# DIVERSITY AND ABUNDANCE OF ARTHROPODS AND PREDATORS OF THE FALL ARMYWORM, *SPODOPTERA FRUGIPERDA* (J.E. SMITH) (LEPIDOPTERA: NOCTUIDAE) IN MAIZE AGROECOSYSTEMS AND THEIR POTENTIAL FOR BIOLOGICAL CONTROL

**BY**

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# DECLARATION

I, ITOHAN IDEMUDIA, hereby declare that this thesis is the result of my original work personally undertaken by me for the award of Degree of Master of Philosophy in Entomology at the African Regional Postgraduate Programme in Insect Science (ARPPIS) in the University of Ghana and has not been presented elsewhere in part or whole for the award of a degree. All the references to other people's work have been duly acknowledged.

Signature…….. Date 11-09-2022……..

ITOHAN IDEMUDIA

Signature…….. Date 11-09-22……..

DR. KEN OKWAE FENING (PRINCIPAL SUPERVISOR

Signature…….. Date Sep 11, 2022……..

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# ABSTRACT

The fall armyworm, *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae) is native to the tropical and subtropical regions of the Americas. It is currently the most devastating invasive arthropod pest of maize in sub-Saharan Africa. Following the first report of *S. frugiperda* in Ghana in 2016, its control has been reliant on synthetic chemical insecticides. Due to reliance and overuse of these insecticides, the pest has evolved resistance and requires higher application frequencies for control. Furthermore, non-target/beneficial organisms are negatively impacted by insecticides. Therefore, this thesis sought to investigate the role of two different management options of *S. frugiperda* on the diversity and abundance of arthropod species, including predators as well as the infestation levels of *S. frugiperda* in maize agroecosystems at the Soil and Irrigation Research Centre (SIREC) of the University of Ghana, Kpong, located within the lower Volta basin of the Coastal Savannah agro-ecological zone of Ghana. The investigations were conducted in the major and minor maize cropping seasons. Also, evaluations of the predatory potential and functional response of the predator *Rhynocoris bicolor* (Fabricius) were made following the recommendations by the Centre of Agriculture and Bioscience International (CABI) and the Plant Protection and Regulatory Services Directorate (PPRSD) of the Ministry of Food and Agriculture (MoFA). The field experiment consisted of two different treatment plots: a biocontrol maize plot (BCM) where augmentative releases of the egg parasitoid, *Telenomus remus* (Nixon) were made and maize plot with farmer's practice (MFP) in which the insecticide; Emamectin benzoate-based product, Ataka Super EC®: Emamectin benzoate 19.2 g/l was applied. A control maize plot without any treatment was included. The predatory potential of the predator *R. bicolor* was determined in laboratory assays at the PPRSD biocontrol laboratory in Pokuase, Accra. Results showed that both in the major and minor maize cropping seasons, significantly more arthropods, including predators

were recorded in the control plots than in the MFP plots. Further, the diversity of the arthropods including predators was significantly lower in the MFP plot than in the control and BCM plots, articulating that the insecticides used by maize growers in Ghana had adverse effects on the arthropod communities and reduce biocontrol services. Conversely, a total of seven predatory arthropods: *Crematogaster striatula* (Emery), *Cosmolestes pictus* (Klug), *Haematochares obscuripennis* (Stal), *Hediocoris tibialis* (Stal), *Rhynocoris* sp. *Sphedanolestes picturellus* (Schouteden), and *Misumenops* sp. were confirmed predators of *S. frugiperda* after laboratory tests. The laboratory assays on *R. bicolor* revealed that the predator exhibits a type II functional response, with *S. frugiperda* as prey. Hence, could be considered a potential biocontrol agent of *S. frugiperda* in Ghana.

# DEDICATION

This thesis is dedicated to my darling husband, Dr. Pascal Osabhahiemen Aigbedion-Atalor and my beloved son, Aaron Obosaebhihiaye Aigbedion-Atalor for their immense love and support.

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**ALP** - Alkaline phosphatase

**ARPPIS** - African Regional Postgraduate Programme in Insect Science

**BCM** - Biocontrol maize plot

**BNARI** - Biotechnology and Nuclear Agriculture Research Institute

**CABI** - Centre of Agriculture and Bioscience International

**CIs** - Confidence intervals

**CRD** - Completely randomized design

**DAAD** - German Academic Exchange Service

**EPPO** - European Public Prosecutor's Office

**FAO** - Food and Agriculture Organization

**FAOSTAT** - Food and Agriculture Organization Corporate Statistical Database

**GAEC** - Ghana Atomic Energy Commission (GAEC)

**IFPRI** - International Food Policy Research Institute

**IITA** - International Institute of Tropical Agriculture

**IPM** - Integrated pest management

**M.PHIL.**-Master of Philosophy

**MFP** - Maize plot with farmer's practice

**MoFA** - Ministry of Food and Agriculture

**MPs** - Maize plants

**Mt/ha** - Metric tons per hectare

**PPRSD** - Plant Protection and Regulatory Services Directorate

**PPT** - Push-pull technology

**SIREC** - Soil and Irrigation Research Centre

**SSA** - sub-Saharan Africa

**UF/IFAS** - University of Florida's Institute of Food and Agricultural Sciences

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background information

Maize (*Zea mays* L.), also referred to as corn, is a cereal crop belonging to the grass family Poaceae, originating from the Western hemisphere (Fast and Caldwell 2000). It is ranked third, after rice and wheat, as the world's most cultivated cereal crop, and it is grown on approximately 197 million hectares in more than 125 developing countries (FAOSTAT, 2021). Maize is a fundamental driver of food security and sustainable livelihood in developing countries (De Groote *et al*., 2013). The demand for maize has been projected to double in the developing world by 2050 (Rosegrant *et al*., 2009). Maize accounts for approximately 30% of the daily food caloric intake of over 4.5 billion people in about 94 developing countries in the world (Oyewo, 2011). Due to its wide geographic and climatic adaptability, maize is successfully cultivated across various agro-ecological zones (temperate zones, sub-tropical zone, and tropical zones) globally, especially in Latin America and sub-Saharan Africa (SSA) (Ranum *et al*., 2014).

In SSA, maize is the most important cereal crop, and it provides food and livelihood means for more than 300 million smallholder farmers (Mathenge *et al*., 2014). It is cultivated on approximately 37 million hectares in SSA (Hruska, 2019). A large proportion of maize produced in SSA is used as human food albeit processed into various forms (Badu-Apraku and Fakorede, 2017). The immature field maize (green maize) is normally eaten as a snack after boiling or roasting as corn on the cob (Badu-Apraku and Fakorede, 2017). The dried maize grains are milled and consumed as a starchy base in the form of porridge, gruels and soups. Maize is also a key

constituent in animal feeds and serves as raw materials in industrial products, including the production of biofuels (Shiferaw *et al*., 2011).

The nutritional composition of maize, include high amounts of carbohydrate (mostly as starch or sugar) and low quantities of proteins, lipids, vitamins, and minerals (Ranum *et al*., 2014). It is a vital source of all the dietary requirements accounting for about 20% of the basic calorie intake of 50% of the population in SSA (Badu-Apraku and Fakorede, 2017). Due to its dietary importance, agricultural policies favouring the promotion of a steady supply of maize through increased productivity have been developed in Africa to improve the value chain (Thorne *et al*., 2002). However, several abiotic and biotic factors such as poor climate conditions, declining soil fertility, socio-economic constraints, pests, and diseases have increased in recent years, thus exemplifying the severe constraints on maize production in SSA. The impacts of pests are particularly severe on impoverished smallholder farmers in rural areas who rely solely on agriculture for their food and means of livelihood.

Among the abundance of arthropod pests significantly threatening maize production in Africa, such as the African sugarcane stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae), the African pink borer *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae), maize leafhopper *Cicadulina mbila* Naude (Hemiptera Cicadullidae), a potential vector of the maize streak virus, the maize stalk borer *Busseola fusca* Fuller (Lepidoptera: Noctuidae), and *Chilo partellus* Swinhoe (Lepidoptera: Crambidae), the fall armyworm *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae), an invasive pest, is currently the most damaging (Tambo *et al*., 2020), and there is no apparent sign of it abating.

In SSA, the annual economic losses in maize yield attributed to *S. frugiperda* has been estimated at US$ 2.5 - 6.2 billion (Abrahams *et al*., 2017; Day *et al*., 2017). Since the first report of this pest in Ghana, in 2017, annual yield losses in maize have been estimated at US$ 177 million (Rwomushana *et al*., 2018). The application of chemical pesticides is the main method used for the control of *S. frugiperda* in Ghana and across SSA (Rwomushana *et al*., 2018), and Asia (Tambo *et al*., 2020). However, over-reliance and irrational use of these chemicals have resulted in the development of resistance in the pest, thus exacerbating its impacts (Carvalho *et al*., 2013). The implications of these are severe, because of the significant increases in management costs resultant from the development of new classes of insecticides and higher frequencies of application required (Tambo *et al*., 2020). Furthermore, the indiscriminate use of insecticides is a threat to environmental health and ecosystem functioning due to its inimical effects on beneficial/non-target organisms, including pollinators, pathogens, parasitoids, and predators. This continues to be the case to date, hence the need for an integrated pest management approach (Tambo *et al*., 2020).

**1.2 Justification**

Maize is a primary cereal crop widely grown by most of the smallholder farmers in Ghana accounting for over 50% of the total cereal production (Akramov and Malek, 2012). Despite its importance in ensuring food security, maize production in Ghana has remained lower than expected (IFPRI, 2014). For example, the average maize yields in the country in 2012 was estimated between 1.2 - 1.8 metric tons (Mt) per hectare (ha), as against an expected potential yield of 4 - 6 Mt/ha (IFPRI, 2014). This was also the case in 2016 where 1.99 Mt/ha was recorded against the potential average yield of 5.5 Mt/ha (MoFA, 2017). The low productivity in maize yield can be attributed to several factors such as drought, low soil nutrients, unfavourable climatic

conditions, poor agronomic practices, diseases and pests' infestations of which *S. frugiperda* has become the most destructive.

Evidently, the impact of *S. frugiperda* in Ghana is alarming and the main management response (i.e., the application of pesticides) adopted by farmers have proven ineffective, justifying the need for the development of integrated pest management (IPM) strategies against the pest (Tambo *et al*., 2020). Globally, there is consensus on the use of IPM; a strategy that aims to preserve the integrity of functioning ecosystems by conserving and promoting the natural mortality factors of pests through the combination of multifaceted pest management methods in a compatible manner for the management of agricultural pests (Stern *et al*., 1959; Barzman *et al*., 2015). Therefore, biological control, that is the use of natural enemies including parasitoids, predators and entomopathogens for the suppression of pest populations below levels of economic and ecological significance is generally considered as an effective and long-term control strategy for managing invasive insect pests and a proven alternative to the use of synthetic insecticides (Agboyi *et al*., 2020).

In contributing to *S. frugiperda* IPM in Ghana, the aim of the research reported in this thesis was to investigate the role of different management practices on the diversity and abundance of arthropod predators and other arthropod communities in the maize agroecosystems. It also sought to understand the potential of *R. bicolor* as a biological control agent of *S. frugiperda* in Ghana. Studies on this predator (i.e., *R. bicolor*) was recommended by the West African sub-station of the Centre for Agriculture and Bioscience International (CABI) and the Plant Protection and Regulatory Services Directorate of the Ministry of Food and Agriculture (PPRSD/MoFA) after

collaborative joint-surveys of natural enemies of *S. frugiperda* in Ghana in 2018. This thesis is the first report of the functional response, efficacy, and potential of *R. bicolor* for the management of *S. frugiperda* in Ghana, with the rationale of providing relief of the pest to smallholder farmers.

## 1.3 Objective

### 1.3.1 Main objective

The study aimed to investigate the effects of augmentative release of an egg parasitoid and insecticide use on the diversity and abundance of arthropods, predators, and *Spodoptera frugiperda* infestation levels in maize agroecosystem in Ghana. Further, it assessed the potential of a promising naturally occuring predator, for biological control of *S. frugiperda.*

### 1.3.2 Specific objectives

1. Determine the diversity and abundance of the general arthropod communities associated with maize agroecosystems in treatment MFP and the control plots.
2. Determine the diversity and abundance of the predators as well as *Spodoptera frugiperda* infestation levels in BCM, control and MFP plots.
3. Evaluate the potential of the predator, *Rhynocoris bicolor* as a biological control agent of *Spodoptera frugiperda*.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Origin and distribution of *Spodoptera frugiperda*

*Spodoptera frugiperda* is native to the tropical and subtropical regions of the Americas, occurring from the farthest south in Argentina to southern Florida and Texas in the north (Nagoshi *et al*., 2012; Early *et al*., 2018). In early 2016, *S. frugiperda* was detected in Benin Republic, Nigeria, São Tomé and Príncipe, and Togo, in West and Central Africa (Georgen *et al*., 2016). This was the first report of *S. frugiperda* in Africa and outside of its native range (Georgen *et al*., 2016). One year later (i.e., 2017), the pest had spread into 30 countries on the continent (Abrahams *et al*., 2017; FAO, 2018a), and by late 2018, 41 of the 54 countries in Africa, including Madagascar had been invaded by *S. frugiperda* (Chinwada, 2018). In 2019, four more countries were invaded by the pest, resulting in a cumulative of 45 invaded countries in Africa (Fig. 2.1). Currently, *S. frugiperda* occurs in all sub-Saharan African counties, except Lesotho (FAO, 2019).

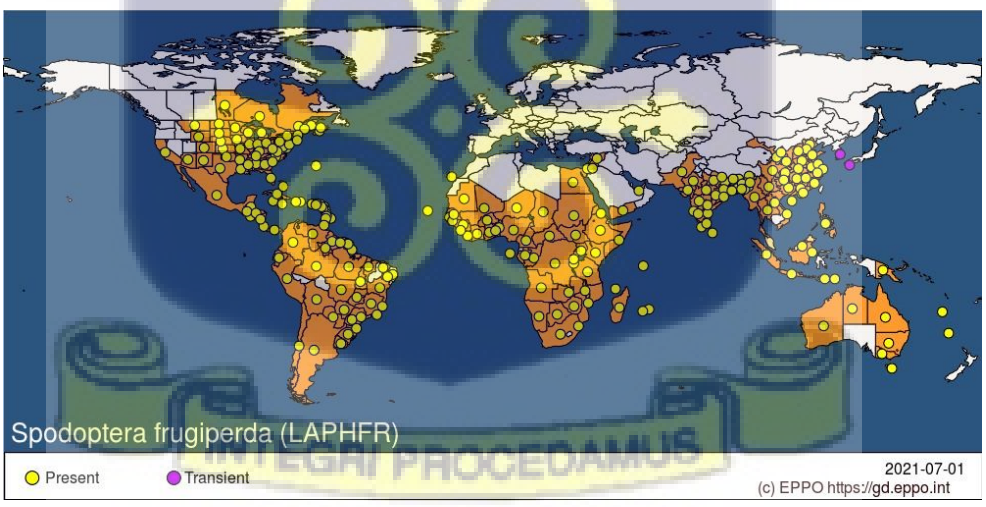


**Figure 2.1:** Global occurrence and distribution of *Spodoptera frugiperda*.

In early 2018, *S. frugiperda* was reported in Asia, following its detection in Karnataka and Andhra Pradesh in India (EPPO, 2018; IITA, 2018; Sharanabasappa *et al*., 2019). Recent reports have confirmed the spread of *S. frugiperda* in 12 other countries in Asia, including Bangladesh, China, Japan, Indonesia, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand, Vietnam, and Yemen (FAO, 2018; Baloch, 2020) (Fig. 2.1). Just recently, in 2020, *S. frugiperda* was detected on the Australian continent (Maino, 2021) (Fig. 2.1).

*Spodoptera frugiperda* was first reported in the Yilo Krobo district of the Eastern region of Ghana in 2016 and later in the Volta and Northern Regions in 2017 (Cock *et al*., 2017). The pest has since spread into all maize agroecosystems and agroecological zones in the country (Fig. 2.2).

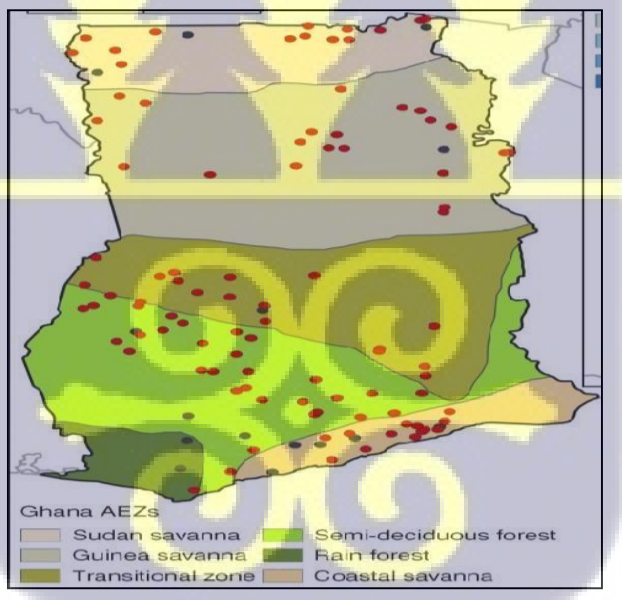


**Figure 2.2:** Occurrence and distribution of *Spodoptera frugiperda* in Ghana.
**Source:** Rwomushana *et al*. (2018).

## 2.2 Taxonomic identity, description and biology of *Spodoptera frugiperda*

### 2.2.1 Taxonomic identity

*Spodoptera frugiperda* was previously identified and described as *Caradrina frugiperda*, *Laphygma frugiperda* Guenee, 1852, *Laphygma inepta* Walker, 1856, *Laphygma macra* Guenee, 1852, *Noctua frugiperda* J.E. Smith, *Phalaena frugiperda* Smith and Abbot, 1797, *Prodenia autumnalis* Riley, 1870, *Prodenia plagiata* Walker, 1856, *Prodenia signifera* Walker, 1856, *Trigonophora frugiperda* Geyer, 1832. However, the preferred and generally acceptable scientific name is ***Spodoptera frugiperda* J.E. Smith**. The taxonomic classification of *S. frugiperda* is given below:

**Kingdom**: Animalia

**Phylum**: Arthropoda

**Class**: Insecta

**Order**: Lepidoptera

**Family**: Noctuidae

**Genus**: *Spodoptera*

**Species**: *Spodoptera frugiperda*

### 2.2.2 Description and biology

*Spodoptera frugiperda* is a holometabolous pest. Its life cycle has an egg, six instar larvae, pupa, and adult stages (Fig. 2.3). In tropical climates, it completes its life cycle in about 30 - 40 days and 55 days under temperate conditions (Prasanna *et al*., 2018). Diapause does not occur in *S. frugiperda*. Therefore, like all ectothermic species, all aspects relating to its

survival, reproduction, and phenology are completely dependent on climate parameters such as temperature and precipitation, as well as availability of host plants, thus a multivoltine pest (i.e., overlapping generations occurring in a year) (Abrahams *et al*., 2017; Prasanna *et al*., 2018).

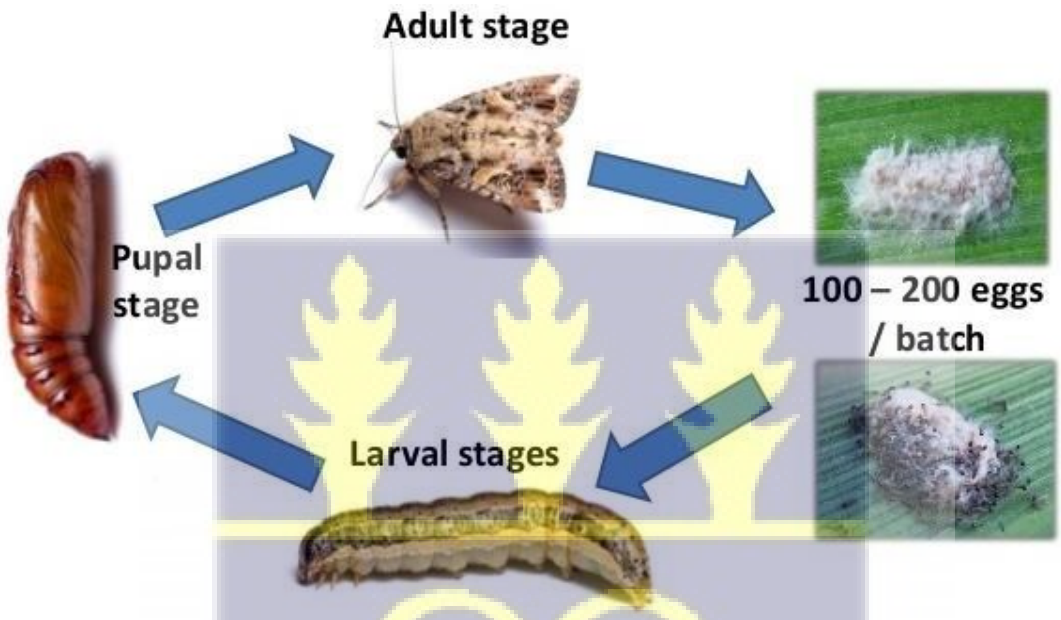


**Figure 2.3:** Life cycle of *Spodoptera frugiperda*. **Source:** Naharki *et al*. (2020).

### 2.2.2.1 Egg

The egg is dome-shaped with a flattened base and an upward curve at the apex and a broadly rounded point (Luginbill, 1928; Capinera, 2000). It is about 0.4 mm in diameter and 0.3 mm in height (Fig 2.4). Eggs are pale yellow or cream-coloured at the time of oviposition and become light brown prior to eclosion (Luginbill, 1928). Maturity takes about 2 - 3 days between 20 - 30°C. Eggs are usually laid in batches, ranging between 150 - 200 eggs which are laid in two to four layers deep on the surface of the leaf (Luginbill, 1928; Prasanna *et al.*, 2018). The egg mass is

usually covered with a protective layer of grey-pink scales (setae) from the female abdomen. The number of eggs per mass varies considerably but is often 100 to 200 and the total egg production per female during her entire life cycle averages about 1500 with a maximum of over 2000 (Luginbill, 1928; Prasanna *et al.*, 2018). Eggs masses may be laid on the underside of the leaves, or top of the leaves (Fig. 2.4). In a few cases, particularly on very young crops, eggs may be laid on the stem (Luginbill, 1928; Prasanna *et al.*, 2018). The eggs hatch into neonate larvae within 4 days (Simmons and Lynch 1990; Prasanna *et al*., 2018).

