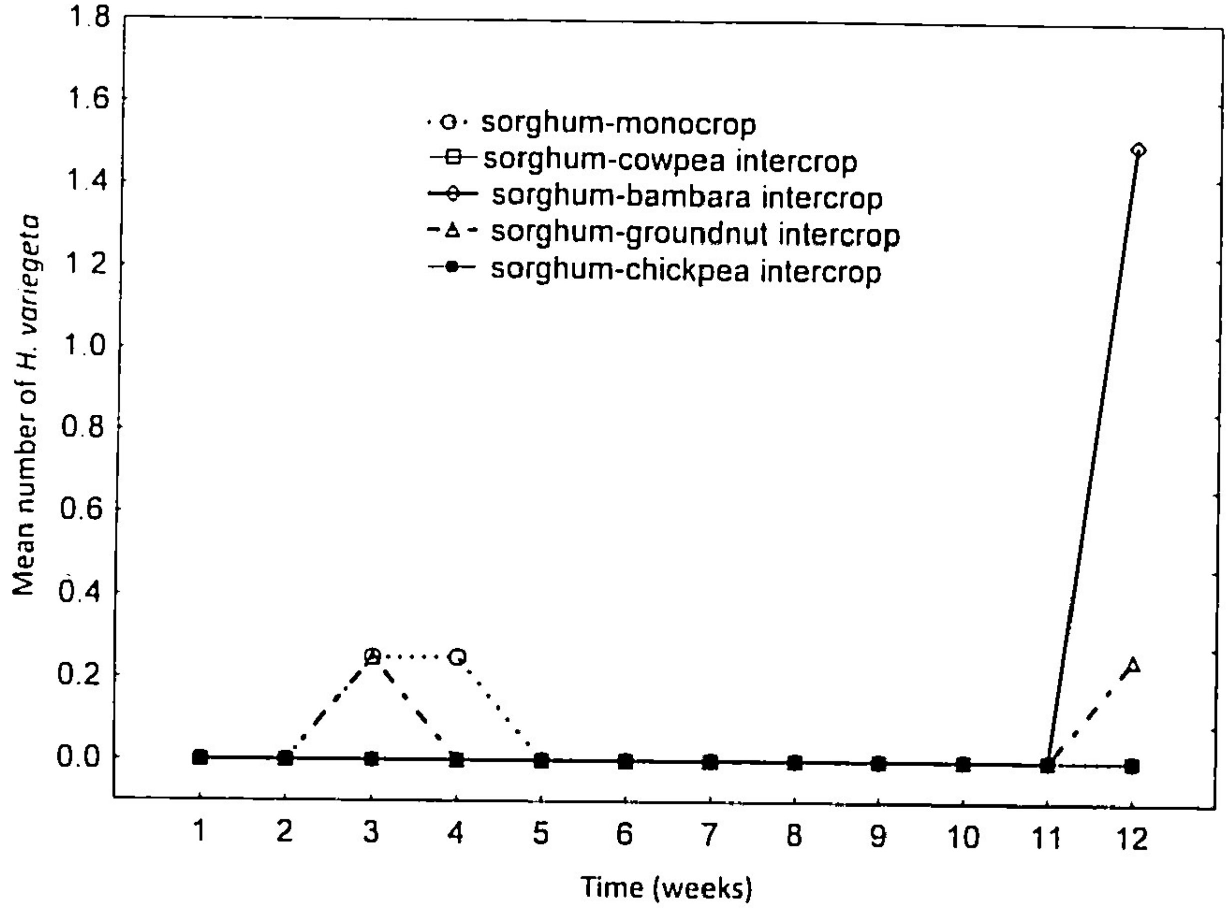


Fig. 8. Mean number of *H. variegeta* over time (weeks) collected from different crop combinations.

The density of *M. sacchari* was not significantly influenced by crop combination ($F_{4,144}$=1.48, P=0.2092) but by time ($F_{11,144}$=9.07, P=0.0001). *Melanaphis sacchari* appeared on sorghum-Bambara groundnut , sorghum–chickpea and sorghum–groundnt intercrops at week 1. The population of *M. sacchari* on sorghum-chickpea intercrop increased at week 2 and then started declining until week 4 when it reached zero (Fig 9). In sorghum-cowpea intercrop, *M. sacchari* increased, at week three it was the highest compared to all the other crop combinations and then started declining until week six when it was zero. *Melanaphis sacchari* on sorghum-groundnut intercrop increased until week three when it started declining until week six when it was zero. At week three, the population of *M. sacchari* in sorghum-cowpea and sorghum-groundnut intercrops had the highest numbers of the aphids. *Melanaphis sacchari* on sorghum mono-crop started decreasing from week one and at week two it was at the same number as sorghum-Bambara groundnut intercrop.

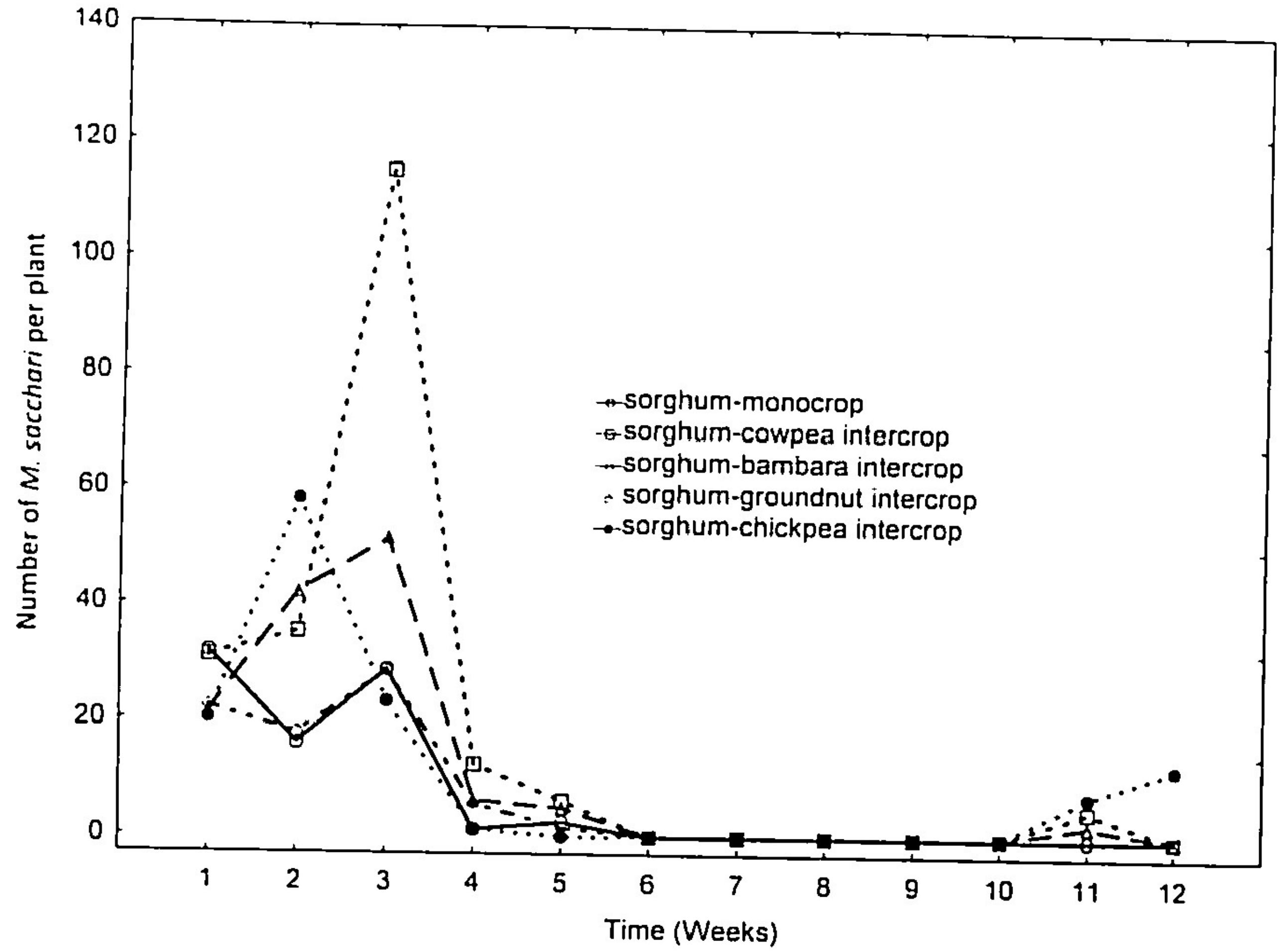


Fig. 9. Mean number of *M. sacchari* over time (weeks) counted from different crop combinations.

The population was lowest at week 2 and started peaking until week 3. At week 3, sorghum-chickpea intercrop had the lowest numbers of *M. sacchari*. At week 6, there were no aphids in all the crop combinations until week 10. The aphid numbers on sorghum- chickpea intercrop kept increasing until the last week of the experiment. Sorghum mono-crop and sorghum-Bambara groundnut intercrop had no aphids until the end. At week 12, all the crop combinations had no aphids except sorghum- chickpea intercrop.

The relationship between sugarcane aphid and five predatory coccinellid beetles is shown in Fig. 10. When the density of *M. sacchari* was high, the predator numbers were also high. *C.*

lunata was high in numbers from week 1 until week 3 while the other predators were not established. After week, two other coccinellid started appearing and increasing in density while *M. sacchari* density declined due to predation. There was a slight increase in predator density after week 3 but significantly declined by week five except *O. cintella* which declined significantly between week six and 7 (Fig. 10).