**Figure 2.4:** Eggs of *Spodoptera frugiperda*. **Source:** UF/IFAS Extension revised, (2017), http://edis.ifas.ufl.edu

**2.2.2.2 Larva**

The larval stage consists of six instars (Pitre and Hogg, 1983). The head capsule widths for the 1st - 6th instar larvae are averaged at 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm, respectively and attain lengths of about 1.7, 3.5, 6.4, 10.0, 17.2, and 34.2 mm, respectively (Pitre and Hogg, 1983) (Fig. 2.5).

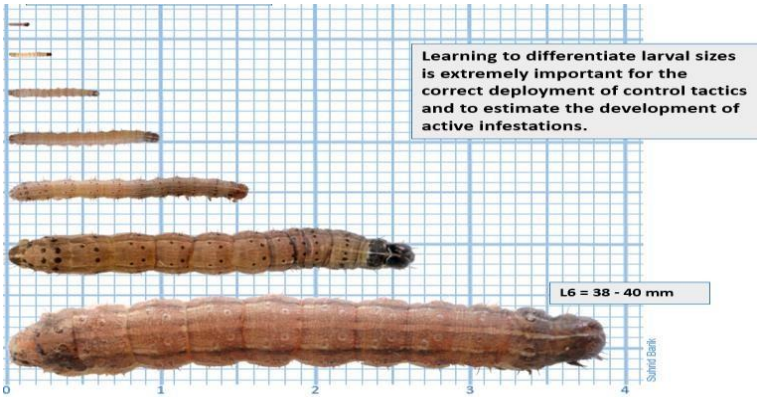


**Figure 2.5:** Neonate and the six instar larvae stages of *Spodoptera frugiperda.*

**Source:** Coverta agriscience, Australia. https://www.corteva.com.au/agronomy-hub/faw.html

The mean development time for each of the six instar larvae has been estimated at 3.3, 1.7, 1.5, 1.5, 2.0, and 3.7 days, respectively at 25 ºC (Pitre and Hogg, 1983). Upon emergence, the first instar larvae are greenish with a blackhead and become orange-coloured at the second instar larvae stage. The dorsal surface of the body becomes brownish and white lateral lines form at this stage (i.e., 2$^{nd}$ instar larvae). The white lateral lines become conspicuous in the third instar larvae. The head of the fourth to the sixth instar larvae is reddish-brown, mottled with white, and the brownish body bears white sub-dorsal and lateral lines. Elevated spots occur dorsally on the body and are usually dark in colour with spines. The head of the mature larva is also marked with a white inverted "Y" and the epidermis of the larva is rough or granular in texture when examined closely (Oliver and Chapin, 1981). Four black spots in square form occur on the last abdominal segment (Pitre and Hogg, 1983).

The young larvae (1st - 3rd instars) are usually found in the leaf whorl of young maize plants. They feed gregariously, mostly at night, on the underside of maize leaves, resulting in semi-transparent patches on the leaves called "windows". They can spin silken threads that propel them to new host plants (Luginbill, 1928; Capinera, 2000). The larvae are often cannibalistic in the second and third instar stages, thus only one or two larvae are found per whorl of the maize plant. The older larvae (4th - 6th instars) are found in the whorl of the plants where most of its damage occurs resulting in ragged holes on leaves. Continuous feeding by larvae can kill the host growing points resulting in no new leaves being formed.

Often only one or two mature larvae are found per plant, as they become cannibalistic when larger and feed on each other to reduce competition for food resources (Chapman *et al*., 1999). They produce large frass quantities that resemble sawdust when dried. Mature larvae can eat their way through the protective leaf bracts into the side of maize cobs and then feed on the developing maize seeds. The duration of the entire larval stage averages about 14 days in sunny seasons and 30 days in the wet season, and then drop to the soil for pupation.

**2.2.2.3 Pupa**

Pupation normally occurs in soil depths of 2 - 8cm (Pitre and Hogg, 1983). The larva constructs a loose cocoon which is about 20 - 30 mm in length by tying together particles of soil with silk. Larvae may web together leaf debris and other material to form a cocoon on the soil surface when the soil is very hard. The pupa is reddish-brown, measuring about 14 - 18 mm in length and about 4.5 mm in width (Luginbill, 1928; Capinera, 2000) (Fig. 2.6). The duration of the pupa stage takes

about 8 - 9 days during sunny seasons but reaches 20 - 30 days during the wet season (Capinera, 2017).

**Figure 2.6:** Pupa of *Spodoptera frugiperda*.

**Source:** CABI, 2019, Fall Armyworm Handbook: identification and management https://www.cabi.org/isc/FullTextPDF/2019/20197200644.pdf

#### 2.2.2.4 Adult male

The body length of the male is 1.6 cm, while the wingspan measures about 3.7 cm. A mottled forewings occur in males (i.e., light brown, grey, and straw). About 75% of the forewing has a discal straw coloured cell and the rest contains triangular white spots proximal to the centre of the wing (Luginbill, 1928; Sparks, 1979) (Fig 2.7).

#### 2.2.2.5 Adult female

The body length of the female is 1.7 cm, while the wingspan measures about 3.8 cm. Ranging between an apparent grey-brown to either a brown or grey mottling, the forewings of females are less distinctly marked than males (Fig 2.7), and the hind wings are straw coloured albeit with a dark-brown margin. The peak of activity of both adults (male and female) occur in warm, humid

evenings, and they are nocturnal species. Almost the entire eggload are laid following a 3-4 days of preoviposition. However, egg-laying may continue for about three weeks and the average life-span of adults is about 10 days, ranging between 7 - 21 days (Luginbill, 1928; Sparks, 1979) (Fig. 2.7).

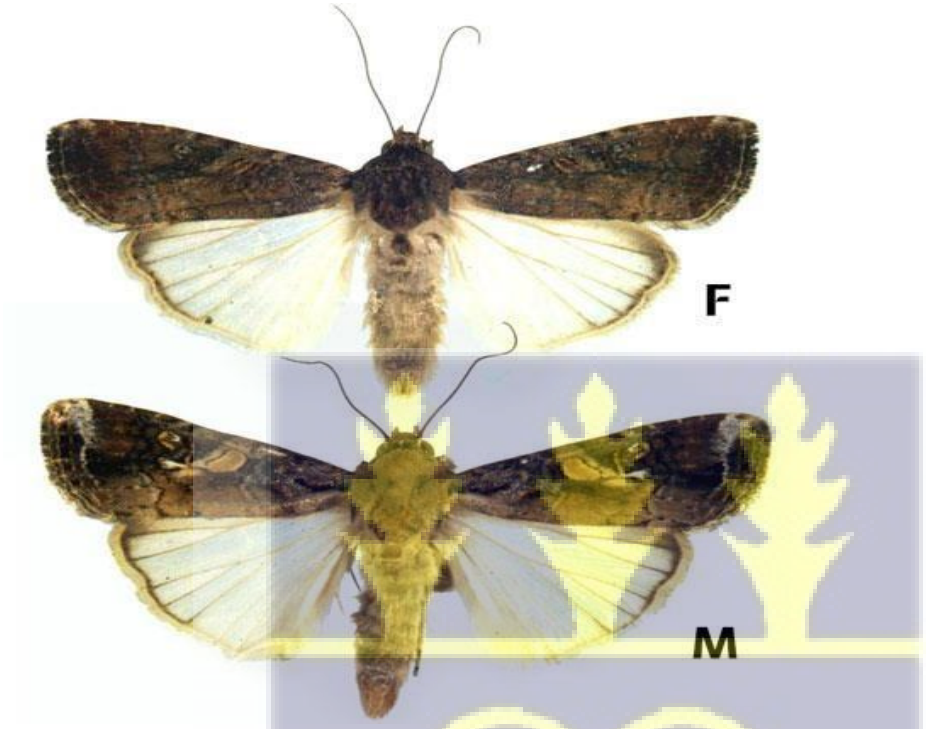


**Figure 2.7:** Adult female and male *Spodoptera frugiperda*.

**F** indicates a female, while **M** indicates a male.

**Source:** Integrated Pest Management University of Missouri https://ipm.missouri.edu/pestMonitoring/faw/identification.cfm

### 2.3 Movement and dispersal

*Spodoptera frugiperda* is nocturnal and can fly over long distances, encompassing 100 kilometres (km) per night (Johnson, 1987; Cock *et al*., 2017). This innate dispersal propensity facilitates its ability to find different habitats and favourable environmental conditions

(Tendeng *et al*., 2019). Three-day-old moths have the strongest flight capacity and can attain an average flight distance, flight duration, and flight velocity of 29.21 km, 11.00 hours, and 2.69 km h–1, respectively in 24 hours (Ge *et al*., 2021). The fast spread of *S. frugiperda* in Africa has been linked to the moth's notable migratory ability, prevailing wind conditions, and the availability of varied host species (CABI, 2019).

### 2.4 Host range of *Spodoptera frugiperda*

*Spodoptera frugiperda* is a polyphagous pest but demonstrates a preference for the Poaceae family (Casmuz *et al*., 2010). It is frequently found attacking wild and cultivated grasses, including maize, rice, sorghum, and sugarcane. In a recent review by Montezano *et al*. (2018), *S. frugiperda* was reported to attack 353 host plant species from 76 plant families, principally Poaceae (n = 106), Asteraceae (n = 31), and Fabaceae (n = 31).

### 2.5 Damage and impacts of *Spodoptera frugiperda*

Feeding by the larvae of *S. frugiperda* on the vegetative and reproductive structures of maize (leaves, tassels and ears) causes severe defoliation and reduction in photosynthesis (Abrahams *et al*., 2017). The first instar larvae usually consume the leaf tissues from one side, leaving the opposite epidermal layer intact. The second and third instar larvae create holes in leaves and feed on the edges of the leaves and then inward. At the seedling and early-whorl stages of maize, infestations induce defoliation and apical meristematic damage. Chimweta *et al*. (2019) and Hruska (2019) both argue that defoliated maize leaves caused by *S. frugiperda* larvae on maize seldom exceeds 50%. Their arguments are supported by the innate capacity of the crop to recover from leaf damage. In the mid-whorl stage, the plant suffers excessive damage due to the burrowing

feeding effects of the fourth to sixth instar larvae of *S. frugiperda*. The resultant effects are stunted growth, deformity, and plant death, thus a decline in the crop population, and substantial yield losses thereof. At the tasselling stage, the larvae of *S. frugiperda* move towards the tassel, causing injury and reduced pollen production and fertility. At the post-tasseling stage (the first reproductive stage when the ear formation starts), the larvae move to the developing ear to feed on the silks, leading to reduced fertilization and hence a reduced number of kernels per ear. A study by Pannuti *et al*. (2016) showed that young maize leaves are suitable for the development and survival of *S. frugiperda* larvae, while mature maize leaves are unsuitable, hence the larvae preference of settling and feeding in the ear of the maize, especially the silk tissues.

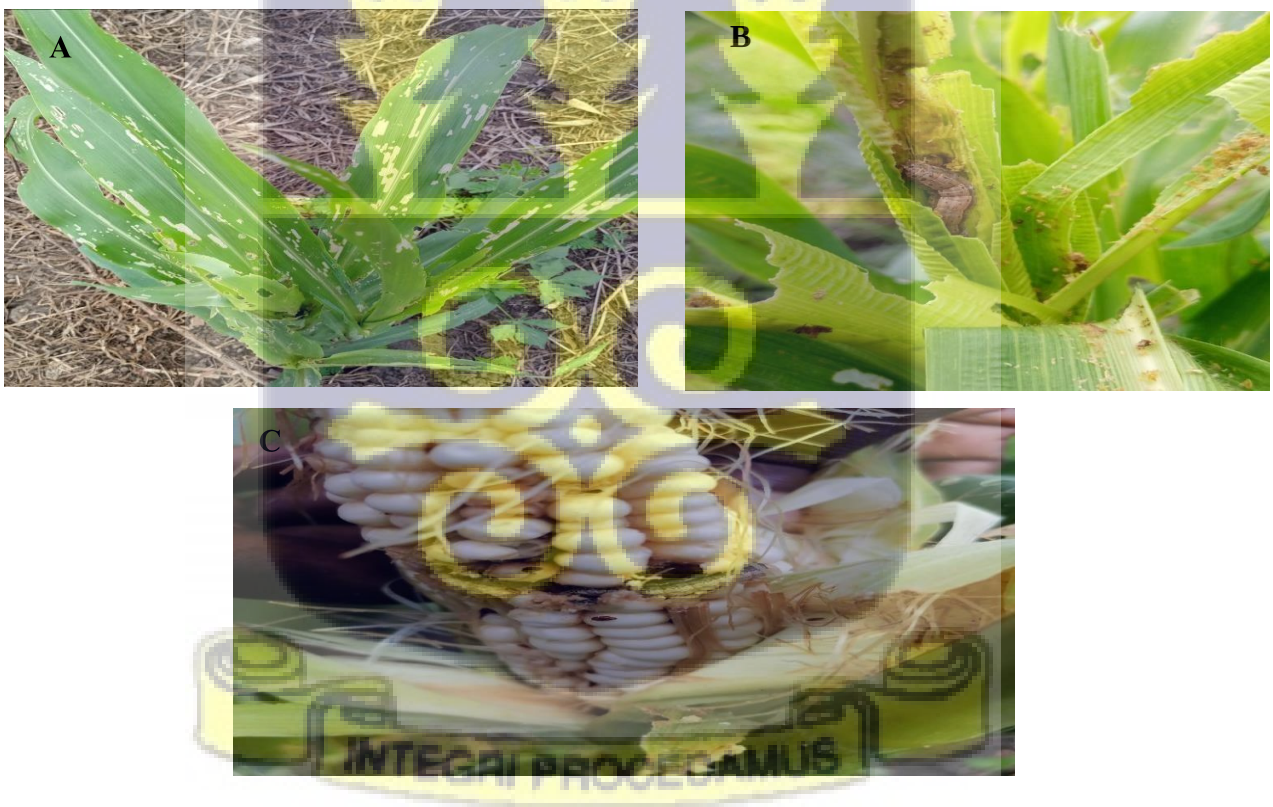


**Plate 2.1**: *Spodoptera frugiperda* feeding damage on maize (A) leaves, (B) whorl, and (C) cob.

**Photo credit:** Itohan Idemudia

Yield losses associated with *S. frugiperda* damage on maize are significant (Table 2.1).

**Table 2.1:** Yield losses in maize caused by *Spodoptera frugiperda* in some African countries, including Ghana.

| Country | Percentage yield losses (%) | References |
|---|---|---|
| Benin | 42.8 - 59.5 | Adeye *et al*. (2018) |
| Ethiopia | 11.9 | Kassie *et al*. (2020) |
| Ghana | 0 – 40 | Houngbo *et al*. (2020) |
| Kenya | 32 – 34 | Kassie *et al*. (2020) |
| South Africa | 26.5 -56.8 | Rwomushana *et al*. (2018) |
| Tanzania | 10.8 | Britz (2020) |
| Uganda | 0 – 50 | Otim *et al*. (2018) |
| Zambia | 0 – 50 | Abrahams *et al*. (2017), Houngbo *et al*. (2020) |
| Zimbabwe | 11.57 | Kansiime *et al*. (2019) |

In Africa, maize losses due to *S. frugiperda* have been estimated at 8.3 to 20.6 million tons, causing annual losses of US $2.5 to 6.2 billion (Abrahams *et al*., 2017; Day *et al*., 2017). Surveys conducted in Ghana and Zambia reported an average yield loss in maize, due to *S. frugiperda*, as 26.6% in Ghana and 35% in Zambia, cumulating to an estimated annual loss of US$ 177 million in Ghana and US$ 159 million in Zambia (Rwomushana *et al*., 2018). In addition, to yield reductions, some African countries have also incurred significant expenditures on insecticides purchase and monitoring. For example, in 2017, the Ghana Government allocated US$ 4 million for the purchase of pesticides and education of farmers. Similarly, the government of Zambia allocated US$ 3 million to subsidize pesticide and protective clothing purchases. Furthermore, the Ugandan Government allocated US$ 7 million for the supply of pesticides to control *S. frugiperda* (Abrahams *et al*., 2017). Therefore, in the absence of appropriate and effective control strategies,

the pest will continue to cause huge destruction to maize production thereby posing a serious threat to sustainable food security.

### 2.6 Management of *Spodoptera frugiperda*

Considering the significant economic impacts of *S. frugiperda* on maize production in Africa, efficient and affordable management practices of the pest for smallholder farmers are required. Some of the recommended and widely adopted management practices that minimize damage caused by *S. frugiperda* include cultural control, chemical control, botanicals, (Abrahams *et al*., 2017); biological control, push-pull technology, host plant resistance and an integrated *S. frugiperda* management strategy (Prasanna *et al*., 2018).

#### 2.6.1 Cultural control

The cultural control method is an essential management strategy for *S. frugiperda* as it is the starting point to minimize the pest's population densities prior to the application of other control methods. It mainly involves the application of proper agronomic practices that promote and strengthen maize agroecosystems, making it less attractive to the pest. Cultural practices that can help reduce the prevalence and high risk of infestation of *S. frugiperda* include the use of clean seed varieties (FAO, 2018), early planting (late-planted maize crops are more susceptible to high infestations of *S. frugiperda* than early planted crops) (Assef and Ayalew, 2019). Also, appropriate planting depth, regular field weeding, appropriate fertilizer application to improve crop vigour, proper irrigation, intercropping - preferably with non-grass species such as cowpea. Furthermore, good cultural practices include crop rotation with non-host plants, removal of damaged plants from the field, and destruction of all crop residues after harvesting.

Other cultural practices that can also be utilized in managing this invasive pest include early and regular visual inspection, handpicking, destroying egg masses and larvae of *S. frugiperda*, ploughing soil deeply to expose larvae and pupae to the upper surface of the soil, and putting sand mixed with lime or ash in the whorl of attacked maize to kill the larvae (Abrahams *et al*., 2017, CABI, 2017). Kumela *et al*. (2019) reported that 14% and 39% of the farmers in Ethiopia and Kenya practised cultural methods such as handpicking in managing *S. frugiperda*. In Ghana, 56% of smallholder maize growers adopt early planting, while 22%, 7%, 58%, and 24% adopt regular weeding, crop rotation, ash or sand, handpicking eggs and larvae of *S. frugiperda*, respectively (Tambo *et al*., 2020).

### 2.6.2 Chemical control

The chemical control method which involves the application of synthetic insecticides is the most adopted method for controlling *S. frugiperda* (Assefa and Ayalew, 2019). For example, following the outbreak of *S. frugiperda* in sub-Saharan Africa, the emergency response action, to mitigate the pest, taken by governments of the affected countries rely solely on chemical pesticides. In the surveys conducted by CABI in 2017, in Ghana and Zambia, it was revealed that though Cypermethrin was the most used chemical pesticide by farmers in the two countries for the control of *S. frugiperda*, Lambda Cyhalothrin was significantly more effective (Rwomushana *et al*., 2018). Also in Ghana, Emamectin benzoate is considered moderately effective against the pest, while most of the farmers who applied Chlorpyrifos deemed it partially effective (Rwomushana *et al*., 2018). However, the over-reliance and seldom rationale application of several chemical pesticides

with common active ingredients have resulted in the development of resistance in *S. frugiperda* to these chemicals (Fatoretto *et al*., 2017).

The resistance or tolerance mechanisms of *S. frugiperda* to insecticides comprises of two components: the detoxification/metabolic mechanism and the target resistance mechanism (Zhang *et al*., 2020). The increased activity of detoxification metabolizing enzymes is fundamental in the pests' resistance to insecticides (Yu *et al*. 2003). Detoxification-related gene families such as mixed-function oxidases (MFO), glutathione S-transferase GSTs, cytochrome P450 (P450), esterases (ESTs), alkaline phosphatase, trypsin, aminopeptidase and chymotrypsin are also associated with insecticide resistance and contribute to the invasiveness of *S. frugiperda* (McCord and Yu 1987; Yu *et al*., 2003; Zhu *et al*., 2015).

Also, chemical insecticides are considered not effective in reducing the populations of *S. frugiperda* due to the polyphagous nature, high reproductive capacity and rapid migratory behaviour of the pest (Goergen *et al*., 2016). Furthermore, some chemical pesticides are highly hazardous pesticides posing negative impacts on the environment, human health and natural enemies (Bateman *et al*., 2018; Prasanna *et al*., 2018).