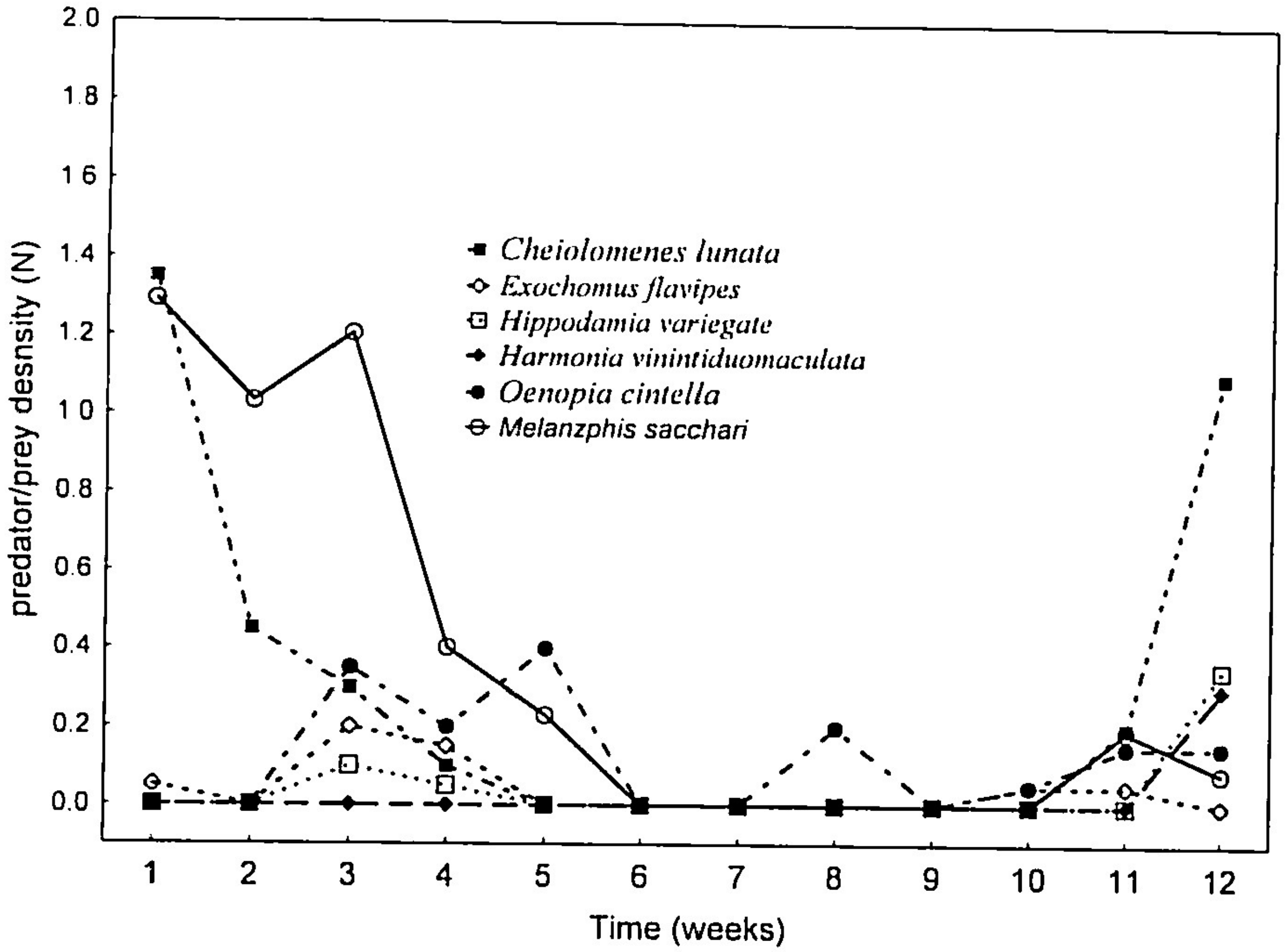


Fig. 10. Relationship between densities of five predatory coccinellid beetles and sugarcane aphid *M. sacchari* measured over 12 weeks.

After week 4 the density of *M. sacchari* decreased to insignificant levels, so did the density of the predators. From week, six there were no aphids and predators except for *O. cintella* which was present from week seven till week nine then started showing up during week 10. When *M. sacchari* appeared again at week 10, the predatory coccinellids also started appearing. It is apparent that the change in the density of the coccinellid predators responded to change in their prey density in this case the sugarcane aphid. A polynomial curve fitting which described data better for all three predatory coccinellids indicated a predator prey response typical of Type II functional response (Fig. 11). An increase in the aphid preyed resulted in an increase in predator density until it levelled off.

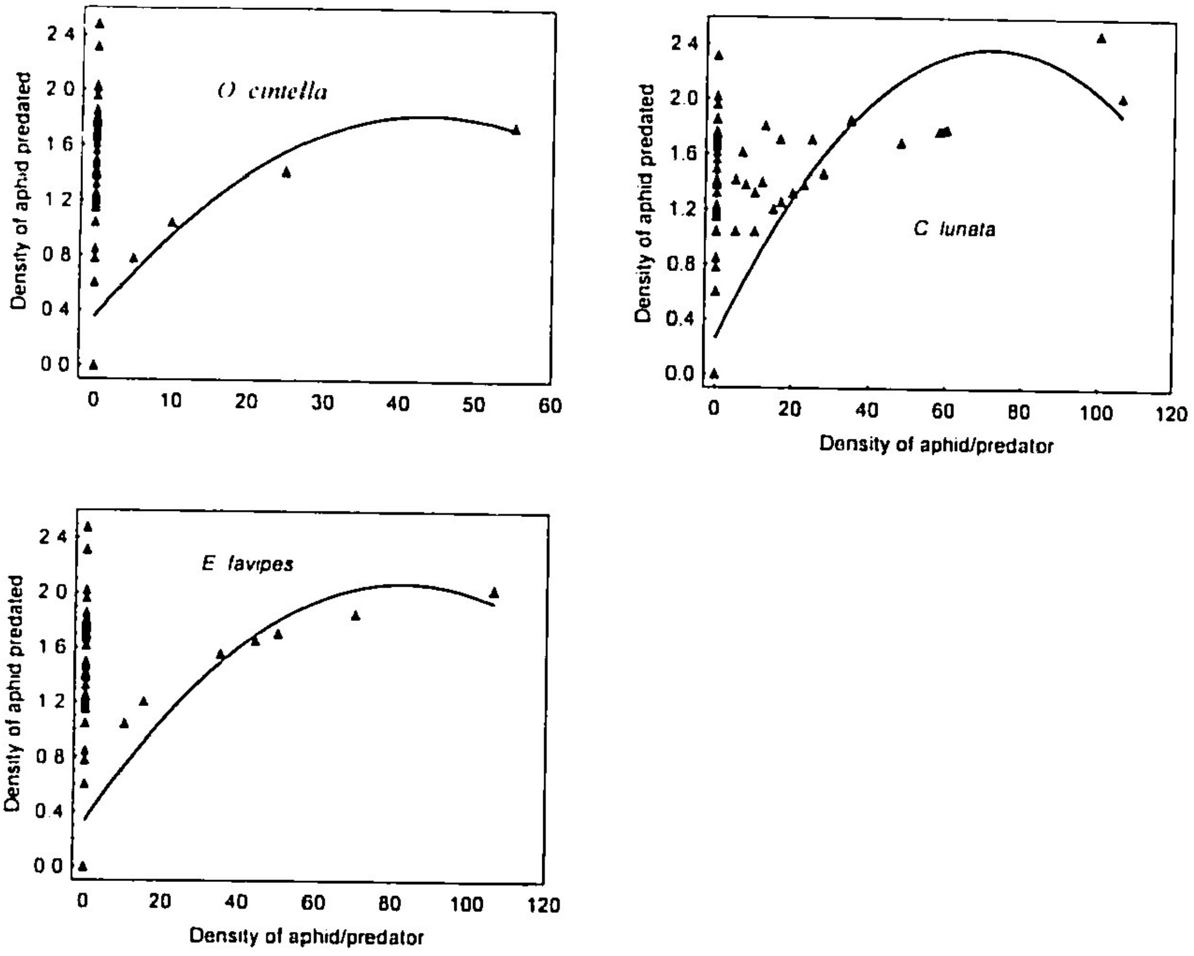


Fig. 11: Response of predatory coccinellid beetles (*O. cintella, C. lunataand E. flavipes)* to *M. sacchari* density under field conditions (data was pooled across the five cropping systems). [*O. cintella*: r = 0.1864, *P* = 0.004, Y = 0.0676x-0.0008x^2 +0.3534] [r = 0.3095 *P* < 0.001, Y = 0.0421x-0.0003x^2 +0.336] [*C. lunata:* r = 0.5108, P<0.001, Y = 0.0588x-0.0004x^2 + 0.2651] [*E. flavipes*: r = 0.31, p <0.0001, Y = 0.34+0.04x-0.0003x^2

Syrphidae sp. 1 larvae density varied significantly over time ($F_{11,144}$=0.522, P=0.001) but did not vary significantly among crop combinations ($F_{4,144}$=0.40,P=0.8058). It started appearing in week 1 in sorghum-groundnut intercrop (Fig. 12). The larval density peaked on week three on all crop combinations, and declined by week four and peaked again after week five. In sorghum mono-crop, the population declined drastically during week five and peaked again at week 6 after that it started declining towards week seven when it disappeared. On sorghum-Bambara groundnut, intercrop the population remained constant from week five until week eight when it started declining until it reached zero on week nine. On sorghum-groundnut intercrop the population peaked around week 10 and dropped on week 11, and disappeared. A sudden peak was observed on week 12 when the experiment was terminated.