### 2.6.3 Botanicals

Botanicals are naturally occurring chemicals extracted or derived from plants with insecticidal properties. The use of botanicals is usually a preferred alternative to synthetic insecticides, such as pyrethroids and organophosphorus that negatively impacts the environment and induce both resurgence and resistance of *S. frugiperda* to the synthetic insecticides (Arya and Tiwari, 2013;

Bateman *et al*., 2018). Some of the extracted botanicals from plants that have been used to effectively control insect pests, including *S. frugiperda* are *Azadirachta indica* Juss. (Meliaceae*)*, *Milletia ferruginea* (Hochst.) Baker (Fabaceae), *Croton macrostachyus* Hochst. (Euphorbiaceae), *Phytolacea docendra*, *Jatropha curcas* L. (Euphorbiaceae), *Nicotiana tabacum* L. *(Solanaceae)* and *Chrysanthemum cinerariifollium* (Jirnmci, 2013). Azadirachtin obtained from neem has been proven to be effective against *S. frugiperda* in the Americas. Silva *et al*. (2015) reported that high mortality of *S. frugiperda* larvae can be obtained by using seed cake extract of *A. indica*. In a study carried out by Martínez *et al*. (2017), it was observed that the ethanolic extracts of *Argemone ochroleuca* from Papaveraceae family resulted in the mortality of *S. frugiperda* larvae due to a depletion in feeding and retarded larval growth. In Ghana, several products based on azadirachtin are already registered for *S. frugiperda* management and control (Rwomushana *et al*., 2018).

**2.6.4 Push-pull technology (PPT)**

The push-pull technology (PPT) is a control technique that involves intercropping cereal crops with a repellent plant (i.e. push plant) such as desmodium, *Desmodium uncinatum* J. (Leguminaceae) that repels insect pests and planting a trap plant (i.e., pull plant) such as Napier grass, *Pennisetum purpureum* Schumach (Poaceae) that is highly apparent and attractive to the target pest, acting as a border crop around the intercropped field to enhance the control of pests (Midega *et al*., 2018; Harrison *et al*., 2019). The PPT has proven to be an effective, affordable, climate-smart, and farmer-friendly control strategy for mitigating *S. frugiperda* populations (Haftay and Fissiha, 2020). The volatile chemicals such as (*E*)-β-ocimene and (*E*)-4, 8-dimethyl-1, 3, 7-nonatriene emitted by the push plants are unattractive to *S. frugiperda* adults and repels them to the pull plant where they lay eggs. When the eggs hatch, the neonates burrow into the pull

plant. The pull plant then produces a sticky glue-like substance that traps and kills the young larvae. In a field experiment in Ethiopia, PPT treated maize plots significantly reduced *S. frugiperda* infestation as compared to monocropping maize plots (Haftay and Fissiha, 2020).

### 2.6.5 Host plant resistance

Plants may evolve resistance to pests through interference with one or multiple aspects of a pest-plant interaction by expressing resistance-related traits (Stout, 2014). Because host-plant resistance constitutes an integral part of integrated pest management, it explores and encompasses the utilization of resistant crop varieties with or without other management strategies, with the rationale of mitigating crop yield and quality losses caused by pests (Stout, 2014). For example, the mechanism of resistance by some pests to *Bacillus thuringiensis* (Bt) crops involves the trigger of toxins and toxin receptor mutation, as well as immune system regulation (Xiao and Wu, 2019). Bt-resistance in *S. frugiperda* has been poorly understood albeit until recently. Some researchers have underscored that resistance to Bt toxin proteins by the pest is due to both the activation and mutation of toxin receptors. For instance, Cry1F resistance in *S. frugiperda* induces down-regulated expression of Bt receptor alkaline phosphatase (ALP) (Monnerat *et al*., 2015; Jakka *et al*., 2016). When the receptor of both Cry1F and Cry1A.105, ABCC2 (ATP-binding cassette sub-family C member 2), mutates, cross-resistance to Cry1F and Cry1A.105 occurs (Flagel *et al*., 2018). Rodriguez-Cabrera *et al*. (2010) articulates decline in *S. frugiperda* sensitivity to Cry1Ca1 toxin is caused by the down-regulated expression of serine protease. In Brazil and USA delta-endotoxins from *Bacillus thuringiensis kurstaki* have been encoded and commercialized in transgenic maize (CABI, 2019).

### 2.6.6 Pheromonal control

The sex pheromone (Z)-9-Tetradecenyl acetate (Z-9-14:OAca) is used for the control of *S. frugiperda*. It is also used for *Spodoptera exigua* (Lepidoptera: Noctuidae) and *Agrotis ipsilon exigua* (Klun *et al*., 1996). Mating disruption in *S. frugiperda* using pheromones is considered a possibility due to the successes recorded on *S. exigua* in which (9Z,12E)-9,12-tetradecadienyl acetate released at high concentrations, caused mating disruption in tomato, lucerne and cotton fields (Shorey *et al*., 1994).

### 2.6.7 Biological control

Biological control of pests utilizes living organisms (natural enemies) to reduce the densities oof pests below critical economic and ecological thresholds, thus less damaging than if left untreated (Eilenberg *et al*., 2001). Biological control is generally believed to be an excellent alternative to chemical control because it is environmentally safe, posing no adverse threat to non-target species, thus and sustainable and feasible plant protection option (Assefa and Ayalew, 2019). A wide range of natural enemies including parasitoids, arthropod predators and entomopathogens have been reported to readily attack the different life stages of *S. frugiperda* in the Americas and Africa (Molina-Ochoa *et al.* 2003; Bateman *et al.* 2018; Prasanna *et al.* 2018, Agboyi *et al*., 2019, 2020; Akutse *et al*., 2019; Kenis *et al*., 2019; Koffi *et al*., 2020).

#### 2.6.7.1 Biopesticides

Several recent reports have higlighed the impotance and effectiveness of virus-based insecticides, notably, the Baculovirus group, including the multiple nucleopolyhedrovirus (SfMNPV) for the control of *S. frugiperda* (Behle and Popham, 2012; Gómez *et al*., 2013; Haase *et al*., 2015). Their

high host specificity, littlee or no toxic or adverse effects to non-target and beneficial organisms, accentuate the importance of biopesticides for *S. frugiperda* control. There is evidence showing that the SfMNPV is specific to *S. frugiperda*. When *S. frugiperda* ingests baculoviruses, feeding rates declines, and the larvae becomes blemish following skin yellowing (CABI, 2019).

Both *Beauveria bassiana* and *Metarhizium anisopliae* are effective biopesticides of *S. frugiperda* eggs and second-instar larvae (Akutse *et al*., 2019). *Beauveria bassiana* can cause 30% moratlity in second-instar larvae, while *M. anisopliae* causes 79.5 - 87.0% in egg mortalities (Akutse *et al*., 2019). Akutse *et al*. (2019) further documented that when *M. anisopliae* is combined with some other fungal isolates, about 96 % mortality of eggs and larvae of *S. frugiperda* occurs. Bateman *et al*. (2018) reviewed registered biopesticide products in 30 countries: 11 in the native range of the pest and 19 in Africa. A total of 50 biopesticide active ingredients were identified for control of *S. frugiperda* (Bateman *et al*., 2018)

**2.6.7.2 Parasitoids**

In the Americas, over 150 parasitoid species recorded from 13 families (nine in Hymenoptera and four in Diptera) have been reported to attack *S. frugiperda* (Molina-Ochoa *et al.* 2003). Among them, the egg parasitoids such as *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae), *Trichogramma atopovirilia* Oatman and platner (Hymenoptera: Trichogrammatidae) and *Telenomus remus* Nixon (Hymenoptera, Platygastridae), larval parasitoids such as *Campoletis sonorensis* Cameron (Hymenoptera: Icheumonidae) and *Chelonus insularis* Cresson (Hymenoptera: Braconidae) and pupa parasitoids such as *Diapetimorpha introita* Cresson (Hymenoptera: Ichneumonidae) and *Ichneumon promissorius* are the most

promising candidates for classical biological control in Africa and across the invasion range of *S. frugiperda* (Molina-Ochoa *et al.* 2003; Beserra *et al.* 2005; Jourdie *et al.* 2009; Pomari *et al.* 2013).

In Africa, surveys conducted by Sisay *et al.* (2018) in three East African countries (Ethiopia, Kenya, and Tanzania) revealed the presence of four hymenopteran species (*Cotesia icipe* Fernandez-Triana and Fiobe (Braconidae), *Chelonus curvimaculatus* Cameron (Braconidae), *Coccygidium luteum* (Brulle) (Braconidae), *Charops ater* Szepligeti (Ichneumonidae) and one dipteran parasitid (*Palexorista zonata* (Curran) (Tachinidae). Except for *C. curvimaculatus* – an egg-larval parasitoid, the others are larval parasitoids (Sisay *et al*., 2018). These species are new associations of the pest that have never been reported in the native range. Among the above parasitoids, *C. icipe* is considered the predominant larval parasitoid in Ethiopia, achieving a parasitism rate of 33.8 - 45.3%. In Kenya, *P. zonata*, is the primary parasitoid of the pest with 12.5% parasitism, while *C. luteum* is the most found parasitoid of *S. frugiperda* in Tanzania, having a parasitic capacity of 4 - 8.3% (Sisay *et al*., 2018).

A survey of *S. frugiperda* natural enemies in maize and sorghum fields between 2017 and 2018 in Niger revealed the occurrence of three egg parasitoids: *Trichogrammatoidea* sp. (Hymenoptera: Trichogrammatidae), *Trichogramma* sp. (Hymenoptera: Trichogrammatidae) and *Telenomus* sp. (Hymenoptera: Platygastridae), one egg-larval parasitoid: *Chelonus* sp. (Hymenoptera: Braconidae), and four larval parasitoids: *Cotesia* sp. (Hymenoptera: Braconidae), *Charops* sp. (Hymenoptera: Ichneumonidae) and unidentified ichneumonid and tachinid fly (Amadou, *et al*., 2018). Surveys conducted in Benin, Cote d'Ivoire, Kenya, Niger, and South Africa indicated the presence of an egg parasitoid, *T. remus* (Kenis *et al*., 2019).

In Ghana, Koffi *et al*. (2020) reported the occurrence of seven parasitoids species: *Chelonus bifoveolatus* (Szpligeti) (Hymenoptera: Braconidae), *Coccygidium luteum* (Brull) (Hymenoptera: Braconidae), *Cotesia icipe* (Fernandez) (Hymenoptera: Braconidae), *Meteoridea testacea* (Granger), *Bracon* sp. (Hymenoptera: Braconidae), *Anatrichus erinaceus* (Loew) (Diptera: Chloropidae), and an undetermined tachinid fly (Diptera: Tachinidae).

**2.6.7.2 Predators**

The occurrence of several insect predators of eggs and larvae of *S. frugiperda* is fundamental in managing populations of the pest. Predators of *S. frugiperda* are often generalists, feeding on multiple prey species. Predators including ground beetles (Coleoptera: Carabidae), ladybird beetles (Coleoptera: Coccinellidae), earwigs (Dermaptera: Forficulidae, Carcinophoridae) and bugs (Hemiptera: Pentatomidae, Anthocoridae, Reduviidae), have been reported to associate with *S. frugiperda* in its native range (Prasanna *et al*. 2018). For instance, the earwig, *Doru taeniatum* Dohrn (Dermaptera: Forficulidae) has been reported as a promising predator of *S. frugiperda* in Central America (Jones *et al*., 1988; Lastres, 1990).

Similarly in Brazil, the predatory earwig, *Doru luteipes* (Scudder) (Dermaptera: Forficulidae) seems to be the most abundant and efficient in reducing populations of *S. frugiperda* and *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) in soybean (Lanza Reis *et al*., 1988; Cruz 1992, 1995). Under laboratory conditions, Sueldo *et al*. (2010) reported the efficiency of the earwig, *Doru lineare* (Eschscholtz) (Dermaptera: Forficulidae) in reducing the abundance of *S. frugiperda* larvae. In India, the adults and nymphs of two native pentatomid predatory bugs, *Eocanthecona furcellata* (Wolff) (Hemiptera: Pentatomidae) and *Andrallus spinidens* (Fabr.)

(Hemiptera: Pentatomidae) were found to be effective predators of the larvae of *S. frugiperda* in organically grown maize (Shylesha and Sravika, 2018). Also, Zeng *et al*. (2021) investigated the predatory capacity, behaviour and functional response of the bug, *Orius similis* (Hemiptera: Anthocoridae) on *S. frugiperda* in China. Results from the study showed that both females and males of *O. similis* successfully preyed on *S. frugiperda* eggs, suggesting that the predator may be a promising candidate for the biological control of *S. frugiperda* eggs and first-instar larvae (Zeng *et al*., 2021).

Ants (Hymenoptera: Formicidae) are often predators of *S. frugiperda* larvae and pupae. Perfecto (1989) studied the interactions among ants, *S. frugiperda*, and pesticides in maize systems in Nicaragua. From the study, it was reported that ants are important predators of *S. frugiperda* and that the use of pesticides had a negative impact on the population and effectiveness of ants as biological control agents of *S. frugiperda*. When the pupae of *S. frugiperda* were placed in the soil in maize fields, it was discovered from the study that 92% of the pupae were removed within four days in fields without insecticide treatments, compared with only 4% in fields with insecticidal treatments.

Assassin bugs (Hemiptera: Reduviidae) is a large family of true bugs that are considered economically important taxa due to their important group of generalist predators associated with various agricultural pests. They are polyphagous, feeding on prey at higher densities (Ambrose, 2003). In Africa, assassin bugs have been seen attacking and killing larvae of *S. frugiperda* in maize fields. For example, Koffi *et al*. (2020), reported the presence of three predators (one species of ant and two species of assassin bugs) namely, *Pheidole megacephala* (F.) (Hymenoptera:

Formicidae), *Haematochares obscuripennis* Stål (Hemiptera: Reduviidae), and *Peprius nodulipes* (Signoret) Hemiptera: Reduviidae) preying on *S. fruigerida* larvae in maize fields in Ghana. Although much is not known of *Rhynocoris bicolor*, this reduviid predator has been reported as a natural enemy of the larvae of *Acraea eponina* (Cramer) (Lepidoptera: Nymphalidae) in Nigeria (CABI, 2019).

### 2.6.8 Integrated management of *Spodoptera frugiperda*

Integrated pest management is a holistic and flexible control strategy that employs a variety of integrated approaches including cultural, chemical and biological control that provides control of pests' populations below economic damage thresholds. Adoption of this management approach has the least disruption of the cropping ecosystem, and it is safe for environmental, human, and animal health. In managing the *S. frugiperda*, it is important to consider an integrated approach as it is sustainable and prevents the development of pest resistance to chemical pesticides and pest resurgence (Orr, 2003). Integrated management of *S. frugiperda* in farmers' fields should be augmented with effective monitoring, growing healthy plants in a healthy system, conserving natural enemies, and training on the application.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Field experimental site

The experimental field study (i.e., objectives 1 and 2) was conducted at the Soil and Irrigation Research Centre (SIREC) of the University of Ghana in Kpong (Fig. 3.1), during the major maize cropping season (May to August) and the minor maize cropping season (August to November) in 2020. The study location (i.e., Kpong) is situated in the Coastal Savanna agro-ecological zone of Ghana – a part of the Accra Plains and it is characterized by a bimodal rainfall pattern (i.e., major and minor rainy seasons). Annual average rainfall, temperature, and relative humidity in Kpong range between 700 - 1100 mm, 28°C, and 59 - 93 % RH, respectively (Fening *et al*., 2020). The soil type at the experimental site (i.e., SIREC) is the black clayey soil also called vertisol – which forms deep wide cracks from the surface downward when dry and becomes sticky when wet with a high-water retention capacity (Fening *et al*., 2020).

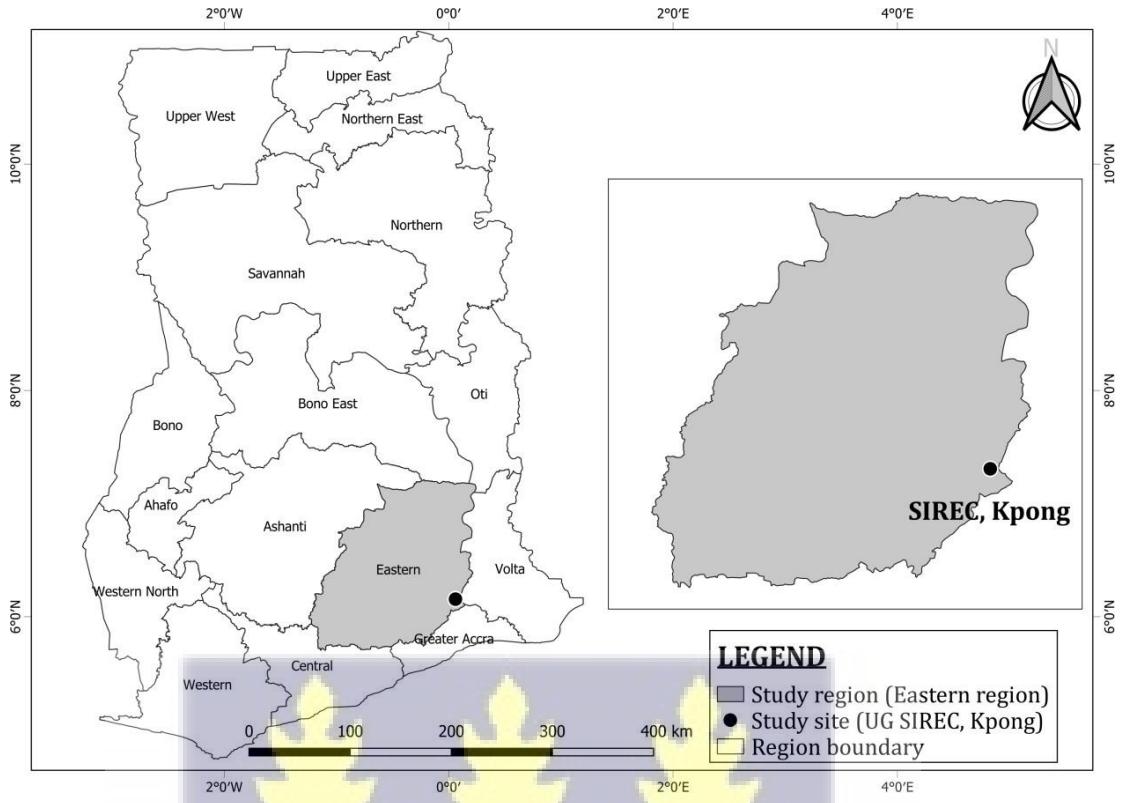


**Figure 3.1:** Map of Ghana showing the study site: Soil and Irrigation Research Centre (SIREC) of the University of Ghana in Kpong where the field research component of this thesis was undertaken from May to November 2020. This original figure was designed and generated in QGIS 3.16.1.

### 3.2 Experimental design and treatments

The field experiment consisted of two different treatment plots: (i) a biocontrol maize plot and (ii) an insecticide application maize plot. A control maize plot (i.e., without treatments i or ii) was included. Four replicates of each of the treatments and control were made in a Randomised Complete Block Design (RCBD), giving a total of 12 maize plots. The biocontrol, control and insecticide plots each measured 0.5 hectares. Each plot had a minimum distance of 200 metres apart. The two field treatments and control are delineated further below:

i. Biocontrol maize plot (**BCM**): The treatment applied in this plot was the egg parasitoid, *T. remus*. Augmentative releases of the egg parasitoid were made in the four replicated plots, a total of 45,000 parasitized eggs of FAW by *T. remus* were released per biocontrol plot.

ii. Maize plot with farmer's practice (**MFP**): The treatment applied in this plot was insecticides (an Emamectin benzoate-based product, Ataka Super EC®: Emamectin benzoate 19.2 g/l) used by local farmers,

iii. Untreated maize plot **(control)**: no release of *T. remus* or insecticide application.

**Table 3.1:** List of the experimental plots and their GPS coordinate in the experimental field site at SIREC

| Experimental plots | Replicates | GPS Coordinate |
|---|---|---|
| BCM | 1 | 6°07'48.6''N 0°04'10.2''E |
| BCM | 2 | 6°08'09.2''N 0°04'35.7''E |
| BCM | 3 | 6°08'04.9''N 0°04'54.3''E |
| BCM | 4 | 6°07'53.2''N 0°04'41.3''E |
| MFP | 1 | 6°08'11.2''N 0°04'44.4''E |
| MFP | 2 | 6°08'09.8''N 0°04'41.6''E |
| MFP | 3 | 6°07'48.6''N 0°04'25.3''E |
| MFP | 4 | 6°08'09.8''N 0°04'41.7''E |
| Control | 1 | 6°07'59.6''N 0°04'36.6''E |
| Control | 2 | 6°07'59.6''N 0°04'36.0''E |
| Control | 3 | 6°07'58.4''N 0°04'40.7''E |
| Control | 4 | 6°07'50.6''N 0°04'37.3''E |

### 3.3 Land preparation and maize cultivation

In the BCM treatment and control plots, a tractor was used in ploughing and harrowing the land before maize seeds were planted. However, no-tillage was made on the MFP plots. The maize variety, Obatanpa which is widely cultivated by farmers in Ghana, was planted in all experimental plots. In the major and minor maize cropping seasons, maize seeds were planted on 29$^{th}$ April 2020 and 30$^{th}$ September 2020 in the BCM and control plots, respectively. Planting on the MFP plots, however, occurred on 6$^{th}$ May 2020 in the major maize cropping season and 23$^{rd}$ September 2020 in the minor maize cropping season. In the BCM and control plots, maize seeds were sown with the following layout: 2 maize plants per hole/hill, with a spacing of 40 cm along rows and 80 cm between rows. However, in the MFP plots, 2 or 3 maize seeds each were planted by the farmers per hole/hill, with a spacing of 40 to 70 cm along rows and 80 to 100 cm between rows.

### 3.4 Weed management

Prior to planting in the BCM and control plots, weeds were managed by applying a pre-emergent weedicide, Agristomp 500E: Pendimethalin 500 g/l, using a calibrated 15 litres capacity knapsack sprayer. Following maize germination, weeding was done manually once in two weeks in both cropping seasons (i.e., major and minor cropping seasons). In the MFP plots, a different pre-emergence weedicide; Sunphosate 360 SL: glyphosate 360 g/l was applied before sowing using a calibrated 15 litres capacity knapsack sprayer. Thereafter, a selective weedicide (Super Nicogan 800 WDG: 570 g/kg Maesotrione + 230 g/kg Nicosulfuron) was applied after germination. The first application of the selective weedicide was done 3 to 4 weeks after the application of the emergence weedicides and the second application was done at the tasseling stage of the crop.

### 3.5 Fertilizer application

Ten days after planting in all treatment and control plots, in both cropping seasons, NPK 20:10:10 + 3S fertilizer was applied in an amount of 60 kg/ha of the nutrients N, $P_2O_5$, and $K_2O$. A second fertilizer application, 30 kg/ha of urea 46% N, was applied to all plots 6 weeks after sowing in both cropping seasons. In the BCM and control plots, the fertilizer was applied into small holes (about 7-10 cm) near individual maize plants. However, in the MFP plots, the fertilizer was broadcast on the soil surface in proximity to the maize plants.

### 3.6 Insecticide application

The insecticide applied on the MFP fields was an Emamectin benzoate-based product (Ataka Super EC®: Emamectin benzoate 19.2 g/l), which is a common and effective insecticide used by farmers for the control of *S. frugiperda* in Ghana. In both cropping seasons, the insecticide was applied once using a calibrated 15 litres tank capacity knapsack sprayer fitted with a fine plastic hollow cone nozzle at the manufacturers recommended dose of 15ml/15liters of water. This was done during the vegetative stage of the crop. However, no insecticide was applied in the BCM and control plots.

### 3.7 Data collection

#### 3.7.1 Field sampling and data collection

Field sampling and data collection (i.e., sampling for arthropods, including predators, and infestation levels of *S. frugiperda*) began two weeks after planting and was sustained for six weeks per season in each plot. Sampling was conducted weekly from 8th May to 12th June 2020 and 19th October to 23rd November in the major and minor maize cropping seasons, respectively.

### 3.7.1.1 Sampling for general arthropods

The sampling for arthropods was conducted in the MFP and control plots using yellow sticky traps (10 cm×20 cm) purchased from Matrix Innovation Company, Accra. The traps were affixed in five sampling points, in a stratified 'X pattern' sampling area, in the MFP and control plots to avoid border effects (Wyckhuys and Neil, 2006). The yellow sticky traps were affixed on both sides using short slender lines on two 2.03 m pegs proximal to maize plants. The pegs were hammered into a ground depth of 0.30m, thus leaving 2 m above ground. The traps were affixed at a height on the pegs corresponding with the heights of the maize plants (Plate 3.1). However, the traps were intermittently adjusted upwards as the maize plants grew taller.

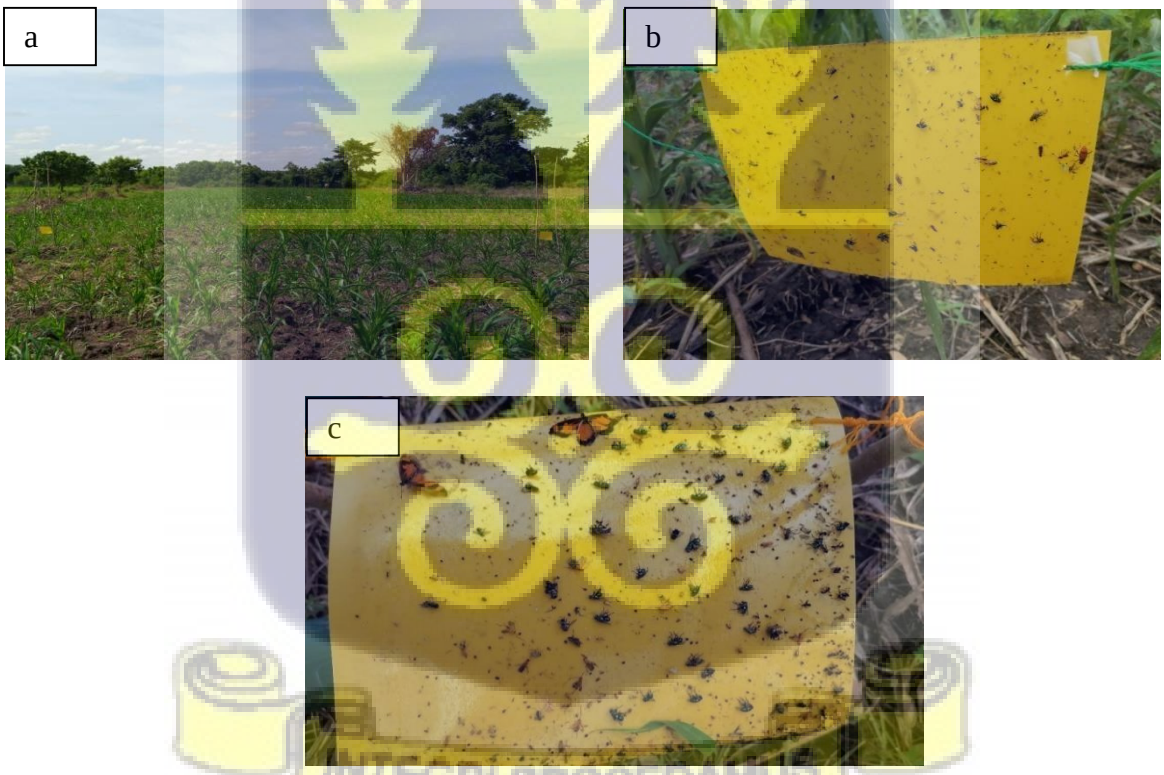


**Plate 3.1:** Experimental field with (a) affixed sticky traps in the field, (b) trap positions in the field, and (c) trap catches.

Traps were collected and replaced weekly. Collected samples were immediately placed in colourless polythene bags (Ziploc bags), labelled, and preserved under laboratory conditions. This process maintained the integrity of the samples, thus preventing trap/samples damage before identification. The traps were not placed in the BCM plots to avoid trapping the released *T. remus* which was introduced intermittently through augmentative releases.

### 3.7.1.2 Sampling for arthropod predators

The sampling for predators of *S. frugiperda* in the BCM, control, and MFP plots was conducted once weekly, from 6 am to 10 am (morning sampling event) and from 4 pm to 6 pm (evening sampling event). In both treatment and control plots (i.e., BCM, control, and MFP), 15 maize plants occurring in each of the five sampling points in the stratified sampling area (i.e., the 'X pattern') were randomly selected and sampled (Fig. 3.2). This yielded a total of 75 sampled maize plants per plot.

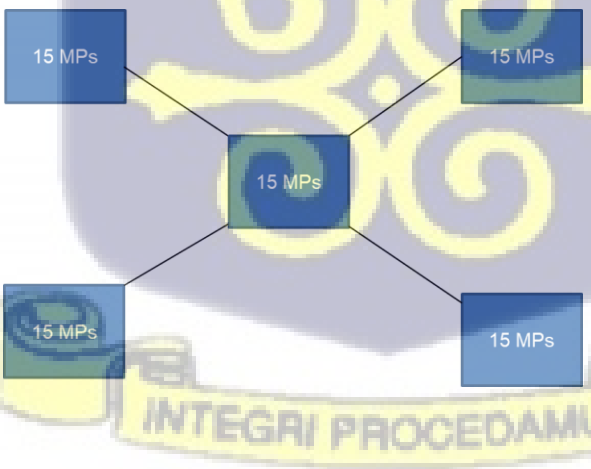


**Figure 3.2:** Schematic design showing the sampling points and the number of sampled maize plants in the stratified sampling (i.e., the 'X pattern') method. MPs = Maize plants.

Visual counts of predators occurring on the plants within the stratified sampling area ("X" pattern) including those preying on the eggs and larvae of *S. frugiperda* were made and predators were collected with either a pair of forceps or an insect aspirator. Collected samples (i.e. the predators) were then coded using different morphological keys to ease the sorting out, stored in 70% alcohol in labelled plastic tubes, and transported to the laboratory for proper identification. Also, some of the collected predators were sampled from other points in each of the experimental plots and were kept in aerated transparent plastic cups (650 ml) and taken to the SIREC laboratory where they were introduced to the egg masses and larvae of *S. frugiperda* under laboratory conditions. Egg masses and larvae of *S. frugiperda* were separately placed in petridishes (diameter 8.5cm, height 1.3cm) using a camel brush and some of the collected predators were introduced under laboratory environmental conditions (Temperature max/min: 32.7°C/26.7°C; R.H max/min: 79%/36%) to investigate their potential for control.

**Plate 3.2:** Visual examination of maize plants in the sampling area ("X" pattern) for predators of the *S. frugiperda*.

#### 3.7.1.3 Assessing infestation levels of *Spodoptera frugiperda*

The same number of maize plants (n = 15) in the same sampling points (i.e., five points) in the same stratified sampling area (i.e., the 'X pattern') in all treatment and control plots (i.e. BCM, control, and MFP), described above (Fig. 3.2) were used to assess the infestation levels of *S. frugiperda.* Here, egg batches and larvae of *S. frugiperda* in the sampling area were collected, counted and then recorded.

#### 3.7.1.4 Meteorological data

Temperature and rainfall data were recorded daily from the SIREC weather station and were examined to determine their influence (if any) on seasonal infestation levels of *S. frugiperda* and the abundance of predators.

### 3.7.2 Arthropod identification and laboratory assays

#### 3.7.2.1 Identification

The collected samples from the field (i.e., arthropods, including predators) were morphologically identified to species level using an insect taxonomic identification key guide, under a stereomicroscope provided by CABI at PPRSD in Pokuase, and with the guidance of an insect taxonomist. Also, ten (10) samples of the predator species were preserved in 70% ethanol and sent to CABI Switzerland where they were morphologically identified and confirmed by a renowned entomologist, Dr, Marc Kenis. All identified groups (i.e., order and family, and species) were recorded in a data recording notebook and then transcribed to Microsoft excel sheets for analysis.

### 3.7.2.2 Potential of the predator, *Rhynocoris bicolor* as a biological control agent of *Spodoptera frugiperda*

Following the recommendation to evaluate the potential of *R. bicolor* as a biological control agent of *S. frugiperda* by CABI and PPRSD/MoFA, the functional response of the predator was determined in laboratory assays. To do this, vibrant colonies of both the pest and predator were first reared and maintained at the PPRSD biocontrol laboratory in Pokuase. Approximately seven generations of *R. bicolor* had been reared in the laboratory prior to this study. Environmental conditions in the laboratory were maintained at 27 ± 1 °C and 60 ± 10% RH.

Fifty pupae of *S. frugiperda* were collected from the insectary of the Biotechnology and Nuclear Agriculture Research Institute (BNARI), Ghana Atomic Energy Commission (GAEC), Accra. The pupae were collected in an aerated transparent plastic jar (500ml) and taken to the PPRSD biocontrol laboratory. Emerging adult moths were transferred into another set of transparent aerated plastic insect rearing cages. The adults were then provided with a 10% honey-water solution marinated in cotton wool. Two freshly collected young maize leaves were excised and the distal ends were plugged into cotton wool balls – soaked in water – and inserted into small vials. The vials, mimicking potted maize plants, were then placed in each cage to serve as the substrate for oviposition. The potted plants were replaced daily and checks for egg masses were made. The eggs were incubated in aerated transparent plastics boxes (650ml) containing a piece of dry tissue paper for moisture absorption. Following hatching, the larvae were fed with maize or castor leaves, depending on the availability of each of the host plants. Over 50 newly emerged larvae were reared together in each rearing container. However, at the second instar larvae stage, only five were placed together to prevent cannibalism.

**Plate 3.3:** Laboratory set-up for rearing *Spodoptera frugiperda.*

Following the establishment of the laboratory *S. frugiperda* colony, described above, 30 *R. bicolor* adults were collected from the mother colony already established in the PPRSD biocontrol laboratory. They were then transferred into transparent aerated plastic insect rearing containers (15 cm x 13 cm x 9 cm) to allow for ventilation. However, only five male-female adult pairs were maintained together in each cage to prevent cannibalism. This is because females can kill and eat males when deprived of food (Personal observation in the laboratory). The adults were fed with a 10% honey-water solution marinated in cotton wool. The rearing containers were examined for

eggs daily, and eggs were collected and then transferred carefully into aerated transparent plastic cups (650 ml) until eclosion of the first nymphal instar, approximately nine days after oviposition.

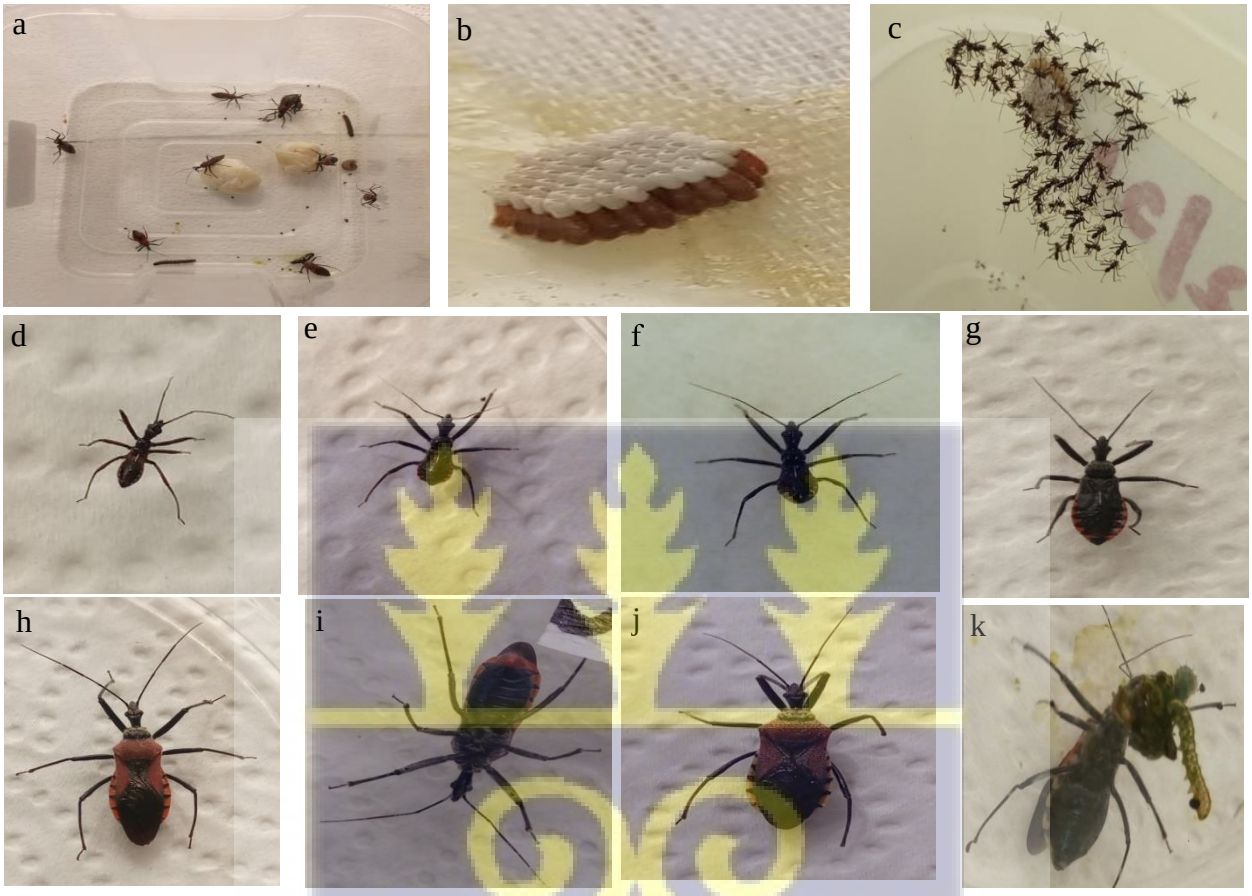


**Plate 3.4:** Life stages of *Rhynocoris bicolor* (a) males and females *R. bicolor* in the rearing arenas, (b) newly hatched eggs of the female *R. bicolor*, (c) 1st Nymphal stage of *R. bicolor*, (d) 2nd Nymphal stage of *R. bicolor*, (e) 3rd Nymphal stage of *R.bicolor*, (f) 4th Nymphal stage of *R. bicolor*, (g) 5th Nymphal stage of *R. bicolor*, (h) dorsal view of male (i) ventral view of male, (j) dorsal view of female, (k) ventral view of female attached with a newly killed *S. frugiperda* larva.

Following the establishment of laboratory colonies of the predator (*R. bicolor*) and prey *(S. frugiperda*), the functional response of *R. bicolor* was investigated from January to April 2021 in the biocontrol laboratory of the PPRSD with environmental conditions, described above, in rearing the predator and *S. frugiperda* colonies. The feeding responses of all nymphal instars and adults

of *R. bicolor* were tested against all instars of *S. frugiperda* larvae. Prior to the assays, each of the tested *R. bicolor* predators was starved for 24 h. The different *S. frugiperda* larval instars were each introduced in six different densities: 5, 15, 25, 30, 35, 40, respectively into Petri dishes (Diameter 8.5cm, height 1.3cm) using a camel's hairbrush. Thereafter, one each of the five nymphal stages and two adult sexes of R. *bicolor* was introduced to each of the larval instars and densities of *S. frugiperda* delineated above. After six hours, the predator was removed, and the number of larvae alive and dead were recorded. The dead larvae were not replaced. Ten replicates were made for each of the prey densities.

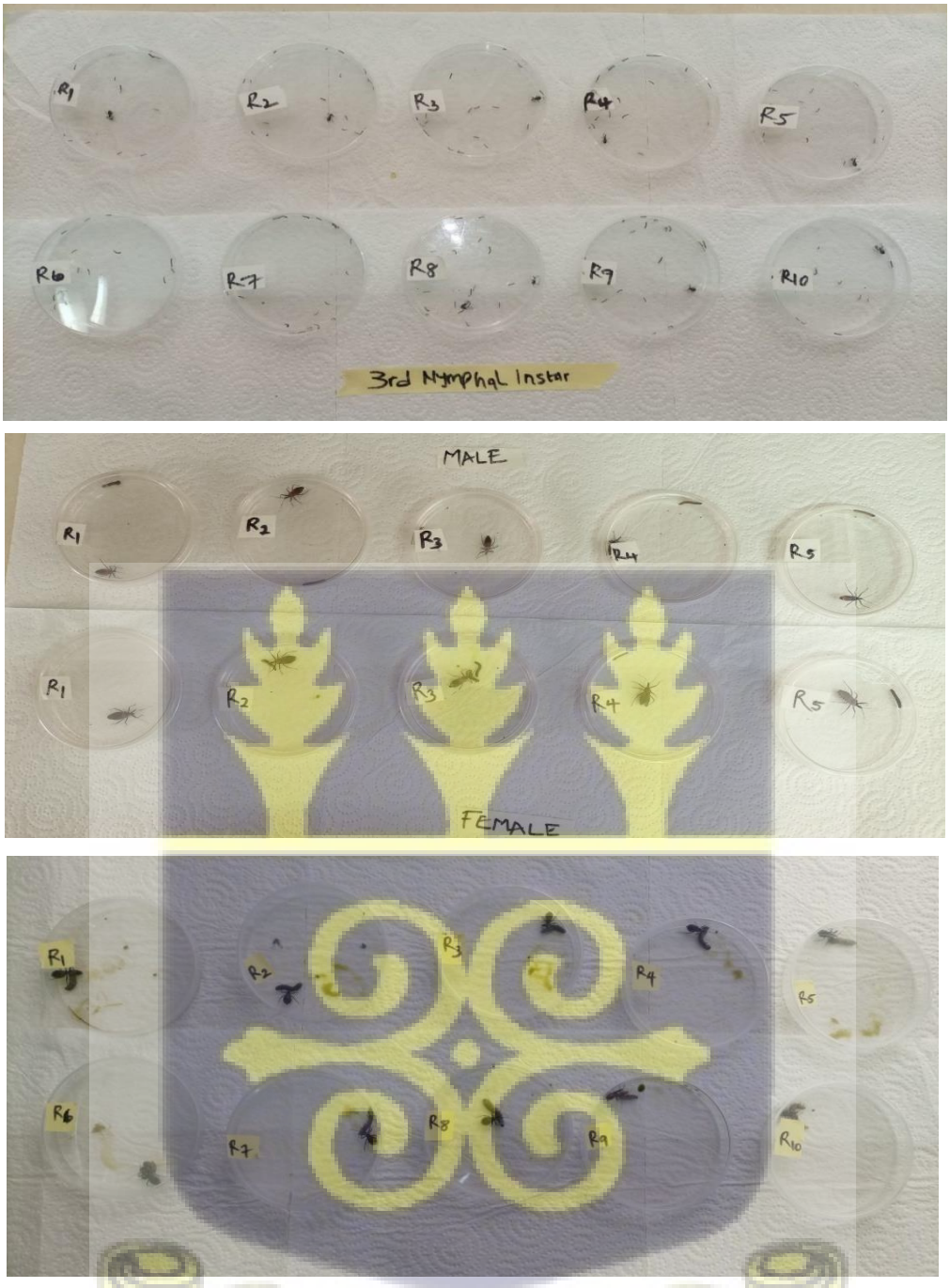


**Plate 3.5:** Experimental design and replicates used in assessing the functional response of *R. bicolor* with *S. frugiperda* as prey in a six-hour assay.