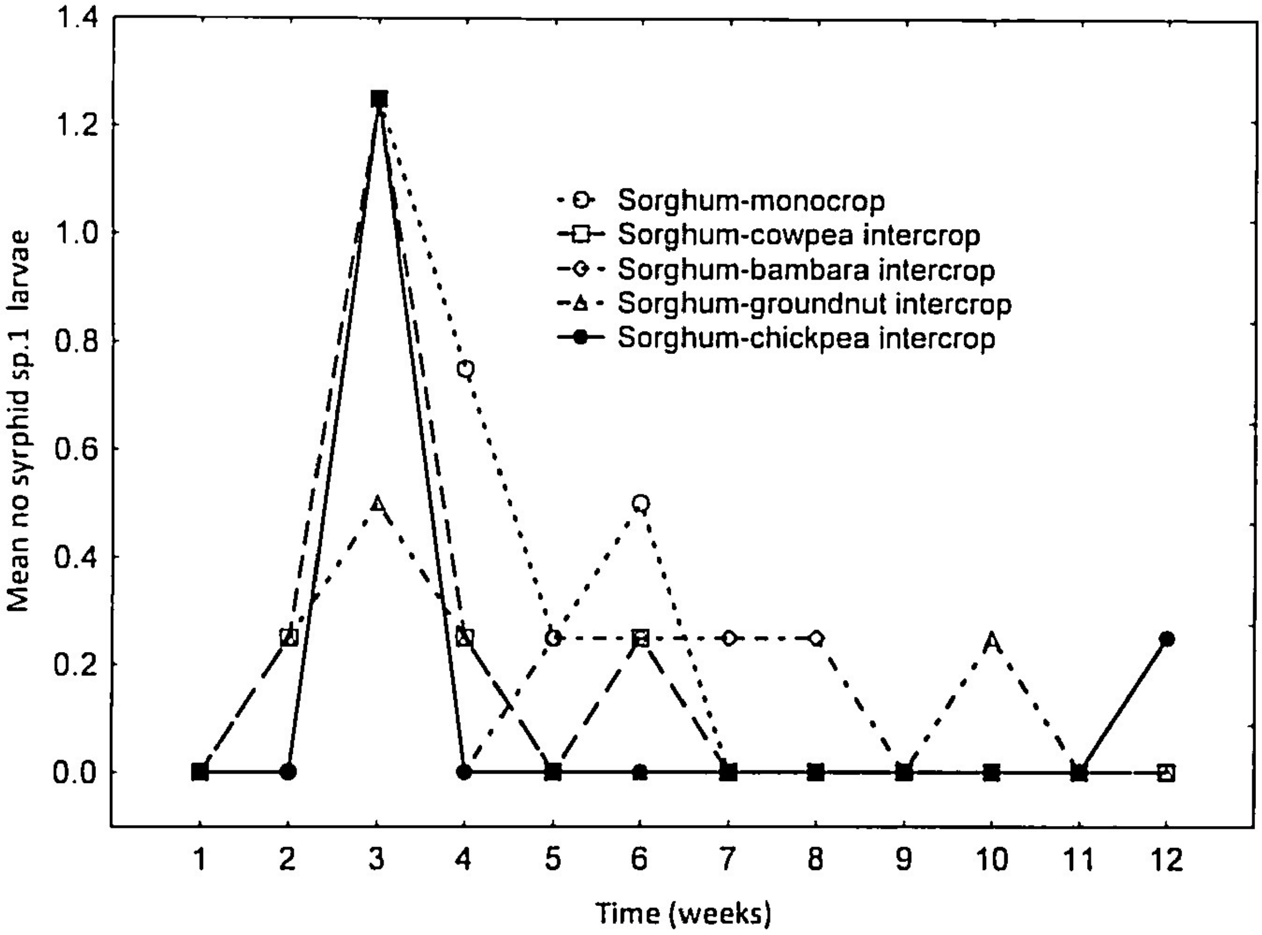


Fig. 12. Population dynamics of predatory Syrphidae larvae sp. 1 sampled from different crop combinations measured over 12 weeks.

The mean number of Syrphidae sp. 2 larvae did not vary significantly among crop combinations ($F_{4,144}$=1.02, P=0.3969) but varied over time ($F_{11,144}$=2.61, P=0.0042). The larvae established by week two and on week three and four it reached the highest peak on sorghum- cowpea intercrop (Fig. 13). The larval density declined from week four and dropped to zero by week five. In sorghum-chickpea intercrop, the larvae appeared on week two and remained constant until week three and 4, declined on week five and then disappeared. The density of larvae appeared on week three in sorghum mono-crop, declined by week four, peaked again in week six, and then dropped to zero on week eight.

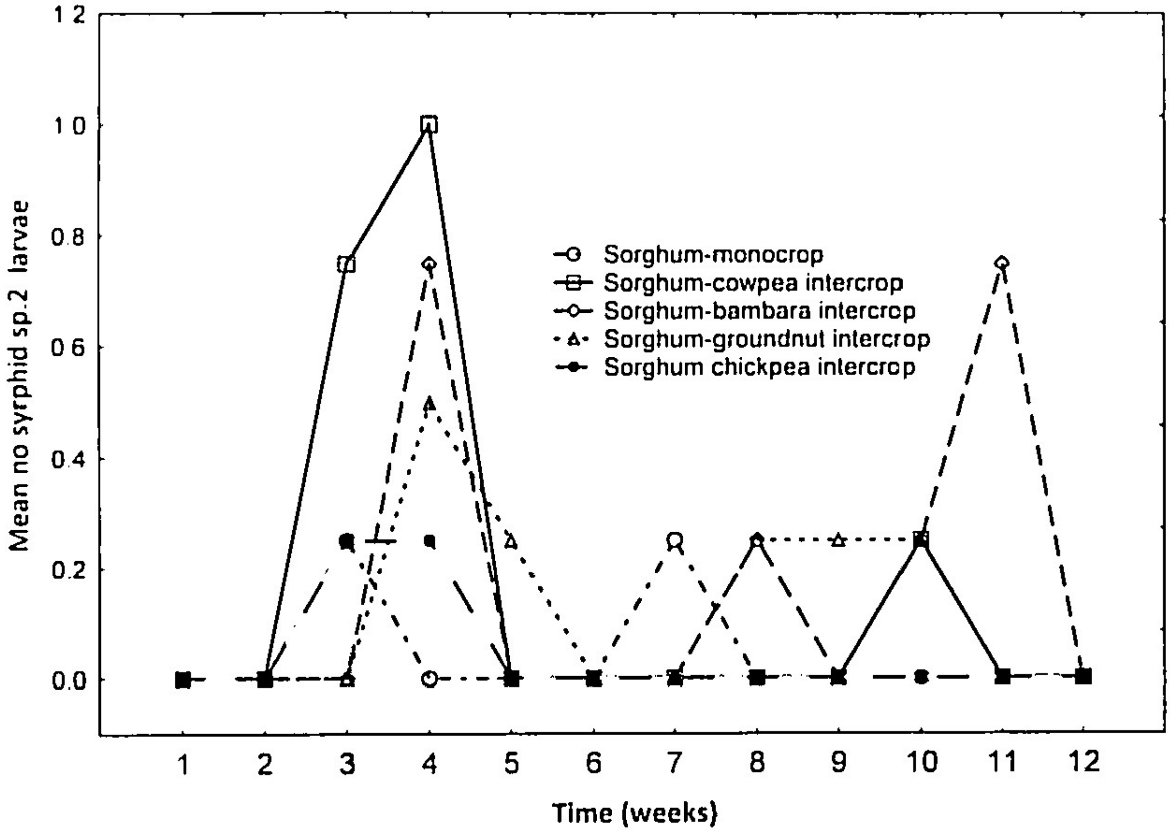


Fig. 13. Population dynamics of predatory Syphid larvae sp. 2 sampled from different cropcombinations measured over 12 weeks

In sorghum- groundnut and sorghum- Bambara groundnut groundnut intercrops, the larvae started appearing after week three and declined on week five in sorghum- groundnut intercrop and peaked on week eight, then dropped again in weak nine where it started peaking again and disappeared by week 12. In sorghum-Bambara groundnut, larval density declined on week six and peaked at week seven and remained constant until week 10, then declined and disappeared by end of week 12.

The mean number of Syrphidae sp. 3 larvae was not significantly affected by crop combination ($F_{4,144}=1.33$, $P=0.2604$) time of sampling ($F_{11,144}=1.43$, $P=0.1641$). The larvae appeared on sorghum-cowpea intercrop and sorghum mono-crop on week two with the highest population on sorghum-cowpea intercrop (Fig 14). The population the dropped on week four and peaked on week five then dropped again on week six.

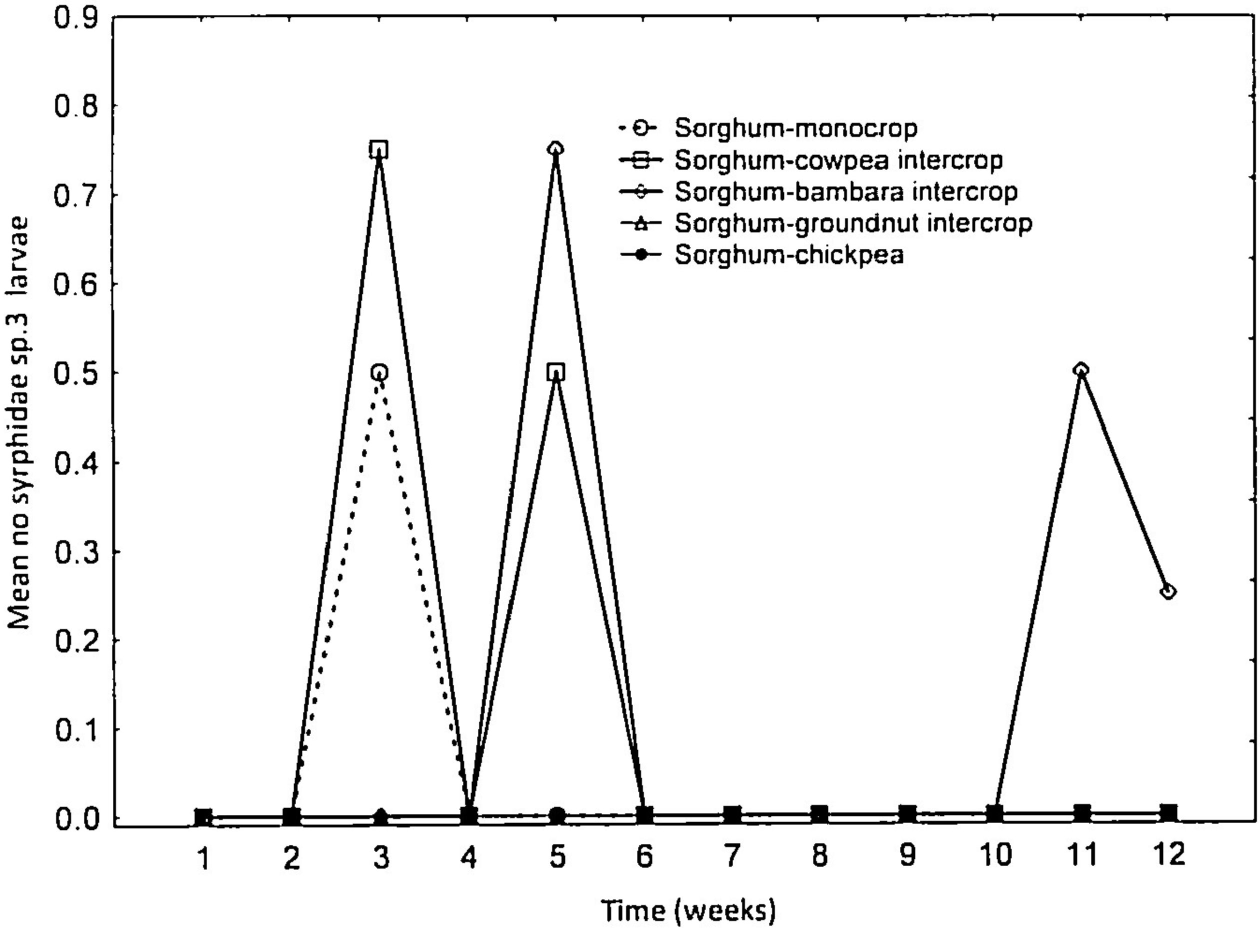


Fig. 14. Population dynamics of predatory Syrphidae larvae sp. 3 sampled from different crop combinations measured over 12 weeks

On sorghum-Bambara groundnut intercrop, the larvae appeared on week four and reached its highest peak by week five and dropped on week six disappeared. A resurgence in larval density on sorghum-Bambara groundnut intercrop occurred on week 10 which peaked on week 11 and only to disappear again towards the end of week 12.