### 3.8 Statistical analysis

#### 3.8.1 Relative abundance and diversity

The relative abundance (RA) of all identified arthropod species including predators per treatment and season were calculated using the expression: $\boldsymbol{RA = \frac{Ni}{Nt} \times 100}$ where Ni = total number of individuals of the ith species and $N_t$ = total number of individuals of all species. Thereafter, Shannon–Wiener diversity index (H) was used to calculate the diversity of the arthropod species including predators among the different treatments and seasons. This was done using the formula: $\textbf{Shannon index (H)} = -\sum_{i=1} \textbf{pi In pi}$ where p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), ln is the natural log, Σ is the sum of the calculations, and *s* is the number of species. Shannon's equitability or evenness ($E_H$) was then calculated using the formula: H/Hmax where H max = ln (S) = the maximum value that H can have for a particular sample, i.e., total even distribution, S = total number of species in the sample.

#### 3.8.2 Infestation level of *Spodoptera frugiperda*

To satisfy the assumptions of parametric tests, the count data (i.e., egg batches and larvae density) from the BCM, MFP, and control plots were first subjected to Shapiro-Wilk's and Bartlett's tests, respectively (Bartlett 1937; Shapiro and Wilk 1965). Both tests indicated that the data violated the assumptions of parametric tests. Therefore, variations in the egg batches and larvae density between treatments (BCM and MFP) and control plots for each of the major and minor cropping seasons were subjected to the Kruskal-Wallis H test. Following the indication of a significant test ($P < 0.05$) in each instance, Dunn's multiple comparisons, with p-values adjusted with the Holm method, was used to identify heterogeneous mean ranks. Variations in the overall egg batch counts

and larvae infestation level of the pest recorded in the major and minor maize cropping seasons also violated the assumptions of parametric tests. So, the Mann-Whitney-Wilcoxon test with continuity correction was used to test for significance in variations.

### 3.8.3 Predation rate and functional response of *Rhynocoris bicolor*

Two different steps, described by Juliano (2001), were used in disentangling the functional response of *R. bicolor*. The first phase was the determination of the type and estimation of the parameters of the functional response curve. Fundamentally, identification of the functional response type, using a proper model, is crucial for calculating functional response parameters such as attack rate and handling time. The response type of *R. bicolor* was investigated by applying a logistic regression of the proportion of prey eaten as a function of the initial prey density offered to the predator. A polynomial logistic regression equation assuming a binomial distribution of data to define the type of functional response (Juliano, 2001) was fitted as in equation 1 below:

$$\frac{Na}{Nt} = \frac{\exp\left(P_0 + P_1 N_t + P_2 N^2{}_t + P_3 N^3{}_t\right)}{1+\exp\left(P_0+P_1N_t+P_2N_{t2}+P3N_{t3}\right)}$$

where $N_t$ is the initial prey density, $N_a$ is the number of prey eaten, and $N_a/N_t$ is the probability of being eaten. $P_0$, $P_1$, $P_2$, and $P_3$ are the intercept, linear, quadratic, and cubic coefficients, respectively. Maximum likelihood was used in calculating the coefficients. The nature of functional response – type II or type III – was obtained by the values of the linear and quadratic coefficients. When the value of a linear parameter is negative, the functional response is described as type II. However, if the linear parameter is positive with a negative quadratic coefficient, then the response is delineated as type III. The type II response shows that the proportion of prey

consumption decreases as the prey density increases, while the type III response indicates that the proportion of prey consumed increases until an inflection point and then decreases.

Following the determination of the functional response type of each of the different life-stages of *R. bicolor*, the second phase was initiated to determine the functional response parameters of each of these stages. To do this, the data were fitted to the Rogers' type II random predator equation, using non-linear least square regression, because prey was not replaced during the entire experiment (Rogers, 1972). The random predictor model was used to calculate the attack rate ($a$) and handling time ($T_h$) of each of the different life-stages of *R. bicolor* as given in equation 2 below:

$$N_a = N_o\,[1 - \exp\,(a\,(T_h N_a - T\,)\,)\,]$$

Where $N_a$ is the number of prey eaten, $N_o$ is the initial prey density (prey.arena−1), $a$ is the attack rate (arena.hour−1), $T_h$ is the handling time (hour.prey−1), and $T$ is time available for predator during the experiment (6 h). Here, the logistic regression and the response parameters (attack rate: $a$ and handling time: $T_h$) were fit using the "*glm*" function and the functional responses were estimated with the "*FRAIR*" (Functional Response Analysis in R) package in R 4.0.0 statistical software (Pritchard *et al*., 2017). The maximum theoretical predation rate per day ($K = T/T_h$) was then calculated. It indicates the maximum amount of prey that a predator can consume in a given time (Hassell, 2000), which in this study was 6 hours.

Lastly, 95% confidence intervals (CIs) were generated by a nonparametric bootstrapping to compare the fitted coefficients using the "*frair_boot*" function. In this context, parameters with non-overlapping 95% CIs are generally considered significantly different (Pritchard *et al*., 2017).

To compare predation rates, the data was first subjected to normality and homoscedasticity testing with Shapiro-Wilk's and Bartlett's tests, respectively (Bartlett 1937; Shapiro and Wilk 1965). Because the data violated the assumptions of parametric tests, a generalized linear model with a negative binomial distribution and log-link function was used to determine significant differences (if any) in the killing efficiency of the different life-stages of *R. bicolor*. Following the indication of a significant test ($P < 0.05$), the homogenous sub-sets were identified with Tukey's HSD test. All analyses were performed in the R studio environment (version 4.0.0) for statistical computing.

# CHAPTER FOUR

# RESULTS

## 4.1 Diversity and abundance of general arthropod communities associated with maize agroecosystems

### 4.1.1 Major maize cropping season

A total of 20, 050 individual arthropods were collected from the MFP and control plots in the major maize cropping season (Table 4.1 and 4.2). The control plots had 11, 865 individual arthopods, while the MFP plots yielded 8185 individual arthropods. Thus, the control plots had a significant higher proportion of arthropods than the MFP plots ($\chi^2$ = 2588.92, df = 1, $P$ < 0.001). Nevertheless, the same number of arthropod orders was recorded in the control plots (n = 10) and MFP plots (n = 10), thus did not significantly differ ($\chi^2$ = 9.10, df = 1, $P$ = 0.671). Also, the identified number of arthropod families from the MFP (n = 54) and control (n = 54) plots did not differ significantly ($\chi^2$ = 49.16, df = 1, $P$ = 0.981), as well as the number of species in each plots; MFP (n = 84) and control plots (n = 89) ($\chi^2$ = 68.36, df = 1, $P$ = 1.702). Insect species in the order Hymenoptera (n = 6186), Diptera (n = 3495), Hemiptera (n = 1151), and Coleoptera (n = 665) constituted the most dominant arthropods in the control plots, representing 52.14%, 29.46%, 9.70%, and 5.60% of the arthropod community. Similarly, these same insect orders were dominant in the MFP plots: Hymenoptera (n = 3816), Diptera (n = 2836), Hemiptera (n = 729), and Coleoptera (n = 502) and had a relative abundance of 46.62%, 34.65%, 8.91%, and 6.13%, respectively. Insects in the family Formicidae were the most abundant in both the control (n = 5607) and MFP plots (n = 3425), with *Oecophylla longinoda* being the most abundant in both plots (Table 4.1 and 4.2)

**Table 4.1:** Order, family, and species diversity of arthropod communities in maize plots with farmers' practice (MFP) in the major maize cropping season and parameters of Shannon index diversity calculation

| **Order** | **Family** | **Species** | **Counts** | ***Pi*** | ***ln(pi)*** | ***pi x ln(pi)*** |
|---|---|---|---|---|---|---|
| **Araneae** | Agelenidae | *Tegenaria* sp. 1 | 21 | 0.002412 | -6.02713 | -0.01454 |
| " | " | *Agelenopsis aperta* (Gertsch) | 43 | 0.00494 | -5.31045 | -0.02623 |
| " | Thomisidae | *Misumenops* sp. 1 | 10 | 0.001149 | -6.76907 | -0.00778 |
| **Blattodea** | Ectobiidae | *Blattella germanica* (Linn) | 19 | 0.002183 | -6.12721 | -0.01337 |
| " | " | *Blattella asahinai* (Mizukubo) | 11 | 0.001264 | -6.67376 | -0.00843 |
| **Coleoptera** | Cantharidae | *Rhagonycha lignosa* (Muller) | 31 | 0.003561 | -5.63767 | -0.02008 |
| " | Carabidae | *Dyschirius* sp. 1 | 6 | 0.000689 | -7.27989 | -0.00502 |
| " | Chrysomelidae | *Hispellinus fimbriatus* (Chapuis) | 97 | 0.011143 | -4.49694 | -0.05011 |
| " | " | *Chrysomela* sp. 1 | 129 | 0.014819 | -4.21184 | -0.06242 |
| " | " | *Chrysomela* sp. 2 | 83 | 0.009535 | -4.65281 | -0.04436 |
| " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 61 | 0.007007 | -4.96078 | -0.03476 |
| " | " | *Cheilomenes sulphurea* (Oliver) | 47 | 0.005399 | -5.22151 | -0.02819 |
| " | " | *Chnootriba* sp. 1 | 35 | 0.004021 | -5.5163 | -0.02218 |
| " | " | *Chilocorus nigrita* (Fab) | 5 | 0.000574 | -7.46221 | -0.00429 |
| " | Staphylinidae | *Paederus* sp. 1 | 8 | 0.000919 | -6.99221 | -0.00643 |
| **Diptera** | Agromyzidae | *Ophiomyia simplex* (Loew) | 31 | 0.003561 | -5.63767 | -0.02008 |
| " | " | *Phytomyza* sp. 1 | 45 | 0.005169 | -5.26499 | -0.02722 |
| " | Anthomyiidae | *Delia brassicae* (Wiedemann) | 61 | 0.007007 | -4.96078 | -0.03476 |
| " | Asilidae | *Promachus vertebratus* (Say) | 18 | 0.002068 | -6.18128 | -0.01278 |
| " | " | *Efferia pogonias* (Wiedemann) | 10 | 0.001149 | -6.76907 | -0.00778 |
| " | Calliphoridae | *Lucilia illustris* (Meigen) | 157 | 0.018036 | -4.01541 | -0.07242 |
| " | " | *Lucilia sericata (Meigen)* | 491 | 0.056404 | -2.87521 | -0.16217 |
| " | " | *Calliphora vicina* (Rob) | 81 | 0.009305 | -4.6772 | -0.04352 |
| " | Chironomidae | *Chironomus plumosus* (Linn) | 11 | 0.001264 | -6.67376 | -0.00843 |
| " | " | *Ablabesmyia monilis* (Linn) | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Culicidae | *Culex pipiens* (Linn) | 60 | 0.006893 | -4.97731 | -0.03431 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | " | *Culex tarsalis* (Coquillett) | 94 | 0.010798 | -4.52836 | -0.0489 |
| " | Diopsidae | *Diopsis thoracica* (Westwood) | 244 | 0.02803 | -3.57448 | -0.10019 |
| " | Drosophilidae | *Drosophila melanogaster* (Meigen) | 74 | 0.008501 | -4.76759 | -0.04053 |
| " | Fanniidae | *Fannia canicularis* (Linn) | 146 | 0.016772 | -4.08805 | -0.06856 |
| " | Muscidae | *Musca domestica* (Linn) | 402 | 0.04618 | -3.0752 | -0.14201 |
| " | Mycetophilidae | *Brevicornu* sp. 1 | 36 | 0.004136 | -5.48813 | -0.0227 |
| " | Sarcophagidae | *Sarcophaga haemorrhoidalis* (Fallen) | 451 | 0.051809 | -2.96019 | -0.15337 |
| " | " | *Blaesoxipha* sp. 1 | 136 | 0.015623 | -4.159 | -0.06498 |
| " | Sciaridae | *Bradysia* sp. 1 | 11 | 0.001264 | -6.67376 | -0.00843 |
| " | Stratiomyidae | *Hermetia illucens* (L) | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Syphridae | *Eristalis tenax* (L) | 7 | 0.000804 | -7.12574 | -0.00573 |
| " | Tachinidae | *Archytas apicifer* (Walker) | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | " | *Compsilura concinnata* (Meigen) | 51 | 0.005859 | -5.13983 | -0.03011 |
| " | Tephritidae | *Zeugodacus cucurbitae* (Coquillet) | 35 | 0.004021 | -5.5163 | -0.02218 |
| " | " | *Bactrocera dorsalis* (Hendel) | 49 | 0.005629 | -5.17983 | -0.02916 |
| " | " | *Dacus ciliatus* (Loew) | 91 | 0.010454 | -4.56079 | -0.04768 |
| " | Tipulidae | *Tipula abdominalis* (Say) | 6 | 0.000689 | -7.27989 | -0.00502 |
| **Hemiptera** | Cercopidae | *Poophilus* sp. 1 | 57 | 0.006548 | -5.0286 | -0.03293 |
| " | " | *Philaenus spumarus* (Linn) | 49 | 0.004595 | -5.38277 | -0.02473 |
| " | Cicadellidae | *Cofana spectra* (Distant) | 415 | 0.047674 | -3.04337 | -0.14509 |
| " | " | *Empoasca* sp. 1 | 182 | 0.020908 | -3.86765 | -0.08086 |
| " | Coriedae | *Homoeocerus auriculatus* (Stal) | 3 | 0.000345 | -7.97304 | -0.00275 |
| " | Pentatomidae | *Nezara viridula* (Linn) | 2 | 0.00023 | -8.37851 | -0.00192 |
| " | Pyrrhocoridae | *Dysdercus superstitiosus* (Schaffer) | 9 | 0.001034 | -6.87443 | -0.00711 |
| " | " | *Dysdercus nigrofasciatus* (Stal) | 11 | 0.001264 | -6.67376 | -0.00843 |
| " | Reduviidae | *Haematochares obscuripennis* (Stal) | 2 | 0.00023 | -8.37851 | -0.00192 |
| " | Scutelleridae | *Calidea dregii* (Germar) | 8 | 0.000919 | -6.99221 | -0.00643 |
| **Hymenoptera** | Apidae | *Apis mellifera* (Linn) | 6 | 0.000689 | -7.27989 | -0.00502 |
| " | Braconidae | *Macrocentrus ancylivorus* (Rohwer) | 91 | 0.010454 | -4.56079 | -0.04768 |
| " | " | *Coccygidium* sp. 1 | 125 | 0.01436 | -4.24334 | -0.06093 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | Chrysididae | *Chrysis coerulans* (Fab) | 24 | 0.002757 | -5.8936 | -0.01625 |
| " | Formicidae | *Camponotus pensylvanicus (De Geer)* | 501 | 0.057553 | -2.85505 | -0.16432 |
| " | " | *Camponotus* sp. 1 | 523 | 0.06008 | -2.81207 | -0.16895 |
| " | " | *Crematogaster striatula* (Emery) | 310 | 0.035612 | -3.33508 | -0.11877 |
| " | " | *Crematogaster* sp. 1 | 546 | 0.062723 | -2.76903 | -0.17368 |
| " | " | *Monomorium pharaonis (Linn)* | 85 | 0.009765 | -4.629 | -0.0452 |
| " | " | *Oecophylla longinoda* (Latreille) | 1073 | 0.123262 | -2.09344 | -0.25804 |
| " | " | *Pheidole megacephala* (Fabricius) | 21 | 0.002412 | -6.02713 | -0.01454 |
| " | " | *Tetramorium immigrans* (Santschi) | 92 | 0.010569 | -4.54986 | -0.04809 |
| " | " | *Solenopsis xyloni* (McCook) | 274 | 0.031476 | -3.45852 | -0.10886 |
| " | Icheumonidae | *Megarhyssa greenei* (Viereck) | 25 | 0.002872 | -5.85278 | -0.01681 |
| " | Platygastridae | *Platygaster* sp. 1 | 32 | 0.003676 | -5.60592 | -0.02061 |
| " | " | *Telenomus remus* (Nixon) | 58 | 0.006663 | -5.01121 | -0.03339 |
| " | Pompilidae | *Pompilus lactuosus* Cresson | 17 | 0.001953 | -6.23844 | -0.01218 |
| " | Vespidae | *Vespula pensylvanica* (Saussure) | 13 | 0.001493 | -6.5067 | -0.00972 |
| **Lepidoptera** | Crambidae | *Argyria* sp. 1 | 41 | 0.00471 | -5.35808 | -0.02524 |
| " | Hesperidae | *Borbo fatuellus* (Hopffer) | 5 | 0.000574 | -7.46221 | -0.00429 |
| " | Noctuidae | *Spodoptera frugiperda* (J.E. Smith) | 13 | 0.001493 | -6.5067 | -0.00972 |
| " | Nymphalidae | *Acraea alciope* (Hew) | 22 | 0.002527 | -5.98061 | -0.01511 |
| " | Pieridae | *Coniesta ignefusalis* (Hampson) | 7 | 0.000804 | -7.12574 | -0.00573 |
| **Mantodea** | Mantidae | *Mantis religiosa* (Linn) | 2 | 0.00023 | -8.37851 | -0.00192 |
| **Odonata** | Coenagrionidae | *Argia sedula* (Hagen) | 17 | 0.001953 | -6.23844 | -0.01218 |
| " | Gomphidae | *Hagenius brevistylus* (Selys) | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Libellulidae | *Libellula pulchella* (Drury) | 5 | 0.000574 | -7.46221 | -0.00429 |
| **Orthoptera** | Acrididae | *Aulocara elliotti (*Thomas) | 38 | 0.004365 | -5.43407 | -0.02372 |
| '' | Gryllidae | *Gryllus* sp. 1 | 16 | 0.001838 | -6.29906 | -0.01158 |
| '' | Pyrgomorphidae | *Zonocerus variegatus* (Linn) | 21 | 0.002412 | -6.02713 | -0.01454 |
| '' | Tettigoniidae | *Microcentrum rhombifolium* (Saussure) | 7 | 0.000804 | -7.12574 | -0.00573 |
| | | | | | | |