On the first week when *M. sacchari* numbers were recorded there were no Syrphidae larval species present but on week 1and 2 Syrphidae sp. 1 appeared and peaked by week 3 then declined concurrently with aphid populations (Fig. 15). Syrphidae sp. 2 and 3 numbers were recorded on week 2 then increased until week 5 when a decline was observed. At week 3, when the density of *M. sacchari* started decreasing the density of Syrphidae sp. 1 and 3 also decreased but Syrphidae sp. 2 kept on increasing until week 4 when it started decreasing. At week 4 Syrphidae sp. 3 density started increasing, and during week 5 it was at the same density as *M. sacchari*. From week 6 until week 12, densities of Syrphidae larvae and aphids displayed a pattern of oscillation (Fig 15).

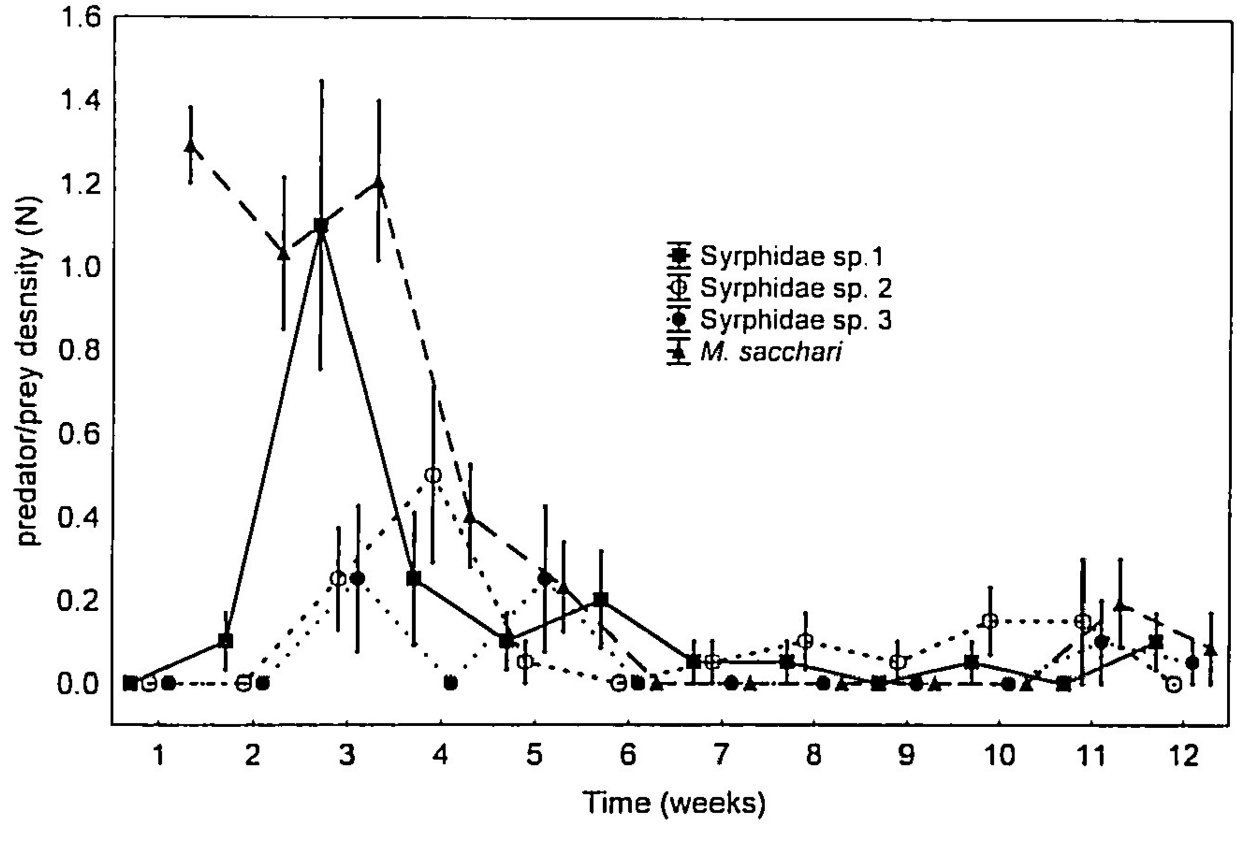


Fig. 15. Relationship between densities of three Syrphid larvae and sugarcane aphid *M. sacchari* measured over 12 weeks. Error bars are standard errors (SE)

A polynomial fitting of the data on relationship between aphids and predatory syrphid larvae was statistically significant, and displayed a functional response pattern typical of type II (Fig. 16).

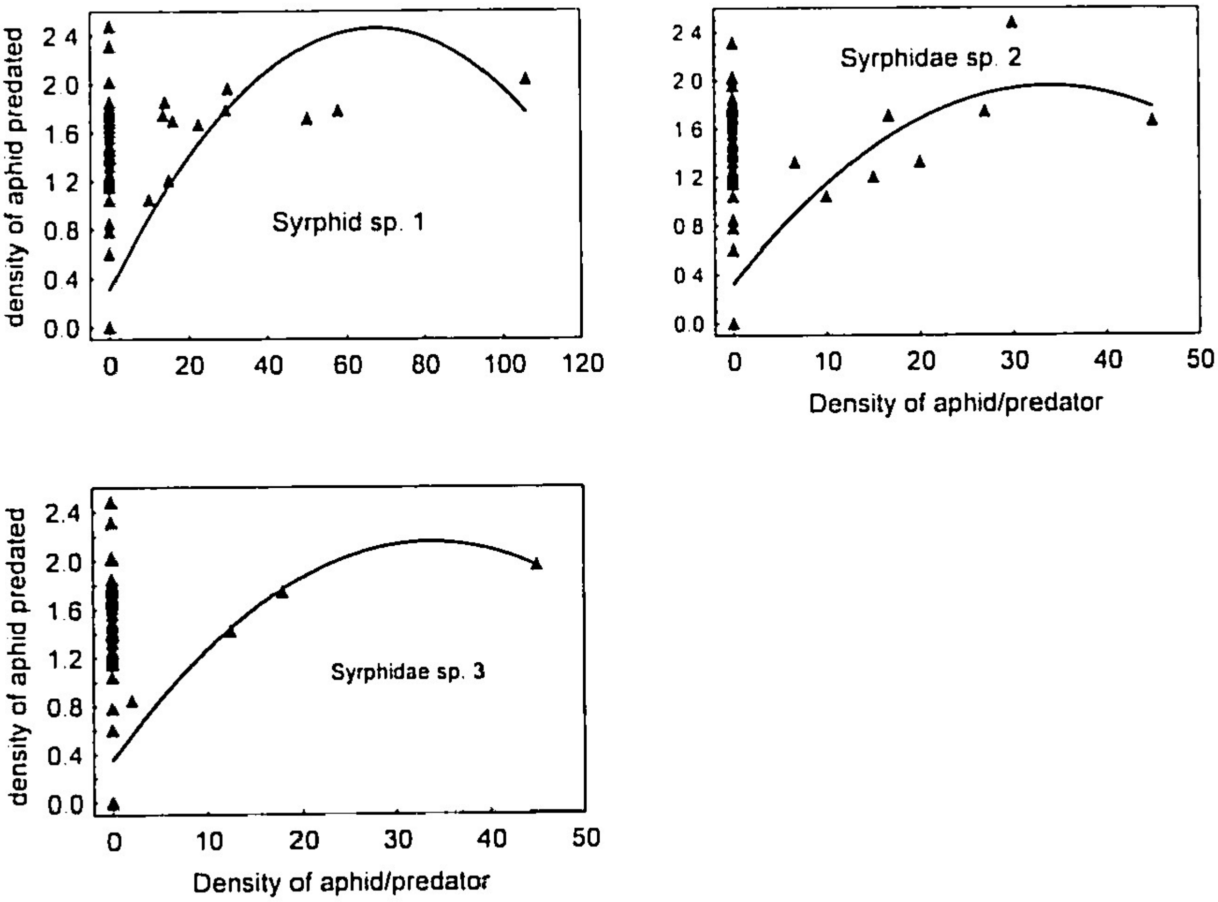


Figure 16: Response of three predatory Syrphid larvae to density of *M. sacchari* under field conditions. [Syrphidae larvae sp. 1: $Y = 0.31+0.064x-0.0005x^2$, $r = 0.37$, $P<0.0001$] [Syrphidae larvae sp. 2: $Y = 0.33+0.096x-0.0014x^2$ $r = 0.33$, $P<0.0001$] [Syrphidae larvae sp. 3: Y = = $0.35+0.107x-0.002x^2$ $r = 0.22$, $P< 0.0001$]

A significant difference in stemborer larval parasitism was observed among treatments with the lowest parasitism recorded on larvae collected from sorghum mono-crop ($F_{7, 12} = 4.38$; $P=0.021$) (Table 4 & Fig 17). Larvae collected from sorghum- groundnut intercrop had the highest level of parasitism than other treatments. *Temelucha sp.*, *Stenobracon rufus* and *Pediobius furvus* were only collected from sorghum-groundnut intercrop.

Table 4. Mean percentage parasitism of *C. partellus* from larvae collected from different crop combinations (±SE).

Crop combinations	Braconidae sp.1[a]	Chalcididae sp.1	*Temelucha sp.*	*Stenobracon rufus*	*Pediobius furvus*
Sorghum monocrop	0.00±0.00a	0.00±0.00a	0.00±0.00a	0.00±0.00a	0.00±0.00a
Sorghum-cowpea	1.00±1.00a	0.25±0.25a	0.00±0.00a	0.00±0.00a	0.00±0.00a
Sorghum-groundnut	5.4300±4.67c	0.25±0.25a	0.25±0.25a	0.25±0.25a	0.75±0.75a
Sorghum-Bambara groundnut	0.00±0.00a	0.33±0.33a	0.00±0.00a	0.00±0.00a	0.00±0.00a
Sorghum chickpea	1.75±1.75ab	0.00±0.00	0.00±0.00a	0.00±0.0a0	0.00±0.00a

[a] Values in columns followed by the same letter do not differ significantly according to Fisher's protected LSD (P ≤ 0.05).

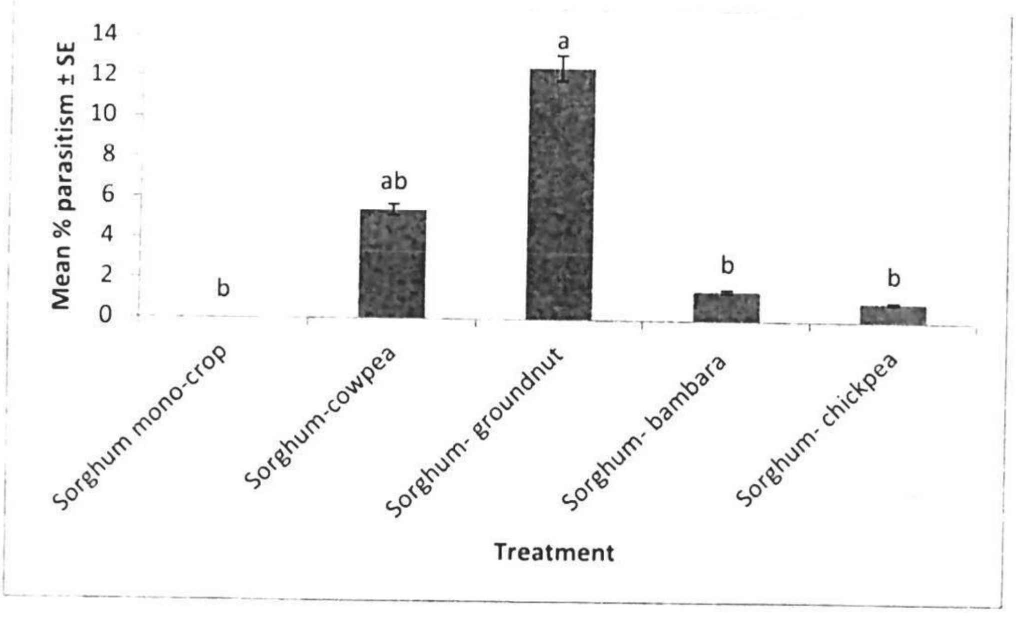


Fig. 17. Total percentage parasitism of *C. partellus* larvae collected from different crop combinations. Letters associated with treatment indicate that a significance occurred, and parasitism means having the same letter not significantly different (P≤0.05).

4.3 Influence of intercropping on stemborer damage to sorghum and yield loss

4.3.1 Stem damage to sorghum

There was no significant difference in percentage of plants with deadhearts ($F_{4, 15}$= 1.22, P = 0.3454) and percentage of plants with whorl leaf damage ($F_{4, 15}$=0.65, P = 0.6341) among crop combinations (Fig 18). Sorghum mono-crop had the highest percentage of plants than intercrop though not significant statistically. Sorghum -groundnut and sorghum- Bambara groundnut crop combinations had highest percentage plants with whorl leaf damage compared to the other crop combination (Fig 19).

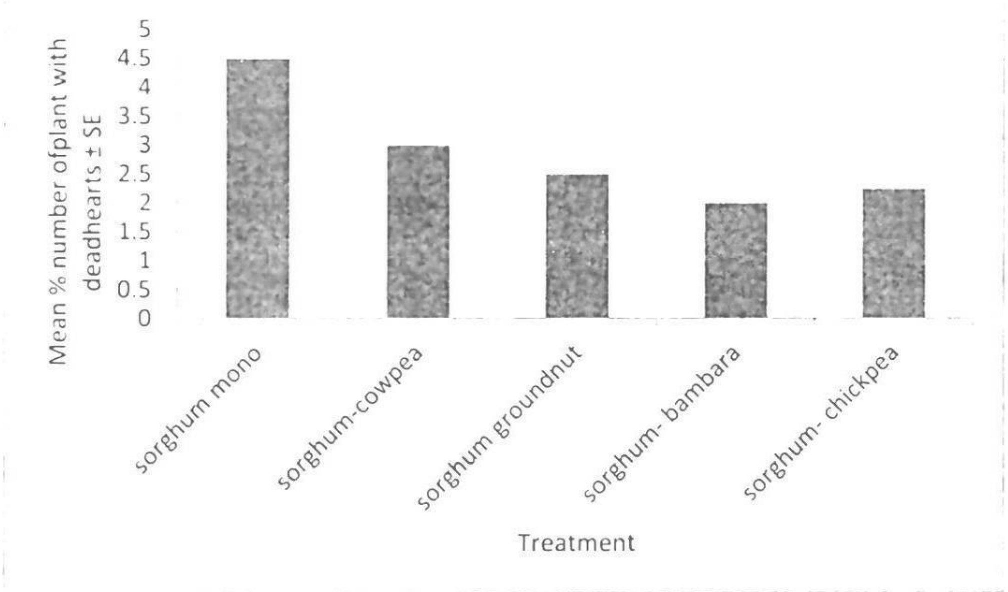


Fig. 18. Number of deadhearts recorded on sorghum seedlings from different crop combinations. No significance occurred between treatments (P≤0.05)

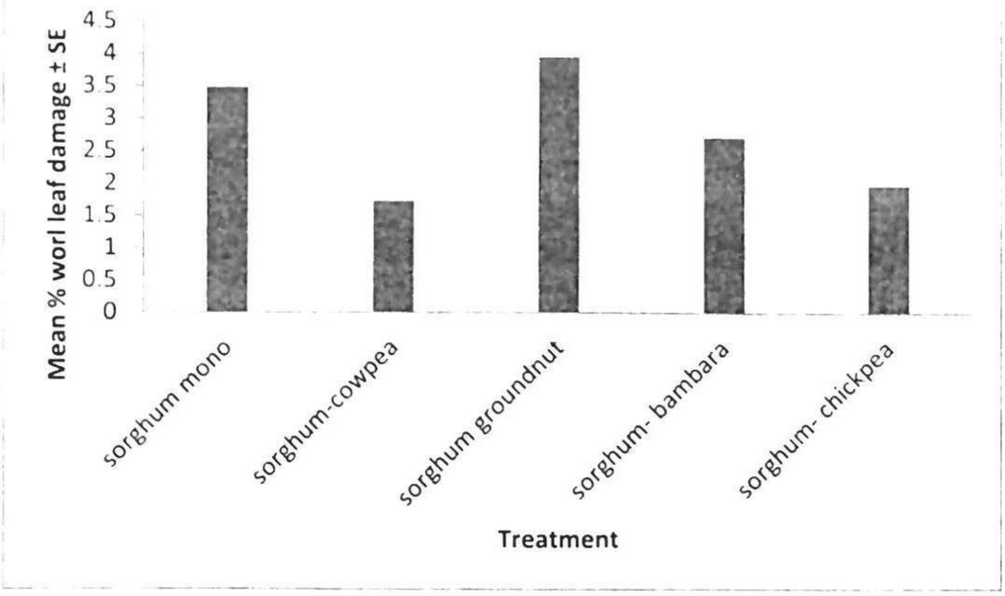


Fig. 19. Percent whorl leaf damage by *C. partellus* on sorghum. No significance occurred between treatments ($P \leq 0.05$).

The data on stem damage is shown in Table 5. There was a significant difference between the numbers of live larvae ($F_{19,18}$= 7.80, P=0.0001) among crop combinations. Sorghum mono-crop had the highest number of live larvae while Sorghum-cowpea had the lowest number of larvae. There was also a significant difference in the number of moth exit holes ($F_{19,80}$=2.16, P = 0.0092) between crop combinations. A significant difference between the intercrops also occurred on the number of tunnels ($F_{19,80}$=2.59, P=0.0016) and length of tunnels ($F_{19,80}$=4.34, $P<0.0001$).

Table 5: Mean sorghum stem damage by larvae of *C. partellus* (±SE).

Crop combination	Mean No. larvae	Mean No. exit holes	Mean No. tunnels	Mean Length of tunnels
Sorghum mono	12.50±1.32a	14.75±2.64a	7.10±0.75a	0.50±0.24a
Sorghum-cowpea	3.65±0.74b	6.45±1.90b	6.10±0.61a	0.308±0.54b
Sorghum-groundnut	4.60±1.03b	7.35±1.08b	4.45±0.34b	0.43±0.05a
Sorghum-Bambara groundnut	4.25±0.65b	5.70±1.08b	4.10±0.37b	0.28±0.37b
Sorghum- chickpea	4.35±0.55b	7.05±1.23b	4.05±0.44b	0.31±0.04b

Values in columns followed by the same letter do not differ significantly according to Fisher's protected LSD ($P \leq 0.05$)

Percentage nitrogen content of sorghum plants after physiological maturity was significantly different between crop combinations (F $F_{4,, 52}$=10.27; P <0.0001) (Fig. 18). The highest nutrient composition was obtained from sorghum mono-crop. A significant relationship was observed between percentage nitrogen of sorghum and damage by *C. partellus* (no. of deadhearts, no. of live larvae, no. of moth exit holes and tunnel length) (Table 6).