**Table 4.2:** Order, family, and diversity of arthropod communities in the control plots (i.e. without any applied treatment) in the major maize cropping season and parameters of Shannon index diversity calculation

| **Order** | **Family** | **Species** | **Counts** | ***Pi*** | ***ln(pi)*** | ***pi x ln(pi)*** |
|---|---|---|---|---|---|---|
| **Araneae** | Agelenidae | *Tegenaria* sp. 1 | 16 | 0.001838 | -6.29906 | -0.01158 |
| " | " | *Agelenopsis aperta* (Gertsch) | 29 | 0.003331 | -5.70436 | -0.019 |
| " | Thomisidae | *Misumenops* sp. 1 | 12 | 0.001379 | -6.58675 | -0.00908 |
| " | " | *Misumenops* sp. 1 | 8 | 0.000919 | -6.99221 | -0.00643 |
| **Blattodea** | Ectobiidae | *Blattella germanica* (Linn) | 18 | 0.002068 | -6.18128 | -0.01278 |
| " | " | *Blattella asahinai* (Mizukubo) | 15 | 0.001723 | -6.3636 | -0.01097 |
| **Coleoptera** | Cantharidae | *Rhagonycha lignosa* (Muller) | 43 | 0.00494 | -5.31045 | -0.02623 |
| " | Carabidae | *Dyschirius* sp. 1 | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | Chrysomelidae | *Hispellinus fimbriatus* (Chapuis) | 147 | 0.016887 | -4.08122 | -0.06892 |
| " | " | *Chrysomela* sp. 1 | 153 | 0.017576 | -4.04121 | -0.07103 |
| " | " | *Chrysomela* sp. 2 | 111 | 0.012751 | -4.36212 | -0.05562 |
| " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 49 | 0.005629 | -5.17983 | -0.02916 |
| " | " | *Cheilomenes sulphurea* (Oliver) | 78 | 0.00896 | -4.71494 | -0.04225 |
| " | " | *Chnootriba* sp. 1 | 14 | 0.001608 | -6.4326 | -0.01035 |
| " | " | *Chilocorus nigrita* (Fab) | 17 | 0.001953 | -6.23844 | -0.01218 |
| " | Staphylinidae | *Paederus* sp. 1 | 27 | 0.003102 | -5.77582 | -0.01791 |
| **Diptera** | Agromyzidae | *Ophiomyia simplex* (Loew) | 7 | 0.000804 | -7.12574 | -0.00573 |
| " | " | *Phytomyza* sp. 1 | 31 | 0.003561 | -5.63767 | -0.02008 |
| " | Anthomyiidae | *Delia brassicae* (Wiedemann) | 25 | 0.002872 | -5.85278 | -0.01681 |
| " | " | *Scatophaga stercoraria* (Linn) | 29 | 0.003331 | -5.70436 | -0.019 |
| " | Asilidae | *Promachus vertebratus* (Say) | 11 | 0.001264 | -6.67376 | -0.00843 |
| " | " | *Efferia pogonias* (Wiedemann) | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Calliphoridae | *Lucilia illustris* (Meigen) | 335 | 0.038484 | -3.25752 | -0.12536 |
| " | " | *Lucilia sericata (Meigen)* | 782 | 0.089833 | -2.4098 | -0.21648 |
| | " | *Calliphora vicina* (Rob) | 317 | 0.036416 | -3.31275 | -0.12064 |

| | | | | | | |
|---|---|---|---|---|---|---|
| '' | Chironomidae | *Chironomus plumosus* (Linn) | 42 | 0.004825 | -5.33398 | -0.02574 |
| '' | '' | *Ablabesmyia monilis* (Linn) | 47 | 0.005399 | -5.22151 | -0.02819 |
| '' | Culicidae | *Culex pipiens* (Linn) | 73 | 0.008386 | -4.78119 | -0.0401 |
| '' | '' | *Culex tarsalis* (Coquillett) | 96 | 0.011028 | -4.5073 | -0.04971 |
| '' | Diopsidae | *Diopsis thoracica* (Westwood) | 305 | 0.035037 | -3.35134 | -0.11742 |
| '' | Drosophilidae | *Drosophila melanogaster* (Meigen) | 33 | 0.003791 | -5.57515 | -0.02113 |
| '' | Fanniidae | *Fannia canicularis* (Linn) | 35 | 0.004021 | -5.5163 | -0.02218 |
| '' | Muscidae | *Musca domestica* (Linn) | 630 | 0.072372 | -2.62593 | -0.19004 |
| '' | Mycetophilidae | *Brevicornu* sp. 1 | 28 | 0.003217 | -5.73945 | -0.01846 |
| '' | Sarcophagidae | *Helicobia rapax* (Walker) | 42 | 0.004825 | -5.33398 | -0.02574 |
| '' | '' | *Sarcophaga haemorrhoidalis* (Fallen) | 271 | 0.031132 | -3.46953 | -0.10801 |
| '' | '' | *Blaesoxipha* sp. 1 | 112 | 0.012866 | -4.35315 | -0.05601 |
| '' | Sciaridae | *Bradysia* sp. 1 | 17 | 0.001953 | -6.23844 | -0.01218 |
| '' | Stratiomyidae | *Hermetia illucens* (L) | 8 | 0.000919 | -6.99221 | -0.00643 |
| '' | Syphridae | *Eristalis tenax* (L) | 5 | 0.000574 | -7.46221 | -0.00429 |
| '' | Tachinidae | *Archytas apicifer* (Walker) | 13 | 0.001493 | -6.5067 | -0.00972 |
| '' | '' | *Compsilura concinnata* (Meigen) | 51 | 0.005859 | -5.13983 | -0.03011 |
| '' | Tephritidae | *Zeugodacus cucurbitae* (Coquillet) | 30 | 0.003446 | -5.67046 | -0.01954 |
| '' | '' | *Bactrocera dorsalis* (Hendel) | 41 | 0.00471 | -5.35808 | -0.02524 |
| '' | '' | *Dacus ciliatus* (Loew) | 63 | 0.007237 | -4.92852 | -0.03567 |
| '' | Tipulidae | *Tipula abdominalis* (Say) | 8 | 0.000919 | -6.99221 | -0.00643 |
| **Hemiptera** | Cercopidae | *Poophilus* sp. 1 | 101 | 0.011603 | -4.45653 | -0.05171 |
| '' | | *Philaenus spumarius* (Linn) | 34 | 0.003906 | -5.54529 | -0.02166 |
| '' | Cicadellidae | *Cofana spectra* (Distant) | 827 | 0.095003 | -2.35385 | -0.22362 |
| '' | | *Empoasca* sp. 1 | 118 | 0.013555 | -4.30097 | -0.0583 |
| '' | Coriedae | *Homoeocerus auriculatus* (Stal) | 6 | 0.000689 | -7.27989 | -0.00502 |
| '' | Pentatomidae | *Nezara viridula* (Linn) | 10 | 0.001149 | -6.76907 | -0.00778 |
| '' | Pyrrhocoridae | *Dysdercus superstitiosus* (Schaffer) | 7 | 0.000804 | -7.12574 | -0.00573 |
| '' | | *Dysdercus nigrofasciatus* (Stal) | 23 | 0.002642 | -5.93616 | -0.01568 |

| | | | | | | |
|---|---|---|---|---|---|---|
| '' | Reduviidae | *Hediocoris tibialis* (Stal) | 4 | 0.00046 | -7.68536 | -0.00353 |
| '' | Scutelleridae | *Calidea dregii* (Germar) | 12 | 0.001379 | -6.58675 | -0.00908 |
| **Hymenoptera** | Apidae | *Apis mellifera* (Linn) | 9 | 0.001034 | -6.87443 | -0.00711 |
| '' | '' | *Macrocentrus ancylivorus* (Rohwer) | 55 | 0.006318 | -5.06432 | -0.032 |
| '' | Braconidae | *Cotesia* sp. 1 | 112 | 0.012866 | -4.35315 | -0.05601 |
| '' | '' | *Coccygidium* sp. 1 | 227 | 0.026077 | -3.6467 | -0.09509 |
| '' | Chrysididae | *Chrysis coerulans* (Fab) | 11 | 0.001264 | -6.67376 | -0.00843 |
| '' | Formicidae | *Camponotus pennsylvanicus* (De Geer) | 406 | 0.04664 | -3.0653 | -0.14297 |
| '' | '' | *Camponotus* sp. 1 | 645 | 0.074095 | -2.6024 | -0.19283 |
| '' | '' | *Crematogaster striatula* (Emery) | 357 | 0.041011 | -3.19392 | -0.13099 |
| '' | '' | *Crematogaster* sp. 1 | 684 | 0.078576 | -2.54369 | -0.19987 |
| '' | '' | *Monomorium pharaonis* (Linn) | 179 | 0.020563 | -3.88427 | -0.07987 |
| '' | '' | *Oecophylla longinoda* (Latreille) | 2361 | 0.271223 | -1.30481 | -0.3539 |
| '' | '' | *Pheidole megacephala* (Fabricius) | 83 | 0.009535 | -4.65281 | -0.04436 |
| '' | '' | *Tetramorium immigrans* (Santschi) | 45 | 0.005169 | -5.26499 | -0.02722 |
| '' | '' | *Solenopsis xyloni* (McCook) | 847 | 0.0973 | -2.32995 | -0.22671 |
| '' | Icheumonidae | *Arotes amoenus* (Cresson) | 20 | 0.002298 | -6.07592 | -0.01396 |
| '' | Platygastridae | *Telenomus remus* (Nixon) | 76 | 0.008731 | -4.74092 | -0.04139 |
| '' | '' | *Platygaster* sp. 1 | 37 | 0.00425 | -5.46073 | -0.02321 |
| '' | Pompilidae | *Pompilus lactuosus* (Cresson) | 22 | 0.002527 | -5.98061 | -0.01511 |
| '' | Vespidae | *Vespula pensylvanica* (Saussure) | 10 | 0.001149 | -6.76907 | -0.00778 |
| **Lepidoptera** | Crambidae | *Argyria* sp. 1 | 63 | 0.007237 | -4.92852 | -0.03567 |
| '' | Hesperidae | *Coeliades forestan* (Stoll) | 11 | 0.001264 | -6.67376 | -0.00843 |
| '' | Noctuidae | *Spodoptera frugiperda* (J.E. Smith) | 27 | 0.003102 | -5.77582 | -0.01791 |
| '' | Nymphalidae | *Acraea alciope* (Hew) | 24 | 0.002757 | -5.8936 | -0.01625 |
| '' | '' | *Euxanthe* sp. 1 | 9 | 0.001034 | -6.87443 | -0.00711 |
| '' | Pieridae | *Coniesta ignefusalis* (Hampson) | 5 | 0.000574 | -7.46221 | -0.00429 |
| **Mantodea** | Mantidae | *Mantis religiosa* (Linn) | 7 | 0.000804 | -7.12574 | -0.00573 |
| **Odonata** | Coenagrionidae | *Argia sedula* (Hagen) | 21 | 0.002412 | -6.02713 | -0.01454 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | Gomphidae | *Hagenius brevistylus* (Selys) | 5 | 0.000574 | -7.46221 | -0.00429 |
| " | Libellulidae | *Libellula pulchella* (Drury) | 4 | 0.00046 | -7.68536 | -0.00353 |
| **Orthoptera** | Acrididae | *Aulocara elliotti (Thomas)* | 43 | 0.00494 | -5.31045 | -0.02623 |
| " | Gryllidae | *Gryllus* sp. 1 | 22 | 0.002527 | -5.98061 | -0.01511 |
| " | Pyrgomorphidae | *Zonocerus variegatus* (Linn) | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | Tettigoniidae | *Microcentrum rhombifolium* (Saussure) | 12 | 0.001379 | -6.58675 | -0.00908 |
| | | | | | | |

### 4.1.2 Minor maize cropping season

In the minor maize cropping season, a total of 17, 002 individual arthropods were recorded from the MFP and control plots. The control plots had a total of 9028 invidual arthropods, while 7974 individual arthropods were collected from the MFP plots (Table 4.3 and 4.4). Statistically, the proportion of the arthropods collected was significantly higher in the control plots than in the MFP plots ($\chi^2$ = 5302.70, df = 1, $P < 0.001$). However, the arthropod orders in the control plots (n = 10) and in the MFP plots (n = 11) were not significantly different ($\chi^2$ = 2.77, df = 1, $P$ = 0.096). Similarly, arthropod families identified in the MFP (n = 53) and control (n = 53) plots did not differ significantly ($\chi^2$ = 50.16, df = 1, $P$ = 1.417). Also, the number of the different species recorded in the MFP (n = 82) and control (n = 81) did not differ significantly ($\chi^2$ = 74.298, df = 1, $P$ = 1.761). Like the major maize cropping season, insects belonging to the order Hymenoptera (n = 4319), Diptera (n = 3109), Hemiptera (n = 725), and Coleoptera (n = 373) were the most abundant arthropods in the MFP plots, accounting for 54.16%, 38.99%, 9.09%, and 4.68% of the total recorded arthropods. This relative abundance trend was also recorded in the control plots wherein insects in Hymenoptera (n = 5017), Diptera (n = 2512), Hemiptera (n = 649), and Coleoptera (n = 470) were the most dominant and represented 55.57%, 27.82%, 7.89%, and 5.12% of the arthropod community in the minor maize cropping season. As in the major maize cropping season, insects in the family Formicidae were the most abundant in both the control (n = 4846) and MFP plots (n = 4078), with *Oecophylla longinoda* (n = 2813) and *Camponotus* sp. (n = 1510) being the most abundant, respectively (Table 4.3 and 4.4).

**Table 4.3:** Order, family, and species diversity of arthropod communities in maize plots with farmers' practice (MFP) in the minor maize cropping season and parameters of Shannon index diversity calculation

| **Order** | **Family** | **Species** | **Counts** | ***Pi*** | ***ln(pi)*** | ***pi x ln(pi)*** |
|---|---|---|---|---|---|---|
| **Araneae** | Agelenidae | *Tegenaria* sp. 1 | 5 | 0.000574 | -7.46221 | -0.00429 |
| " | " | *Agelenopsis aperta* (Gertsch) | 19 | 0.002183 | -6.12721 | -0.01337 |
| " | Philodromidae | *Tibellus* sp. 1 | 4 | 0.00046 | -7.68536 | -0.00353 |
| **Blattodea** | Ectobiidae | *Blattella germanica* (Linn) | 9 | 0.001034 | -6.87443 | -0.00711 |
| " | " | *Blattella asahinai* (Mizukubo) | 12 | 0.001379 | -6.58675 | -0.00908 |
| **Coleoptera** | Cantharidae | *Rhagonycha lignosa* (Muller) | 97 | 0.011143 | -4.49694 | -0.05011 |
| " | Carabidae | *Dyschirius* sp. 1 | 10 | 0.001149 | -6.76907 | -0.00778 |
| " | Chrysomelidae | *Hispellinus fimbriatus* (Chapuis) | 37 | 0.003561 | -5.63767 | -0.02008 |
| " | " | *Chrysomela* sp. 1 | 69 | 0.007926 | -4.83755 | -0.03834 |
| " | " | *Chrysomela* sp. 2 | 50 | 0.005514 | -5.20045 | -0.02868 |
| " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 52 | 0.005974 | -5.12041 | -0.03059 |
| " | " | *Cheilomenes sulphurea* (Oliver) | 27 | 0.003102 | -5.77582 | -0.01791 |
| " | " | *Chnootriba* sp. 1 | 20 | 0.002298 | -6.07592 | -0.01396 |
| " | " | *Chilocorus nigrita* (Fab) | 7 | 0.000804 | -7.12574 | -0.00573 |
| " | Staphylinidae | *Paederus* sp. 1 | 12 | 0.001379 | -6.58675 | -0.00908 |
| **Diptera** | Agromyzidae | *Ophiomyia simplex* (Loew) | 10 | 0.001149 | -6.76907 | -0.00778 |
| " | " | *Phytomyza* sp. 1 | 6 | 0.000689 | -7.27989 | -0.00502 |
| " | Anthomyiidae | *Delia brassicae* (Wiedemann) | 9 | 0.001034 | -6.87443 | -0.00711 |
| " | Asilidae | *Promachus vertebratus* (Say) | 37 | 0.003676 | -5.60592 | -0.02061 |
| " | " | *Efferia pogonias* (Wiedemann) | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | Calliphoridae | *Lucilia illustris* (Meigen) | 261 | 0.018495 | -3.99025 | -0.0738 |
| " | | *Lucilia sericata (Meigen)* | 471 | 0.031132 | -3.46953 | -0.10801 |
| " | | *Calliphora vicina* (Rob) | 166 | 0.007582 | -4.882 | -0.03701 |
| " | Chironomidae | *Chironomus plumosus* (Linn) | 41 | 0.00471 | -5.35808 | -0.02524 |
| " | " | *Ablabesmyia monilis* (Linn) | 39 | 0.00448 | -5.40809 | -0.02423 |
| " | Culicidae | *Culex pipiens* (Linn) | 175 | 0.020103 | -3.90687 | -0.07854 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | " | *Culex tarsalis* (Coquillett) | 138 | 0.015853 | -4.1444 | -0.0657 |
| " | Diopsidae | *Diopsis thoracica* (Westwood) | 174 | 0.007352 | -4.91277 | -0.03612 |
| " | Drosophilidae | *Drosophila melanogaster* (Meigen) | 39 | 0.003676 | -5.60592 | -0.02061 |
| " | Fanniidae | *Fannia canicularis* (Linn) | 182 | 0.020908 | -3.86765 | -0.08086 |
| " | Muscidae | *Musca domestica* (Linn) | 592 | 0.045032 | -3.10039 | -0.13962 |
| " | Mycetophilidae | *Brevicornu* sp. 1 | 49 | 0.005629 | -5.17983 | -0.02916 |
| " | Rhagionidae | *Rhagio mystaceus* (Macquart) | 6 | 0.000689 | -7.27989 | -0.00502 |
| " | Sarcophagidae | *Sarcophaga haemorrhoidalis* (Fallen) | 55 | 0.006318 | -5.06432 | -0.032 |
| " | " | *Blaesoxipha* sp. 1 | 24 | 0.002757 | -5.8936 | -0.01625 |
| " | Sciaridae | *Bradysia* sp. 1 | 12 | 0.001379 | -6.58675 | -0.00908 |
| " | Stratiomyidae | *Hermetia illucens* (L) | 38 | 0.004365 | -5.43407 | -0.02372 |
| " | Syphridae | *Eristalis tenax* (L) | 44 | 0.005055 | -5.28746 | -0.02673 |
| " | Tachinidae | *Archytas apicifer* (Walker) | 136 | 0.015623 | -4.159 | -0.06498 |
| " | " | *Compsilura concinnata* (Meigen) | 207 | 0.023779 | -3.73893 | -0.08891 |
| " | Tephritidae | *Zeugodacus cucurbitae* (Coquillet) | 21 | 0.002412 | -6.02713 | -0.01454 |
| " | " | *Bactrocera dorsalis* (Hendel) | 68 | 0.007467 | -4.89727 | -0.03657 |
| " | " | *Dacus ciliatus* (Loew) | 78 | 0.00896 | -4.71494 | -0.04225 |
| " | Tipulidae | *Tipula abdominalis* (Say) | 5 | 0.000574 | -7.46221 | -0.00429 |
| **Hemiptera** | Cercopidae | *Poophilus* sp. 1 | 231 | 0.026536 | -3.62924 | -0.09631 |
| " | " | *Philaenus spumarus* (Linn) | 94 | 0.010798 | -4.52836 | -0.0489 |
| " | Cicadellidae | *Cofana spectra* (Distant) | 246 | 0.02826 | -3.56632 | -0.10078 |
| " | " | *Empoasca* sp. 1 | 83 | 0.009535 | -4.65281 | -0.04436 |
| " | Coriedae | *Homoeocerus auriculatus* (Stal) | 13 | 0.001493 | -6.5067 | -0.00972 |
| " | Pentatomidae | *Nezara viridula* (Linn) | 10 | 0.001149 | -6.76907 | -0.00778 |
| " | Pyrrhocoridae | *Dysdercus superstitiosus* (Schaffer) | 18 | 0.002068 | -6.18128 | -0.01278 |
| " | " | *Dysdercus nigrofasciatus* (Stal) | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Reduviidae | *Rhynocoris* sp. 1 | 1 | 0.000115 | -9.07165 | -0.00104 |
| " | Scutelleridae | *Calidea dregii* (Germar) | 25 | 0.002872 | -5.85278 | -0.01681 |
| **Hymenoptera** | Apidae | *Apis mellifera* (Linn) | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Braconidae | *Coccygidium* sp. 1 | 27 | 0.003102 | -5.77582 | -0.01791 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | Chrysididae | *Chrysis coerulans* (Fab) | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Formicidae | *Camponotus pensylvanicus (De Geer)* | 412 | 0.047329 | -3.05063 | -0.14438 |
| " | " | *Camponotus* sp. 1 | 1510 | 0.173464 | -1.75179 | -0.30387 |
| " | " | *Crematogaster striatula* (Emery) | 111 | 0.012751 | -4.36212 | -0.05562 |
| " | " | *Crematogaster* sp. 1 | 569 | 0.065365 | -2.72777 | -0.1783 |
| " | " | *Monomorium pharaonis (Linn)* | 54 | 0.006203 | -5.08267 | -0.03153 |
| " | " | *Oecophylla longinoda* (Latreille) | 1165 | 0.133831 | -2.01118 | -0.26916 |
| " | " | *Pheidole megacephala* (Fabricius) | 11 | 0.001264 | -6.67376 | -0.00843 |
| " | " | *Tetramorium immigrans* (Santschi) | 45 | 0.005169 | -5.26499 | -0.02722 |
| " | " | *Solenopsis xyloni* (McCook) | 201 | 0.02309 | -3.76835 | -0.08701 |
| " | Icheumonidae | *Megarhyssa greenei* (Viereck) | 48 | 0.005514 | -5.20045 | -0.02868 |
| " | Platygastridae | *Platygaster* sp. 1 | 53 | 0.006088 | -5.10136 | -0.03106 |
| " | " | *Telenomus remus* (Nixon) | 71 | 0.008156 | -4.80897 | -0.03922 |
| " | Pompilidae | *Pompilus lactuosus* Cresson | 30 | 0.003446 | -5.67046 | -0.01954 |
| **Lepidoptera** | Crambidae | *Argyria* sp. 1 | 24 | 0.002757 | -5.8936 | -0.01625 |
| " | Hesperidae | *Borbo fatuellus* (Hopffer) | 3 | 0.000345 | -7.97304 | -0.00275 |
| " | Noctuidae | *Spodoptera frugiperda* (J.E. Smith) | 21 | 0.002412 | -6.02713 | -0.01454 |
| " | Nymphalidae | *Acraea alciope* (Hew) | 14 | 0.001608 | -6.4326 | -0.01035 |
| " | Lycaenidae | *Anthene amarah* (Guer) | 5 | 0.000574 | -7.46221 | -0.00429 |
| **Mantodea** | Mantidae | *Mantis religiosa* (Linn) | 1 | 0.000115 | -9.07165 | -0.00104 |
| **Neuroptera** | Mantispidae | *Mantispa brunnea* | 7 | 0.000804 | -7.12574 | -0.00573 |
| **Odonata** | Gomphidae | *Hagenius brevistylus* (Selys) | 3 | 0.000345 | -7.97304 | -0.00275 |
| **Orthoptera** | Acrididae | *Aulocara elliotti (Thomas)* | 22 | 0.002527 | -5.98061 | -0.01511 |
| " | Gryllidae | *Gryllus* sp. 1 | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Pyrgomorphidae | *Zonocerus variegatus* (Linn) | 12 | 0.001379 | -6.58675 | -0.00908 |
| " | Tettigoniidae | *Zabalius lineolatus* (Stall) | 4 | 0.00046 | -7.68536 | -0.00353 |
| | | | | | | |