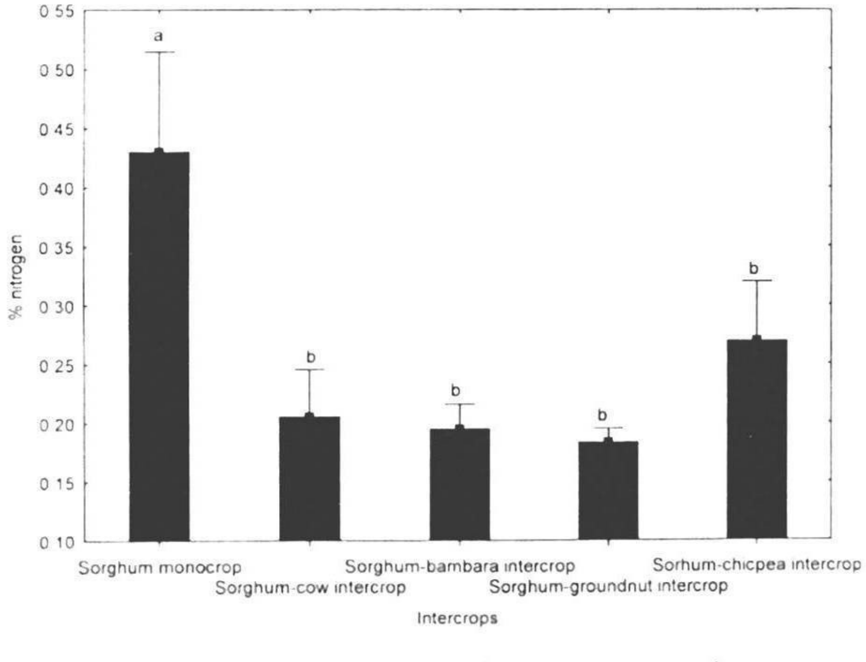


Fig. 20. Nutrient composition based on percentage nitrogen content of sorghum plants under intercropping and mono-crop. Letters associated with treatment indicate that a significance occurred, and parasitism means having the same letter not significantly different (P≤0.05).

Table 6. Relationship between % N and various sorghum damage by *C. partellus*

Stemborer damage	Intercept ±SE	Slope±SE	r^2	*P*
% whorl damage	3.71±3.98	0.470±0.51	0.22	0.421
No. deadhearts	7.69±1.26	0.96±0.16	0.93	0.009
No. live larvae	29.32±3.54	0.98±0.12	0.94	0.004
No. moth exitholes	29.29±2.58	0.98±0.087	0.97	0.001
No. stem tunnels	9.21±3.50	0.84±0.32	0.70	0.078
Tunnel length	0.67±0.22	0.87±0.28	0.76	0.050

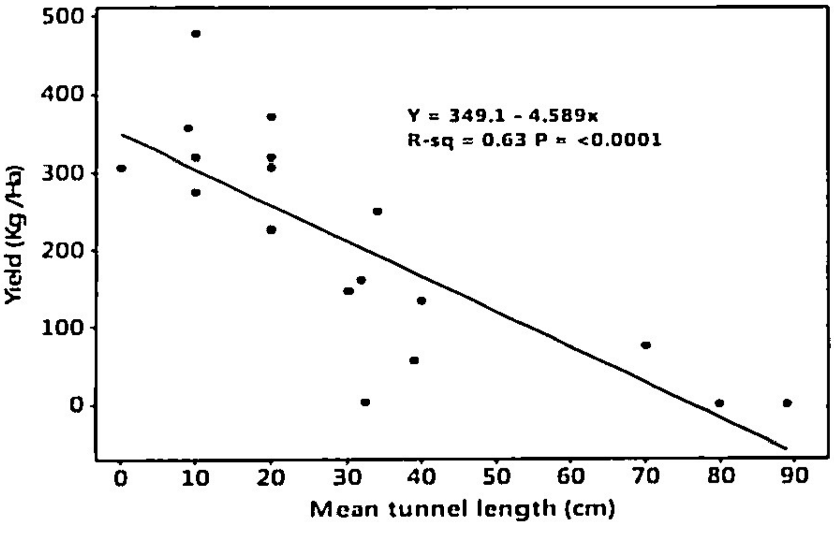
4.3.2 Yield and yield components

Yield components did not vary among sorghum intercrop and sorghum mono-crop (Table 7). The lowest harvest index was obtained from sorghum mono-crop while sorghum-groundnut had the highest index. Higher seed weight and panicle weight occurred on sorghum-Bambara groundnut intercrop and lowest on sorghum mono-crop. There was a significant difference in yield ($F_{7, 12}$=3.13, P= 0.0398) among crop combinations, with sorghum mono-crop having the lowest and sorghum-groundnut intercropping showing the highest yield. There significant negative relationship between tunnel length and larval density indicating that when the tunnel length increased yield was significantly reduced (Fig 21).

Table 7: Comparison of means of yield and yield components.

Crop combination	Harvest index (±SE)	Seed weight(g) (±SE)	Panicle weight(kg) (±SE)	Yield (kg/Ha)[a] (±SE)
Sorghum mono	0.14±0.08a	8.00±4.61a	0.24±0.11a	33.86±18.91b
Sorghum-cowpea	0.23±0.02a	17.30±1.00a	0.33±0.10a	218.26±46.10a
Sorghum-groundnut	0.31±0.04a	16.31±0.60a	0.44±0.07a	278.93±32.14a
Sorghum-Bambara groundnut	0.24±0.63a	18.57±1.72a	0.44±0.15a	273.39±77.37a
Sorghum-chickpea	0.23±0.08a	15.00±5.06a	0.38±0.13a	234.82±82.16a

[a] Values in columns followed by the same letter do not differ significantly according to Fisher's protected LSD ($P \leq 0.05$).



21. Relationship between yield and mean tunnel length.

Tunnelling of the stem by stemborer affected yield and this was more pronounced on sorghum mono-crop (Table 7). Conversely, an increase in yield loss was significantly related to increase in the number of larvae per stem (Fig. 22).

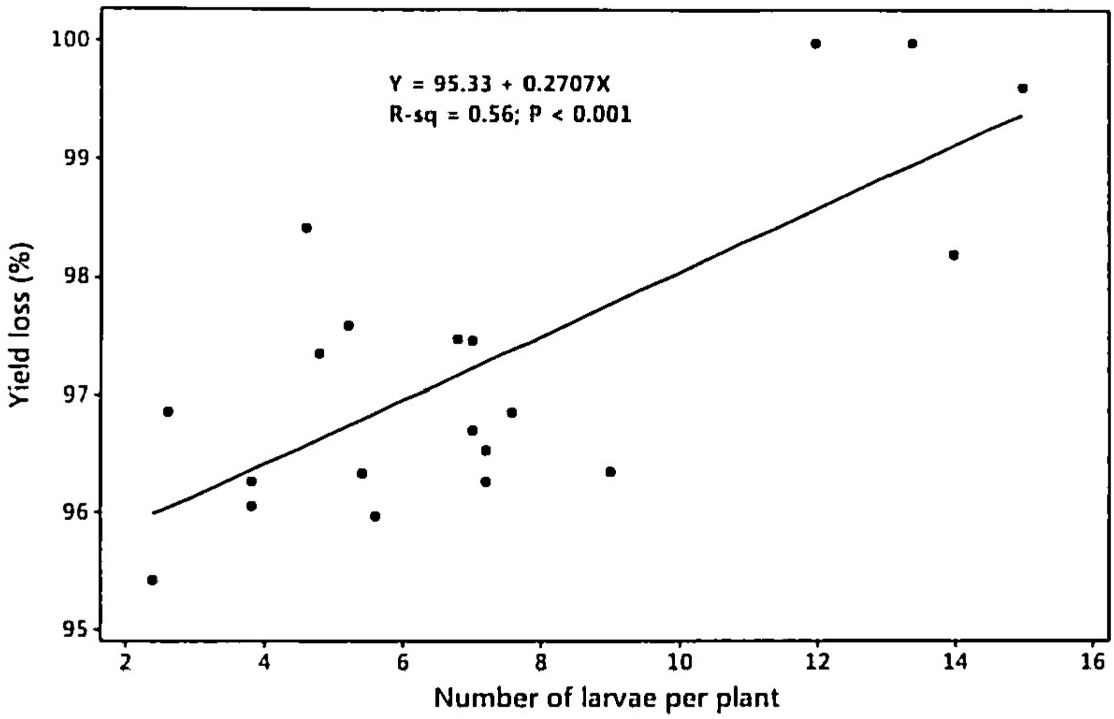


Fig.

Fig. 22. Relationship between yield loss and the number of larvae per plant.

Pearson correlation analysis also indicated that grain yield of sorghum was closely related to length of tunnels caused by *C. partellus* (Table 8). Multiple regression analysis using the best subsets showed that the predictor model included number of larvae per plant, number of stem tunnels and stem tunnel length, which were related to a significant reduction in yield. These variables accounted for up to 72.4% variation in sorghum grain yield (Table 9).

Table 8: Pearson correlation coefficients between yield and damage variables.

	Deadhearts	Leaf damage	No. larvae	No. exit holes	No. of tunnels	Length of tunnels
Leaf damage	-0.30					
No. larvae	0.15	-0.10				
No. exit holes	0.04	0.003	0.14			
No. tunnels	0.16	0.13	0.54**	-0.07		
Length of tunnels	-0.04	0.25	0.46*	0.36	0.13	
Yield (kg/ha)	-0.18	0.10	-0.70***	-0.06	-0.09	-0.67***

Table 9. Multiple regression results showing relationship between yield and variables associated with yield.

Predictor variable	β ± SE	T	P	MSE	R^2	Cp	VIF
Intercept	24.27±7.03	3.45	0.003				
No of borers	-23.42±5.86	-4.00	0.001				1.78
No of tunnels	23.40±10.8	2.16	0.046				1.43
Length of tunnels	-6.00±2.25	-2.66	0.017	3.67	72.5(0.72)	6.1	1.29

VIF = variance inflation ratio; MSE = mean square error; Cp = Mallow's Cp value. β = coefficient, SE = standard error

The highest yield loss occurred on sorghum mono-crop (Table 10). Cost of intercrop was highest on sorghum-groundnut intercrop and lowest on sorghum-Bambara groundnut intercrop. The highest gross monitory profit was obtained on sorghum-groundnut and the lowest on sorghum-cowpea intercrop (Table 10). Sorghum-Bambara groundnut intercrop had the highest benefit to cost ratio (BCR) followed by sorghum-cowpea intercrop and the lowest was obtained from sorghum-groundnut intercrop. The highest gain threshold was obtained from sorghum-groundnut intercrop and the lowest from sorghum- cowpea intercrop. The highest EIL was obtained from sorghum-groundnut intercrop while the lowest was obtained from sorghum-Bambara groundnut intercrop.