**Table 4.4:** Order, family, and diversity of arthropod communities in the control plots (i.e. without any applied treatment) in the minor maize cropping season and parameters of Shannon index diversity calculation

| **Order** | **Family** | **Species** | **Counts** | ***Pi*** | ***ln(pi)*** | ***pi x ln(pi)*** |
|---|---|---|---|---|---|---|
| **Araneae** | Agelenidae | *Tegenaria* sp. 1 | 45 | 0.005169 | -5.26499 | -0.02722 |
| " | '' | *Agelenopsis aperta* (Gertsch) | 88 | 0.010109 | -4.59432 | -0.04644 |
| " | Oonopidae | *Telchius maculosus* (Denis) | 12 | 0.001379 | -6.58675 | -0.00908 |
| " | Thomisidae | *Misumenops* sp. 1 | 34 | 0.003906 | -5.54529 | -0.02166 |
| **Blattodea** | Ectobiidae | *Blattella germanica* (Linn) | 12 | 0.001379 | -6.58675 | -0.00908 |
| | '' | *Blattella asahinai* (Mizukubo) | 9 | 0.001034 | -6.87443 | -0.00711 |
| **Coeloptera** | Staphylinidae | *Paederus* sp. 1 | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Cantharidae | *Rhagonycha lignosa* (Muller) | 105 | 0.012062 | -4.41769 | -0.05329 |
| " | Carabidae | *Dyschirius* sp. 1 | 10 | 0.001149 | -6.76907 | -0.00778 |
| " | Chrysomelidae | *Hispellinus fimbriatus* (Chapuis) | 91 | 0.010454 | -4.56079 | -0.04768 |
| " | '' | *Chrysomela* sp. 1 | 128 | 0.014704 | -4.21962 | -0.06205 |
| " | '' | *Chrysomela* sp. 2 | 55 | 0.006318 | -5.06432 | -0.032 |
| " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 27 | 0.003102 | -5.77582 | -0.01791 |
| " | " | *Cheilomenes sulphurea* (Oliver) | 21 | 0.002412 | -6.02713 | -0.01454 |
| " | " | *Chnootriba* sp. 1 | 19 | 0.002183 | -6.12721 | -0.01337 |
| " | " | *Chilocorus nigrita* (Fab) | 6 | 0.000689 | -7.27989 | -0.00502 |
| **Diptera** | Anthomyiidae | *Fucellia rufitibia* (Stein) | 47 | 0.005399 | -5.22151 | -0.02819 |
| " | Agromyzidae | *Ophiomyia simplex* (Loew) | 16 | 0.001838 | -6.29906 | -0.01158 |
| " | Asilidae | *Promachus vertebratus* (Say) | 33 | 0.003791 | -5.57515 | -0.02113 |
| " | " | *Efferia pogonias* (Wiedemann) | 35 | 0.004021 | -5.5163 | -0.02218 |
| " | Calliphoridae | *Lucilia illustris* (Meigen) | 119 | 0.01367 | -4.29253 | -0.05868 |
| " | " | *Lucilia sericata (Meigen)* | 245 | 0.028145 | -3.57039 | -0.10049 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | " | *Calliphora vicina* (Rob) | 74 | 0.008501 | -4.76759 | -0.04053 |
| " | Ceratopongidae | *Culicoides veripennis veripennis (Coquillet* | 58 | 0.006663 | -5.01121 | -0.03339 |
| " | Chironomidae | *Chironomus plumosus* (Linn) | 61 | 0.007007 | -4.96078 | -0.03476 |
| " | " | *Ablabesmyia monilis* (Linn) | 40 | 0.004595 | -5.38277 | -0.02473 |
| " | Culicidae | *Culex pipens* Linn. | 212 | 0.024354 | -3.71507 | -0.09048 |
| " | " | *Culex tarsalis* Coquillet | 197 | 0.022631 | -3.78845 | -0.08574 |
| " | Diopsidae | *Diopsis thoracica* (Westwood) | 100 | 0.011488 | -4.46648 | -0.05131 |
| " | Drosophilidae | *Drosophila melanogaster* (Meigen) | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | Fanniidae | *Fannia canicularis* (Linn) | 172 | 0.019759 | -3.92416 | -0.07754 |
| " | Muscidae | *Musca domestica* (Linn) | 348 | 0.039977 | -3.21945 | -0.1287 |
| " | Mycetophilidae | *Exechia spinuligera* (Lundstrom) | 59 | 0.006778 | -4.99412 | -0.03385 |
| " | Rhagionidae | *Rhagio mystaceus* (Macquart) | 9 | 0.001034 | -6.87443 | -0.00711 |
| " | Sarcophagidae | *Sarcophaga haemorrhooidalis* (Fallen) | 149 | 0.017117 | -4.06771 | -0.06963 |
| " | " | *Blaesoxipha* sp. 1 | 63 | 0.007237 | -4.92852 | -0.03567 |
| " | Sciaridae | *Bradysia* sp. 1 | 55 | 0.006318 | -5.06432 | -0.032 |
| " | Stratiomyidae | *Hermetia illucens* (L) | 30 | 0.003446 | -5.67046 | -0.01954 |
| " | Syphridae | *Allograpta obliqua* (Say) | 74 | 0.008501 | -4.76759 | -0.04053 |
| " | Tachinidae | *Compsilura concinnata* (Meigen) | 181 | 0.020793 | -3.87316 | -0.08053 |
| " | Tephritidae | *Zeugodacus cucurbitae* (Coquillet) | 15 | 0.001723 | -6.3636 | -0.01097 |
| " | " | *Bactrocera dorsalis* (Hendel) | 20 | 0.002298 | -6.07592 | -0.01396 |
| " | " | *Dacus ciliatus* (Loew) | 59 | 0.006778 | -4.99412 | -0.03385 |
| " | Tipulidae | *Tipula abdominalis* (Say) | 15 | 0.001723 | -6.3636 | -0.01097 |
| **Hemiptera** | Cercopidae | *Poophilus* sp. 1 | 151 | 0.017346 | -4.05437 | -0.07033 |
| " | " | *Philaenus spumarius* (Linn) | 92 | 0.010569 | -4.54986 | -0.04809 |
| " | Cicadellidae | *Cofana spectra* (Distant) | 241 | 0.027685 | -3.58686 | -0.0993 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | " | *Empoasca* sp. 1 | 128 | 0.014704 | -4.21962 | -0.06205 |
| " | Coriedae | *Homoeocerus auriculatus* (Stal) | 12 | 0.001379 | -6.58675 | -0.00908 |
| " | Pentatomidae | *Nezara viridula* (Linn) | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Pyrrhocoridae | *Dysdercus superstitiosus* (Schaffer) | 2 | 0.00023 | -8.37851 | -0.00192 |
| " | " | *Dysdercus nigrofasciatus* (Stal) | 17 | 0.001953 | -6.23844 | -0.01218 |
| " | Scutelleridae | *Calidea dregii* (Germar) | 2 | 0.00023 | -8.37851 | -0.00192 |
| **Hymenoptera** | Andrenidae | *Andrena* sp. 1 | 4 | 0.00046 | -7.68536 | -0.00353 |
| " | Apidae | *Apis mellifera* (Linn) | 5 | 0.000574 | -7.46221 | -0.00429 |
| " | Braconidae | *Coccygidium* sp. 1 | 18 | 0.002068 | -6.18128 | -0.01278 |
| " | Chrysididae | *Chrysis coerulans* (Fab) | 24 | 0.002757 | -5.8936 | -0.01625 |
| " | Formicidae | *Camponotus pennsylvanicus* (De Geer) | 246 | 0.02826 | -3.56632 | -0.10078 |
| " | " | *Camponotus* sp. 1 | 872 | 0.100172 | -2.30086 | -0.23048 |
| " | " | *Crematogaster striatula* (Emery) | 109 | 0.012522 | -4.3803 | -0.05485 |
| " | " | *Crematogaster* sp. 1 | 325 | 0.037335 | -3.28783 | -0.12275 |
| " | " | *Monomorium pharaonis* (Linn) | 65 | 0.007467 | -4.89727 | -0.03657 |
| " | " | *Oecophylla longinoda* (Latreille) | 2813 | 0.323148 | -1.12965 | -0.36504 |
| " | " | *Pheidole megacephala* (Fabricius) | 26 | 0.002987 | -5.81356 | -0.01736 |
| " | " | *Tetramorium immigrans* (Santschi) | 79 | 0.009075 | -4.7022 | -0.04267 |
| " | " | *Solenopsis xyloni* (McCook) | 311 | 0.035727 | -3.33186 | -0.11904 |
| " | Platygastridae | *Telenomus remus* (Nixon) | 64 | 0.007352 | -4.91277 | -0.03612 |
| " | " | *Platygaster* sp. 1 | 29 | 0.003331 | -5.70436 | -0.019 |
| " | Pompilidae | *Pompilus lactuosus* (Cresson) | 27 | 0.003102 | -5.77582 | -0.01791 |
| **Lepidoptera** | Crambidae | *Argyria* sp. 1 | 15 | 0.001723 | -6.3636 | -0.01097 |
| " | Hesperidae | *Coeliades forestan* (Stoll) | 9 | 0.001034 | -6.87443 | -0.00711 |
| " | Noctuidae | *Spodoptera frugiperda* (J.E. Smith) | 30 | 0.003446 | -5.67046 | -0.01954 |

| | | | | | | |
|---|---|---|---|---|---|---|
| " | Nymphalidae | *Acraea alciope* (Hew) | 13 | 0.001493 | -6.5067 | -0.00972 |
| " | " | *Euxanthe* sp. 1 | 15 | 0.001723 | -6.3636 | -0.01097 |
| **Mantodea** | Mantidae | *Mantis religiosa* (Linn) | 2 | 0.00023 | -8.37851 | -0.00192 |
| **Odonata** | Coenagrionidae | *Argia sedula* (Hagen) | 19 | 0.002183 | -6.12721 | -0.01337 |
| " | Libellidae | *Libellula pulchella* (Drury) | 5 | 0.000574 | -7.46221 | -0.00429 |
| **Orthoptera** | Acrididae | *Aulocara elliotti (Thomas)* | 20 | 0.002298 | -6.07592 | -0.01396 |
| " | Gryllidae | *Gryllus* sp. 1 | 8 | 0.000919 | -6.99221 | -0.00643 |
| " | Pyrgomorphidae | *Zonocerus variegatus* (Linn) | 28 | 0.003217 | -5.73945 | -0.01846 |
| " | Tettigoniidae | *Microcentrum rhombifolium* (Saussure) | 16 | 0.001838 | -6.29906 | -0.01158 |
| | | | | | | |

### 4.1.3 Diversity indices

The control plots had a higher Shannon-Wiener diversity index value (H = 4.10) and species equitability/evenness than the MFP plots in the major maize cropping season. Similarly, in the minor cropping season, the H index and species evenness values in the control plots were higher than in the MFP plots. Nevertheless, the Jaccard similarity index indicated high similarity between the arthropod communities in the MFP and control plots in both the major and minor cropping seasons (Table 4.5).

**Table 4.5** Diversity indices of arthropod species in the treatment (MFP) and control plots in the major and minor maize cropping seasons

| **Cropping season** | **Diversity indices** | **MFP** | **Control** |
|---|---|---|---|
| Major | Shannon, H | 3.36 | 4.10 |
| | Evenness | 0.76 | 0.91 |
| | Jaccard similarity | | **0.93** |
| | | | |
| Minor | Shannon, H | 3.10 | 3.23 |
| | Evenness | 0.70 | 0.74 |
| | Jaccard similarity | | **0.91** |

## 4.2 Diversity and abundance of predators and *Spodoptera frugiperda* infestation levels

### 4.2.1 Abundance of predators

In the major maize cropping season, a total of 2742 individual predators were recorded. The control plots had the highest record (n = 1216), while counts of 885 and 641 were recorded in the BCM and MFP plots, respectively. In the minor maize cropping season, 3353 individual predators were recorded. Like the major cropping season, the control plots had the highest records (n = 1647), while 1004 and 702 were counted in the BCM and MFP plots, respectively (Table 4.6). Statistically, significantly more predators were recorded in the minor cropping season than in the major cropping season (U = 82.18, df = 1, $P < 0.001$).

| **Table 4.6:** Predators occurring in the treatment (BCM and MFP) and control plots in the major and minor maize cropping season | | | | | | |
|---|---|---|---|---|---|---|
| **Cropping season** | **Order** | **Family** | **Species** | **BCM** | **MFP** | **Control** |
| **Major** | Araneae | Agelenidae | *Agelenopsis aperta* (Gertsch) | 91 | 73 | 98 |
| | " | " | *Tegenaria* sp. 1 | 45 | 33 | 60 |
| | " | Corinnidae | *Hortipes pollux* (Bosselaers and Jocqué) | 2 | 1 | 5 |
| | " | Gnaphosidae | *Zelotes* sp. 1 | 1 | 1 | 3 |
| | " | Lycosidae | *Oculicosa supermicrobilis* (Zyuzin) | 1 | 0 | 1 |
| | " | Oonopidae | *Telchius maculosus* (Denis) | 3 | 2 | 3 |
| | " | Oxyopidae | *Oxyopes jacksoni* (Lessert) | 1 | 0 | 6 |
| | " | Philodromidae | *Philodromus collinus* | 7 | 7 | 8 |
| | | " | *Philodromus* sp. 1 | 2 | 1 | 4 |
| | " | " | *Tibellus* sp. 1 | 2 | 1 | 4 |
| | " | Sparassidae | *Palystes* sp. 1 | 11 | 8 | 16 |
| | " | Theridiidae | *Cryptachaea* sp. 1 | 1 | 1 | 1 |
| | " | Thomisidae | *Misumenops* sp. 1 | 57 | 45 | 35 |
| | " | " | *Misumenops* sp. 2 | 0 | 9 | 15 |
| | " | " | *Thomisus* sp. 1 | 3 | 0 | 6 |
| | Coleoptera | Carabidae | *Dyschirus* sp. 1 | 3 | 1 | 10 |
| | " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 17 | 9 | 26 |
| | " | " | *Cheilomenes sulphurea* (Oliver) | 25 | 17 | 34 |
| | " | " | *Chilocorus nigrita* (Fab) | 6 | 3 | 6 |
| | " | " | *Chnootriba* sp. 1 | 1 | 0 | 3 |
| | Dermaptera | Forficulidae | *Forficula auricularia* | 32 | 7 | 53 |
| | Hemiptera | Reduviidae | *Cosmolestes pictus* (Klug) | 1 | 3 | 1 |
| | " | " | *Haematochares obscuripennis* (Stal) | 2 | 4 | 15 |
| | " | " | *Rhynocoris* sp. 1 | 1 | 0 | 1 |
| | " | " | *Sphedanolestes picturellus* (Schouteden) | 1 | 1 | 2 |
| | Hymenoptera | Formicidae | *Camponotus pennsylvanicus* (De Geer) | 183 | 137 | 189 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | " | " | *Camponotus* sp. 1 | 58 | 55 | 151 |
| | " | " | *Crematogaster striatula* (Emery) | 49 | 38 | 110 |
| | " | " | *Crematogaster* sp. 1 | 170 | 114 | 223 |
| | " | " | *Solenopsis xyloni* (McCook) | 71 | 60 | 96 |
| | " | " | *Monomorium pharaonis* (Linn) | 18 | 2 | 6 |
| | " | " | *Pheidole megacephala* (Fabricius) | 2 | 1 | 4 |
| | " | " | *Tetramorium immigrans* (Santschi) | 18 | 7 | 21 |
| **Minor** | Araneae | Agelenidae | *Agelenopsis aperta* (Gertsch) | 159 | 120 | 177 |
| | " | " | *Tegenaria* sp. 1 | 56 | 31 | 71 |
| | " | Corinnidae | *Hortipes pollux* (Bosselaers and Jocqué) | 1 | 0 | 2 |
| | " | Gnaphosidae | *Zelotes* sp. 1 | 3 | 3 | 6 |
| | " | Lycosidae | *Oculicosa supermicrobilis* (Zyuzin) | 1 | 0 | 4 |
| | " | Oonopidae | *Telchius maculosus* (Denis) | 5 | 3 | 8 |
| | " | Oxyopidae | *Oxyopes jacksoni* (Lessert) | 2 | 2 | 3 |
| | " | Philodromidae | *Philodromus collinus* | 6 | 5 | 9 |
| | " | " | *Philodromus* sp. 1 | 2 | 1 | 6 |
| | " | " | *Tibellus* sp. 1 | 4 | 3 | 11 |
| | " | Sparassidae | *Palystes* sp. 1 | 5 | 4 | 7 |
| | " | Theridiidae | *Cryptachaea* sp. 1 | 2 | 1 | 2 |
| | " | Thomisidae | *Misumenops* sp. 1 | 63 | 43 | 76 |
| | " | " | *Misumenops* sp. 2 | 21 | 14 | 29 |
| | " | " | *Thomisus* sp. 1 | 4 | 2 | 7 |
| | Coleoptera | Carabidae | *Dyschirus* sp. 1 | 2 | 0 | 5 |
| | " | Coccinellidae | *Cheilomenes propinqua vicina* (Mulsant) | 10 | 1 | 17 |
| | " | " | *Cheilomenes sulphurea* (Oliver) | 4 | 2 | 13 |
| | " | " | *Chilocorus nigrita* (Fab) | 2 | 0 | 6 |
| | " | " | *Chnootriba* sp. 1 | 12 | 10 | 28 |
| | Dermaptera | Forficulidae | *Forficula auricularia* | 25 | 18 | 42 |
| | Hemiptera | Reduviidae | *Cosmolestes pictus* (Klug) | 1 | 0 | 3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | " | " | 5 | 1 | 9 |
| | " | " | *Hediocoris tibialis* (Stal) | 0 | 1 | 1 |
| | " | " | *Rhynocoris* sp. 1 | 1 | 1 | 0 |
| | " | " | *Sphedanolestes picturellus* (Schouteden) | 0 | 2 | 1 |
| | Hymenoptera | Formicidae | *Camponotus pennsylvanicus* (De Geer) | 213 | 151 | 329 |
| | " | " | *Camponotus* sp. 1 | 23 | 25 | 146 |
| | " | " | *Crematogaster* sp. 1 | 98 | 79 | 233 |
| | " | " | *Crematogaster striatula* (Emery) | 109 | 57 | 164 |
| | " | " | *Monomorium pharaonis* (Linn) | 21 | 0 | 40 |
| | " | " | *Pheidole megacephala* (Fabricius) | 5 | 2 | 8 |
| | " | " | *Solenopsis xyloni* (McCook) | 139 | 111 | 160 |
| | " | " | *Tetramorium immigrans* (Santschi) | 0 | 9 | 24 |

Laboratory tests confirmed a total of seven predators attacking *S. frugiperda* (Table 4.7; Plate 4.1)

**Table 4.7:** Predators attacking *Spodoptera frugiperda* in the laboratory. Unfortunately, colonies of the predators were unsuccessfully reared for further testing and assessments.

| Family | Species | Prey stage(s) |
|---|---|---|
| Formicidae | *Crematogaster striatula* (Emery) | Larvae instar 1 |
| Reduviidae | *Cosmolestes pictus* (Klug) | Larvae 1-6 |
| Reduviidae | *Haematochares obscuripennis* (Stal) | Larvae 1-6 |
| Reduviidae | *Hediocoris tibialis* (Stal) | Larvae 1-6 |
| Reduviidae | *Rhynocoris* sp. 1 | Larvae 1-6 |
| Reduviidae | *Sphedanolestes picturellus* (Schouteden) | Larvae 1-6 |
| Thomisidae | *Misumenops* sp. 1 | Larvae 1-2 |


**Plate 4.1:** Some predators attacking *Spodoptera frugiperda* in the laboratory. These predators were collected from the treatments (BCM and MFP) and control plots.

Variations occurred in the number of predators recorded weekly in the BCM, MFP, and control plots in the major and minor maize cropping seasons (Fig. 4.1).