4.3.3 Yield loss assessment and economic injury levels

Table 10. Yield loss and economic injury level of *C. partellus* on sorghum based on different sorghum intercrops.

Intercrop	Number of larvae/stem	Yield (Kg ha^{-1})	Yield increase over control Kg ha^{-1})	Yield loss (%)	Cost of intercrop (BWP ha^{-1})	Gross monetary profit (BWP ha-^{1}	benefit to cost ratio	Gain threshold	EIL
Sorghum-groundnut	4.6	278.93	245.07	0.00	419.07	906.76	2.16:1	2.26	8.39
Sorghum-cowpea	3.65	218.26	184.4	21.75	200.42	682.28	3.40:1	1.08	4.01
Sorghum-chickpea	4.35	234.82	200.53	15.81	280.36	743.53	2.65:1	1.51	5.61
Sorghum-Bambara groundnut	4.25	273.39	239.53	1.99	149.73	886.26	5.92:1	0.80	3.00
Sorghum-monocrop	12.50	33.86	-	87.86	-		-	-	-

CHAPTER 5: DISCUSSION

5.1 Insect diversity and abundance

Species diversity and abundance differed between the crop combinations. The difference can be attributed to the vegetation variation between the crops planted in each treatment. The significant differences between the sorghum mono-crop and sorghum intercrop in species composition and abundance show that where there was a diversity of different crops associated with intercrops, there were more arthropod species compared to mono-crops.

The most abundant insect species were the herbivores, *Chilo partellus* and *Melanaphis sacchari*. *Chilo partellus* was prevalent in the sorghum mono-crop than in the sorghum-legume intercrop. These two herbivorous insects are major pests of sorghum in Botswana (Ingram, 1973; Obopile and Mosinkie, 2003; Manthe, 1992). The reduction in the capacity of the herbivores to find their host plant in polycultures may explain the lower densitiy of *C. partellus* on intercrops than mono-crop. The lower density of insect pests on intercrop is in agreement with the 'resource concentration hypothesis' (Root, 1973). Risch *et al.*,(1983) and Altieri, (1993), reported that the visual and chemical stimuli in polycultures, resulting from both host and non-host plants will result in a reduction in the rate at which herbivores are able to colonize, and will also reduce their subsequent searching behaviour for host plants within these diverse habitats. In this study, the density of the stem borers varied significantly between the sorghum mono-crop and the sorghum intercrop combinations indicating that intercropping lowers stemborer numbers.

High incidence of larvae was recorded on the sorghum mono-crop than on the sorghum-legume intercrops. The study by Amoako-Atta *et al.* (1983), showed that the borer incidence on the maize and sorghum mono-crops was earlier (>14 days after germination) and heightened with time, whereas intercropping of the cereals with non- cereals caused a significant delay (>42 days after germination) in the stem borer establishment within the intercropping systems which would reduce damage by the larvae. In another study where push pull system of maize with lablab was used to control stemborer and striga weed it was found that there were significantly lower proportions of stemborer in intercropping systems than in the mono-crop plots (Khan *et al.*, 2008).

Higher abundances of predators in the more diverse habitats associated with the intercropping plots were consistent with most of the published literature (van Emden, 1990; Symondson *et al.*, 2002; Andow, 1991; Wratten and van Emden, 1995; Trefas and van Lenteren, 2008). In the current study PCA and hierarchical cluster analysis, showed that insect species were separated between mono-crop and intercrops. The first principal component was positively correlated with the intercrops. The second principal component correlated negatively with the sorghum- cowpea intercrop. Principal component analysis represents the general variability of sampled material (Kucharczyk and Kucharczyk, 2012). The significance of this variability is to differentiate the species composition between the intercrops. Cluster analysis shows similarities of insect species and how they are linked. The cluster analysis was used to group the different crop combinations by similarities in species composition. Two clusters were formed with one separating sorghum mono-crop then followed by sorghum- chickpea and sorghum- Bambara groundnut, and furthest where cluster of sorghum- cowpea and sorghum-groundnut intercrops. These separations show that insect diversity differs among the different crop combinations and each of the cluster formed had more similarities in insects than the other cluster as reported by Zibaee *et al.*, (2008).

5.2 Predation and parasitism

Predators and parasitoids differed between the different crop combinations. The predators were predominantly coccinelidae from the order Coleoptera and syrphid fly larvae from order Diptera. Other predators were arachnidae and formicidae that are considered egg predators of

Lepidoptera (Bonhof *et al*, 1997). The parasitoids were from the family Braconidae, Chalcididae, Ichneumodidae and Eulophidae. These results showed a synchrony in population dynamics of herbivorous prey (aphids) and predators (Coccinellidae and Syrphidae), suggesting that predators were more abundant in intercropping systems as a consequence of seeking herbivores rather than searching for beneficial factors such a suitable microclimate and supplementary food resources which are provided by intercropping as it has been suggested by natural enemies hypothesis (Asiry, 2013). Root, (1973), hypothesized that the probability of suppressing herbivore populations by generalist and specialist natural enemies would be greater in polycultures than monocultures; often called the 'natural enemies hypothesis' (Root, 1973; Russell, 1989; Andow, 1991).

Intercropped systems tend to provide preferable microclimatic conditions and increased availability of food sources (including secondary invertebrates, as well as prey, pollen and nectar) for predatory invertebrates (Barbosa, 1998). As a result, colonization rates and population size of natural enemies are expected to be larger in these systems than in monocultures (Vandermeer, 1989; Andow, 1991). While the differences in density of coccinellids were not significant, their consistency was higher numerically and more prevalent in the sorghum- legume intercrops than in the sorghum monocrop. The syphid flies were also more prevalent in the intercrops. Bombosch (1966) showed that Syphid adult ovarioles do not mature unless the female feeds on pollen. Syrphid flies are frequent visitors and pollinators of a diverse range of plant species (Sugiura, 1996).

The preservation of resident natural enemy populations within crops combined with management to enhance their abundance and activity represents a fundamental tenet of conservation biological control (Khan *et al.*, 2008). While predatory invertebrates feed predominantly on other invertebrates, nectar and pollen are often utilized and can provide key resources for some species (Treacy *et al.*, 1987; Bugg *et al.*, 1989). Nectar and pollen appear to be important in keeping parasitoids (Hansen, 1983) and this might explain why there were parasitoids in the sorghum-intercrop system and none in the sorghum mono-crop in the current study. Sorghum- cowpea intercrop had the highest percentage parasitism. Getu *et al.* (2003). reported higher parasitism of *C. partellus* when cereals were intercropped with haricot bean and cowpea than when wild grass hosts of stem borers were present.

Intercropping can also provide alternative hosts or prey at times of host scarcity on a primary crop and food resources for adult parasitoids and predators, for example nectar and pollen (Treacy *et al.*, 1987; Bugg *et al.*, 1989; Barbosa, 1998; Coll and Bottrell, 1995). This would explain why a predator like *O. cintella*, was present in the absence of aphid prey as they feed on pollen, nectar and honeydew.

The level of parasitism differed significantly among intercrop and mono-crop, which was shown by presence of parasitoids such as *Temelucha* sp., *Stenobracon rufus* and *Pediobius furvus* that were only on the sorghum- groundnut intercrop, followed by sorghum-cowpea intercrop. Access to a diversity of plant species might well prove advantageous to natural enemies as different species of pollen affect fecundity and longevity differently (Leuis, 1963). *Hamonia vingintiomaculata* appeared at the end of the last week of the current study and according to Zanuncio *et al.* (2008) and Pereira *et al.* (2010), ecological conditions are also known determinants for predators time response. The predator-prey relationship showed a pattern consistent with functional response. Incipient outbreaks of herbivores are checked early by the functional response of enemy whose numbers have been maintained by the diverse resources available in complex environments (Stout and Vandermeer, 1975). In the current study the behaviour of the coccinellidae was affected by the density of the aphids regardless of the treatment. The response curves showed that as the density of the aphid increased the density of the coccinellidae increased and a decline in the aphid density caused a decline in coccinellidae. The predators responded more intensely to high density of *M.*

sacchari as shown by the response of *O. cintella*, *C. lunata* and *E. flavipes* to the aphid densities that were statistically significant.

The diversity-stability hypothesis also has implications for benefits in terms of pest control associated with intercropping management practices. This hypothesis suggests that pest control in annual polycultures is more stable than in monocultures as polycultures provide increased diversity of resources, and can therefore support a higher diversity of natural enemies. The predator/prey relationship show this stability as different species of Coccinellidae and Syrphidae were able to regulate populations of *M. sacchari*.

5.3 Influence of intercropping on stemborer damage to sorghum and yield loss

The results show that sorghum was infested by *C. patellus* and there was no infestation by *B. fusca*, this supports the studies that *B. fusca* is being replaced by *C. partellus*. In Botswana, (Good hope region) *B. fusca* accounted for 3.5% of the stemborer population (Obopile and Mosinkie 2001). The results from the current study showed that there was higher *C. partellus* damage on the sorghum mono-crop than on the sorghum-legume intercrop. Studies in the tropical and temperate zones reported decreased pest densities in diversified cropping systems (Kruess and Tschanke, 2000). Smith and McSorley (2000) also reported that intercropping often reduces pest populations compared with monoculture. Some studies (Adesiyun, 1983; Gahukar, 1989 and Kwapong, 1990) showed that the female would oviposit some of the eggs on the legume in the intercropped system and the hatched larvae would not be able to reach the sorghum. This may account for the reduced number of larvae on sorghum in the intercrops. With alternate row arrangements of host and non-host plants, the ovipositing female and dispersing larvae move easily within than between rows (Chabi Olaye *et al.*, 2005).

Okweche *et al.* (2013) found positive and highly correlated relationship between percentages bored stem and deadhearts in maize seedlings. Damage was greatly reduced in the sorghum-legume intercrop where significant lower number of larvae were recorded than on the sorghum mono-crop. Yield was negatively correlated with stem tunnelling by stemborer, which is known to affect the meristematic tissues of the plant leading to stem breakage thus causing great reduction in the yield of the sorghum mono-crop as it sustained highest damage (Bosque-Perez and Mareck, 1991). Barrow (1987) also reported that yield loss in maize was correlated with stem breakage caused by tunnelling by stemborers.

A study by Baidoo (2004), found that the greater nitrogen content of the stem of maize varieties "Ewifompe" and "Obaatanpa" resulted in greater stemborer infestation in these varieties. "Abutui" maize variety which had the least percentage nitrogen in both seasons also suffered the least infestation. The results from previous studies support the current findings that indicated that plants with the highest percentage nitrogen suffered great damage (length of tunnels) from the stemborer larvae. Sorghum mono-crop plants had the highest percentage N and sustained the highest damage levels while sorghum- legume intercropping had the lowest percentage N. This was confirmed by significant reduction stem tunnelling length, number of tunnels and stemborer infestations. Elevated nitrogen levels have been found to increase both survival and fecundity of stemborer, *Sesamia calamistis* (Seatamou *et al.*, 1995).

The greater nitrogen content increased the nutritional quality of the plant making it more attractive. This was confirmed by regression analysis, which revealed positive relationship between stem damage (live larvae, tunnelling, number tunnels and moth exit holes) and percentage nitrogen. An increase in the quality of the plant caused an increase in damage by stemborers on sorghum in the current study. Intercropping has been reported to adversely affect nutritional quality and suitability of the host plants to herbivores compared to monocultures (van Lenteren, 1998). These results support the 'disruptive crop hypotheses' in which a second non-host plant species is suggested to affects the ability of the pest to find its proper host plant species, and this can be due to both reduced chemical and visual cues and stimuli (Finch and Collier, 2000).

The yield obtained from sorghum received in the current research was low and this may have been due to the low rainfall that was received during the season (Fig. 23) However, from the obtained yield, sorghum mono-crop had the highest yield loss at 87% significantly lower than the sorghum-legume intercrops. Up to 80% yield, loss has been attributed to stemborer damage in Africa (van den Berg, 2009). In Zimbabwe, *C. partellus* caused yield loss of 50-60% in sorghum (Sithole, 1989). In the current study yield was negatively correlated with the number of stem tunnels, number of larvae and stem tunnel length and these caused variation in yield among the different intercrops. The latter two are the damage that is caused by the larvae. Yield reductions due to stemborers occur as a result of leaf feeding, stem tunnelling and direct damage to cereal grain (Setamou *et al.*, 2000).

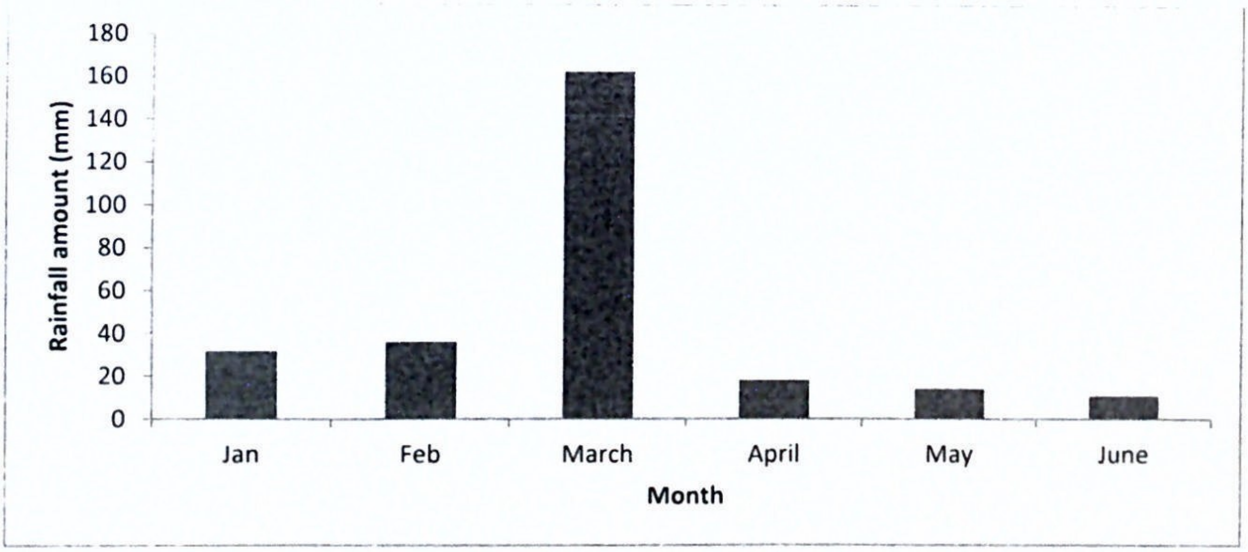


Fig. 23. Rainfall distribution during 2015/2016 cropping seasons.

In Africa, yield reduction by stemborer feeding and tunnelling can fall between 10%-100% depending on the season and status of the plant (Ndemah and Schulthess, 2002). In the current study yield loss associated with sorghum mono-crop was 87.9% falling within the range reported by Addo-Bediako and Thanguane, (2012). They further indicated direct relationship between stemborer density and grain yield in most sorghum cultivars and revealed that grain yield was higher in cultivars with less stemborer density than those with higher stemborer density. Research by Chabi-Olaye *et al.* (2005) showed that 3-8 times more stem tunnelling and 1-3 times more cob damage were recorded in maize mono-crops with high stemborer larval densities (21-48%) and yield loss 1.8-3.0 times greater than in the intercropped system. In the current study, larval densities were up to 3 times more in the sorghum mono-crop than on the intercrops. The land was fallow and due to no previous crops, there was less contribution to pest numbers. If the planting dates of sorghum and legumes were varied by staggering, the pests and insect numbers would have varied since the stemborer affects sorghum at seedling stage.

The EIL values in the current study ranged from 3 to 8.39 larvae per plant. The EIL developed for stemborers on maize by Sheshu-Reddy and Sum (1991), under mono-cropping system ranged between 3.2 to 3.9 larvae per plant for 20-40 day old plants. The EIL obtained from this research was higher than the EIL obtained in mono-cropped systems except for sorghum-Bambara groundnut intercrop. The EIL from the current study is based on intercropping system which manipulate the crop environment and modify crop susceptibility to pest-induced injury thus increasing the level at which economic damage occurs (Pedigo and Rice, 2006).

EIL is a critical point where the costs associated with pest management equal the benefits from the pest management actions (Stern, 1959; Pedigo *et al.*, 1986). It depends on the cost of control, damage of the pest and the value of the crop, but due to the temporal and dynamic nature of these, it can be difficult to calculate the EIL. When the pest has reached this point there would no longer be any need for control as this would then lead to an economic loss. The cost differed between the intercrops leading to differences in gain threshold. The benefit to cost ratio depends on the monetary profit. Sorghum plants grown under sorghum-groundnut intercrop tolerated the highest number of larvae per plant (EIL=8.39) which was confirmed by producing the highest yields. However, the benefit to cost ratio (BCR) of intercropping sorghum with groundnut was lowest because of high cost of this crop combination (BWP 419). Sorghum- Bambara groundnut intercrop had the highest benefit to cost ratio and had lowest cost of intercropping. The benefit to cost ratio takes into account the amount of monetary gain realized by performing a project versus the amount in cost to execute the project. Since sorghum-Bambara groundnut intercrop had the highest BCR, it means that it is economically viable compared to the other intercrops.

The establishment of exact EIL's of intercropping as preventive for pest organisms may help to re-evaluate their pest status (Mumford, 1982) and has potential to decrease the use of some preventative pesticide measures (Stejskal and Lukas, 2002). However when preventive methods are used, they bring a challenge because of the assumption of zero population in such systems

The establishment of ET for preventive management may be complex not with regard to pest numbers but solely to the proper timing (Stejskal, 2003). In the current study, intercropping was used as a pest management tool and it does not take into consideration the number of pests as it is a preventative tool but it reduced the pest numbers as shown in the results. It also increased the EIL values in the intercropped sorghum. Pedigo *et al.* (1986) suggests that the best method for developing comprehensive economic thresholds through an economic injury level is by examining the host physiology and physiological response to injury. Sorghum plants tend to produce tillers in response to deadhearts to compensate for yield loss. The gain threshold increased with the increase in cost of intercrop. Studies done were mostly on EIL of stemborers in maize not on sorghum, and not focused on preventative methods as in the current study.

The EILs obtained were from a one cropping season and due to the change in climate and the difference in season, the EIL value may also change with time. The change in climate may affect the physiological response of the plant to stemborer damage and the behaviour of the biological control agents. The cost of intercropping may increase thus increasing the EIL determined in the current study. The market value of sorghum may change because EIL is inversely related to market value crop.

CHAPTER 6: CONCLUSIONS AND RECCOMMENDATIONS

6.1 Conclusion

A significant diversity of insects and their allies were observed in intercrops compared to mono-crop, showing that intercropping increases species richness and diversity. The diverse array of insects support the resource concentration hypothesis that suggests that diverse plant species in polycultures increase species diversity and therefore lowers insect damage on crops than in monocultures. Higher level of predators and parasitic insects in intercrops compared to mono-crops in this study support the second hypothesis known as the natural enemies hypotheses, which proposes that in the intercropping system where there is increased plant diversity there is an increase in natural enemies diversity compared to mono-crops. As a result low pest incidence and damage occurs. A significant increase in nutrient composition on sorghum under mono-crop compared to intercrops agree with the host plant quality hypothesis which state that intercropping negatively affects the host quality and the chemical suitability of the plants for herbivores when compared to the monocultures. The unsuitability of sorghum plants which was negatively correlated with stemborer damage are therefore responsible for lower damage on intercrops than sorghum mono-crops.

Reduction in stemborer damage incidence and damage resulted in an increase in sorghum yield potential during this study. Intercropping sorghum with legumes was able to lower the stemborer populations compared to the sorghum mono-crop. The best intercrop selected was sorghum-Bambara groundnut intercrop due to its highest benefit to cost ratio although it had a lower EIL value compared to sorghum-groundnut intercrop.

6.2 Recommendations

Intercropping sorghum with legumes was able to reduce yield losses caused by stemborer damage therefore can be recommended as component of integrated pest management. Sorghum can be intercropped with Bambara groundnut to lower stemborer numbers as it is the most economic compared to the other legumes used in the research. However if farmers choose not to grow Bambara groundnut they could choose cowpea because of the benefit to cost ratio and the cost incurred for growing the crop. The yield from the legumes was not obtained in this study because of the poor rainfall and the current study was limited to one season because of limited finances and university regulations. The yields obtained from legume crops will be an additional income to the farmer, thus having greater impact than when planting sorghum alone. A minimum of two years of the study would produce more reliable data than a one-year research as in the current study.

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