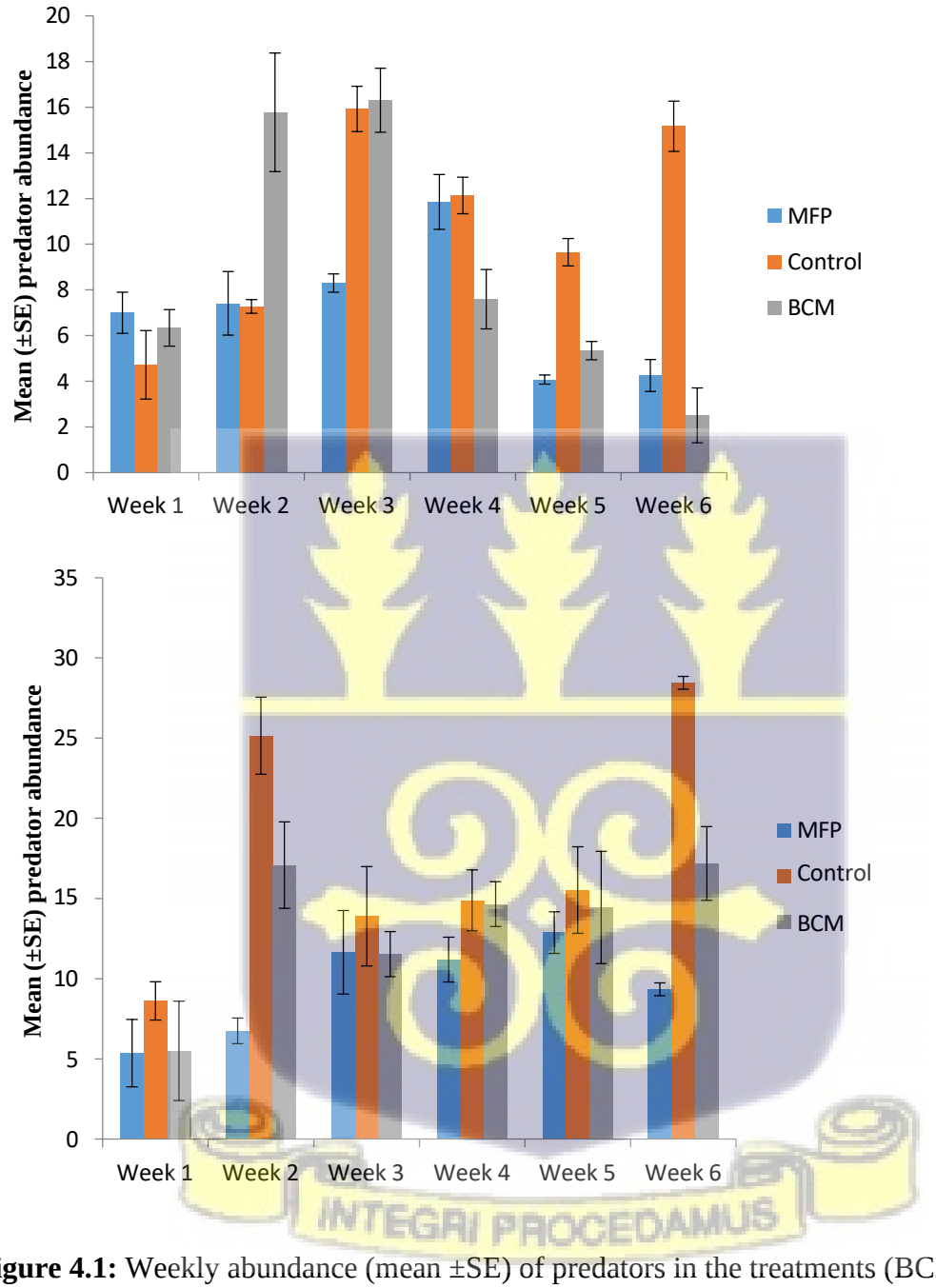


**Figure 4.1:** Weekly abundance (mean ±SE) of predators in the treatments (BCM and MFP) and control plots in the (a) major maize cropping season, and (b) minor maize cropping season.

### 4.2.2 Diversity indices

The control plots had a higher Shannon-Wiener index value than the two treatment plots in both the major and minor maize cropping seasons. However, species equitability and evenness were similar between the control and treatment plots in both seasons. Jaccard similarity index indicated high similarity between the predator species in the BCM, MFP and control plots in both the major and minor maize cropping seasons (Table 4.8).

**Table 4.8:** Diversity indices of predators in the treatments (BCM and MFP) and control plots in the major and minor maize cropping seasons

| **Cropping season** | **Diversity indices** | **BCM** | **MFP** | **Control** |
|---|---|---|---|---|
| Major | Shannon, H | 2.52 | 2.44 | 2.62 |
| | Evenness | 0.37 | 0.38 | 0.37 |
| | Jaccard similarity | | | **0.98** |
| | | | | |
| Minor | Shannon, H | 2.45 | 2.36 | 2.59 |
| | Evenness | 0.35 | 0.36 | 0.35 |
| | Jaccard similarity | | | **0.96** |

### 4.2.3 *Spodoptera frugiperda* infestation levels

Variation in the egg masses and larvae of *S. frugiperda* was recorded in the treatments (i.e. BCM and MFP) and control plots weekly. However, the weekly infestation levels of the pest (i.e. both egg masses and larvae) were higher in the major maize cropping season than in the minor cropping season (Fig. 4.2).

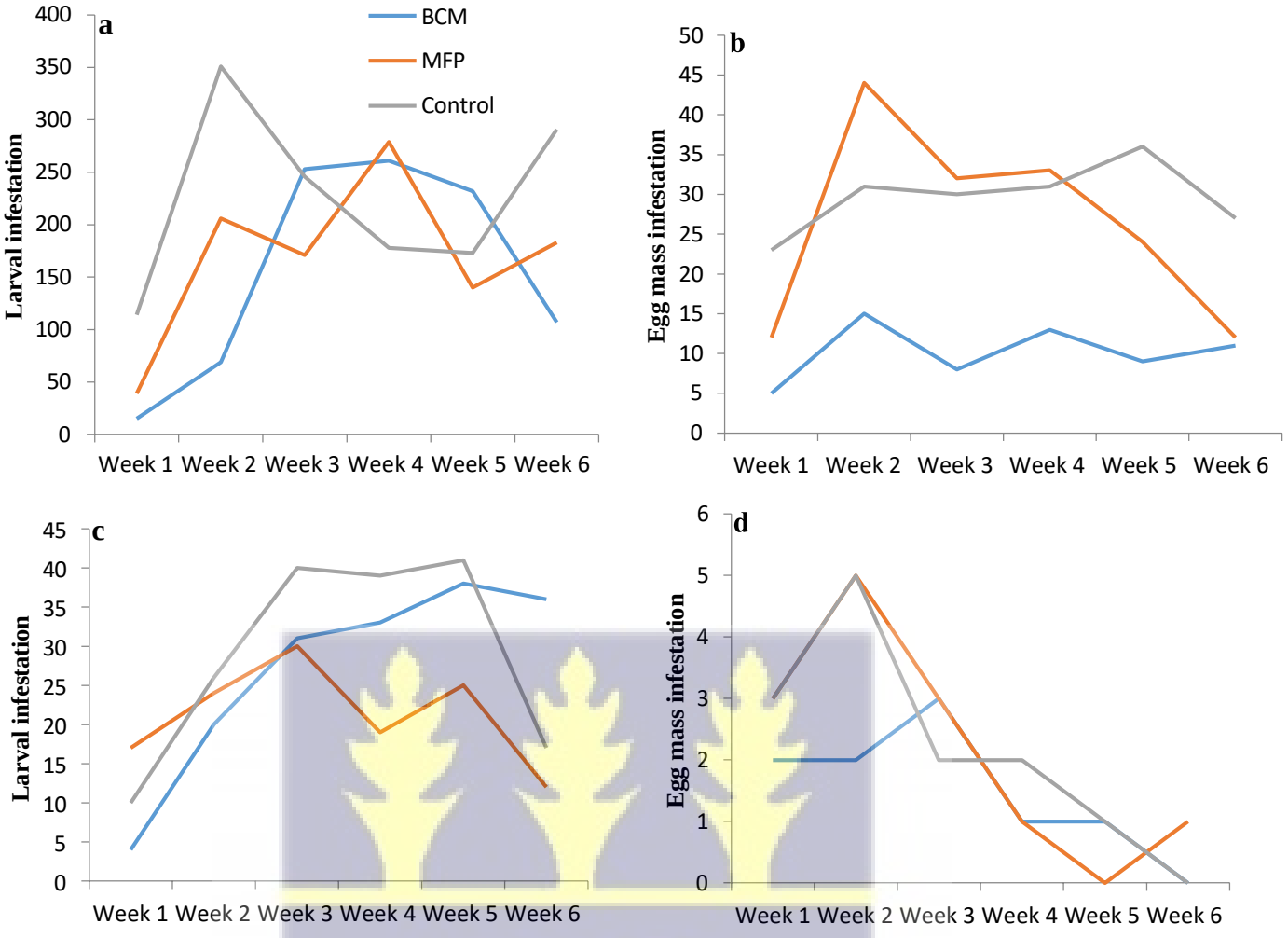


**Figure 4.2:** Weekly infestation level of *Spodoptera frugiperda* in the treatment (BCM and MFP) and control plots. (a) = larval counts in the major maize cropping season, (b) egg mass counts in the major maize cropping season, (c) larval counts in the minor maize cropping season, and (d) egg mass counts in the minor maize cropping season.

In the major cropping season, the number of egg batches in the BCM, MFP, and control plots was significantly different (H = 9.106, df = 2, *P* = 0.010). Egg batches were significantly more in the control and MPF plots than in the BCM plots (Fig. 4.3a). However, the larvae infestation level did not differ between the two treatments and control plots (H = 1.501, df = 2, *P* = 0.470). In the minor cropping season, there were no significant differences in the egg batches (H = 0.51822, df = 2, *P* = 0.772), as well as in larvae infestation level (H = 2.198, df = 2, P = 0.333) of the pest in the BCM, MPF, and control plots (Fig. 4.3b). However, both the number of egg

batches (H = 26.115, df = 1, $P < 0.001$), and larvae infestation level of the pest (H = 20.907, df = 1, $P < 0.001$) were significantly higher in the major cropping season than in the minor cropping season in the two treatments and control plots (Figs. 4.3a and 4.3b).

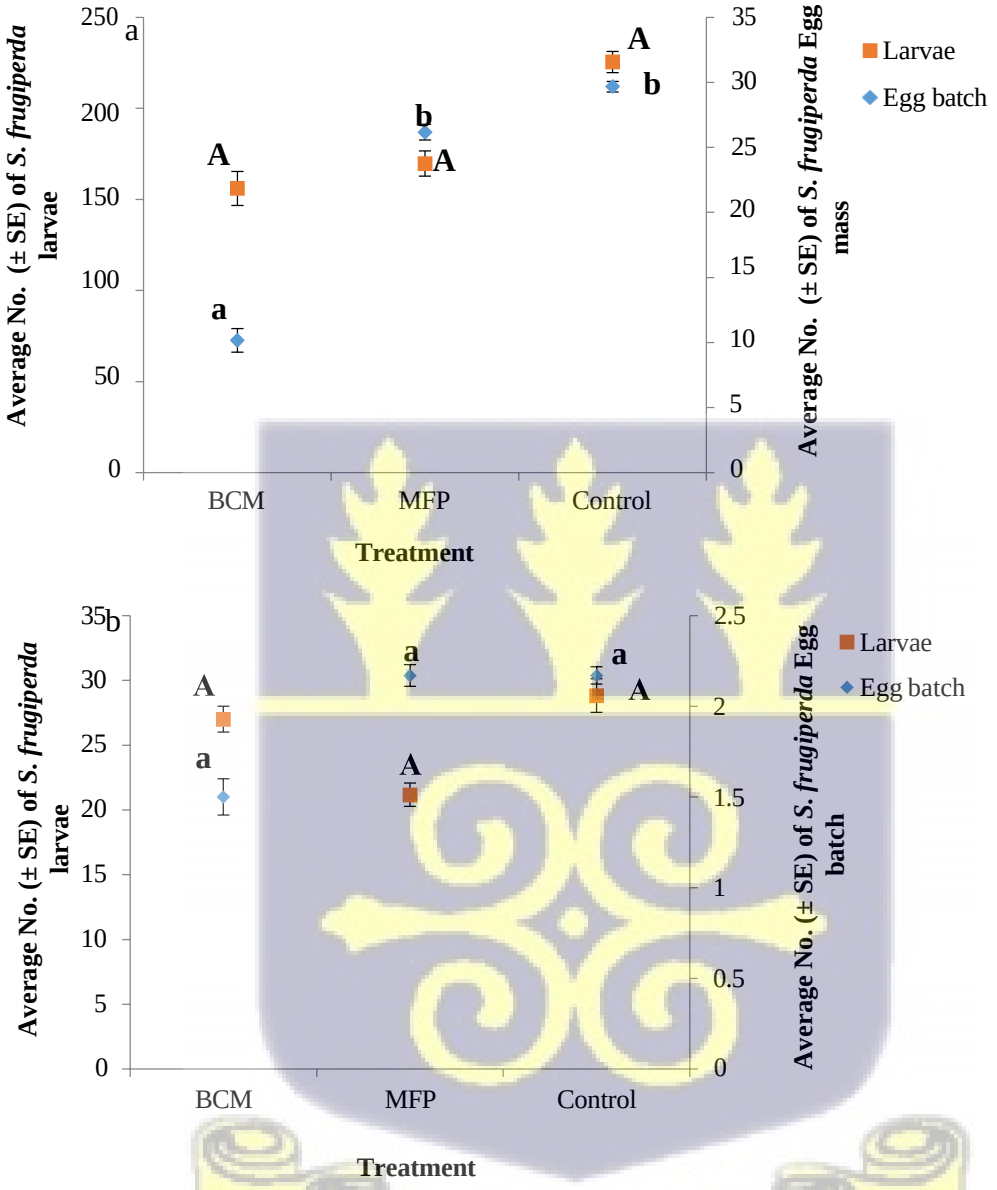


**Figure 4.3:** *Spodoptera frugiperda* infestation (Egg batch and larvae density) in the two different treatments and control plots in the (a) major maize cropping season and (b) minor maize cropping season. Error bars with lowercase letters compared variations in egg batches, while uppercase letters compared variations in larvae densities. Different letters in each instance (i.e. lowercase and uppercase) indicate significantly different following a Kruskal-Wallis ($P < 0.05$) and Dunn's multiple comparison tests. Note: Each egg batch indicate a count > 50 eggs/batch.

Overall, a significantly higher infestation level (egg batches and larvae density) of the *S. frugiperda* occurred in the major cropping season than in the minor cropping season (Table 4.9).

**Table 4.9:** *Spodoptera frugiperda* egg batches and larvae infestation levels (pooled from the BCM, MFP, and control plots) recorded in the major and minor maize cropping season

| **Parameter** | **Major season** | **Minor season** | **Statistics** |
|---|---|---|---|
| Egg batch | 22.56 ± 1.31a | 1.94 ± 0.05b | $U$ = 26.115, P < 0.001 |
| Larvae | 183.78 ± 4.89b | 25.67 ± 2.18b | $U$ = 20.907, P < 0.001 |

Means with different lowercase letters along rows indicate significantly different as indicated by the Mann-Whitney-Wilcoxon *U* test with continuity correction**.**

#### 4.2.3.1 Influence of climate on *Spodoptera frugiperda* infestation levels

Analysis of the monthly climate parameters (i.e. temperature and rainfall) showed no significant difference between temperatures occurring in the major (May to August) (32.02±0.31ºC) and minor cropping seasons (August to November) (32.12 ± 0.12ºC) ($F_{1,13}$ = 68.03, $P$ = 1.926). However, significantly more rainfall occurred in the major cropping season (18.43±1.85) than in the minor cropping season (10.40±0.27), with a clear peak in July ($F_{1,13}$ = 117.11, $P$ = 0.026) (Fig. 4.4). No significant correlation between temperature and *S. frugiperda* egg batches as well as larvae infestation was recorded. This was also the case between rainfall and *S. frugiperda* egg batches as well as larvae infestation.

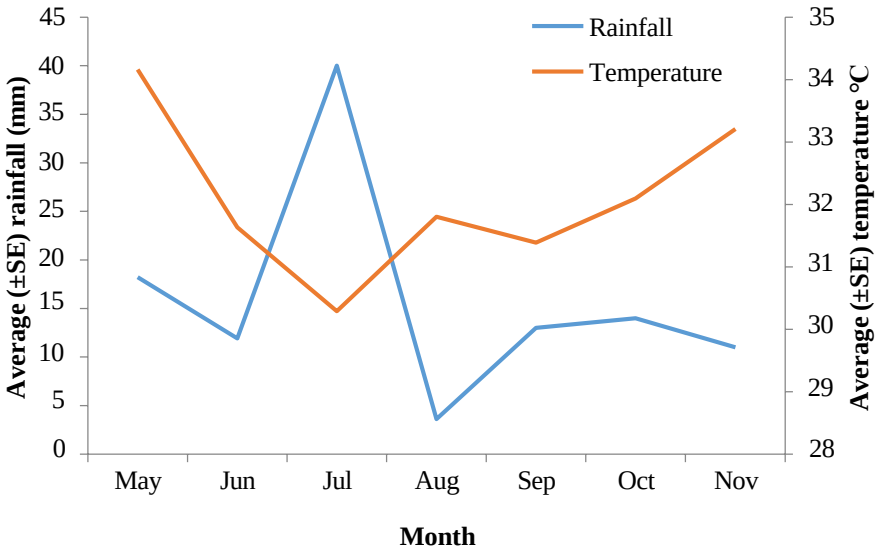


**Figure 4.4:** Climate parameters (temperature and rainfall) occurring in the major (May - August) and minor (August - November) cropping seasons.

## 4.3 Potential of the predator, *Rhynocoris bicolor* as a biological control agent of *Spodoptera frugiperda*

### 4.3.1 Predation rate

All life-stages (i.e., the five nymph instars and adults) of *R. bicolor* used in the laboratory functional response assays successfully attacked, killed, and fed on the larvae of *S. frugiperda* under the established experimental conditions. *Rhynocoris bicolor* also successfully attacked the three different age stages (newly-emerged, 2-day old, and 6-day old) of *S. frugiperda* larvae tested. However, the first and second nymph stages of the predator could not successfully attack and kill the six-day-old larvae of the pest (Table 4.10).

Across all densities and larvae age of *S. frugiperda* tested, the efficiency of the different life-stages of *R. bicolor* in killing the pest was significantly different (Table 4.10). The adult female was the most efficient, killing a higher number of larvae. Overall, all five nymph stages of the predator were more efficient in killing the young larvae (newly-emerged and 2-day old) of *S.*

*frugiperda* than older larvae (i.e. 6-day old larvae). This was also the case with the adults (Table 4.10

**Table 4.10:** Mean number (± SE) of prey (*S. frugiperda* larvae), at different prey densities, consumed by the five nymph stages and adults (female and male) of *Rhynocoris bicolor*. ***n***: number of replicates.

| **Prey age** | **Prey density** | ***N*** | **Average (±SE) number of consumed prey** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Nymph 1 | Nymph 2 | Nymph 3 | Nymph 4 | Nymph 5 | Female | Male |
| NE | 5 | 10 | 1.94 ± 0.37a | 4.67 ± 0.30b | 4.30 ± 0.41b | 4.55 ± 0.60b | 4.72 ± 0.22b | 4.90 ± 0.14b | 3.72 ± 0.10b |
| | 15 | 10 | 1.20 ± 0.10a | 12.24 ± 1.36b | 14.19 ± 1.10b | 14.10 ± 1.40b | 14.10 ± 0.51b | 14.58 ± 1.00b | 9.66 ± 0.50b |
| | 25 | 10 | 20.38 ± 1.40a | 20.55 ± 1.91a | 22.00 ± 1.30a | 22.16 ± 0.91a | 21.17 ± 1.47a | 20.08 ± 1.10a | 11.60 ± 1.39b |
| | 30 | 10 | 20.41 ± 1.10a | 20.71 ± 1.64a | 21.51 ± 1.20a | 21.52 ± 1.20a | 21.00 ± 1.33a | 21.21 ± 1.82a | 16.31 ± 1.37b |
| | 35 | 10 | 20.57 ± 0.90a | 20.04 ± 1.25a | 21.37 ± 1.20a | 21.38 ± 1.20a | 21.03 ± 1.50a | 21.62 ± 1.07a | 18.56 ± 1.74a |
| | 40 | 10 | 20.43 ± 1.50a | 20.54 ± 0.73a | 21.50 ± 1.20a | 21.43 ± 1.71a | 20.61 ± 1.20a | 22.76 ± 1.11a | 18.03 ± 1.31a |
| | | | | | | | | | |
| 2-day old | 5 | 10 | 2.61 ± 0.30a | 4.50 ± 0.82b | 4.15 ± 0.26b | 4.44 ± 0.17b | 4.75 ± 0.33b | 5.00 ± 0.16b | 3.23 ± 0.54ab |
| | 15 | 10 | 5.04 ± 0.70a | 8.52 ± 0.18b | 9.11 ± 0.21b | 9.50 ± 0.81b | 9.00 ± 0.20b | 14.12 ± 1.11c | 7.79 ± 0.10ab |
| | 25 | 10 | 5.28 ± 0.10a | 6.73 ± 0.50a | 9.90 ± 1.78a | 22.17 ± 1.95b | 14.23 ± 1.8c | 21.64 ± 1.03b | 12.86 ± 0.63ac |
| | 30 | 10 | 6.99 ± 0.50a | 6.36 ± 0.22a | 9.94 ± 0.30a | 22.33 ± 2.17b | 20.74 ± 1.06b | 19.32 ± 1.47b | 12.20 ± 1.50a |
| | 35 | 10 | 7.32 ± 0.10a | 13.80 ± 0.97b | 11.82 ± 1.11b | 23.30 ± 1.32c | 20.44 ± 1.53c | 18.91 ± 1.81c | 11.90 ± 0.10b |
| | 40 | 10 | 8.05 ± 0.33a | 19.52 ± 1.13b | 19.60 ± 1.63b | 22.22 ± 0.85b | 20.1 0± 1.41b | 24.24 ± 1.06b | 12.70 ± 1.28c |
| | | | | | | | | | |
| 6-day old | 5 | 10 | – | – | 2.63 ± 0.10ab | 4.40 ± 0.30a | 4.43 ± 0.10a | 3.81 ± 0.20a | 1.23 ± 0.10b |
| | 15 | 10 | – | – | 1.61 ± 0.10a | 3.15 ± 0.91ab | 4.22 ± 0.10b | 7.30 ± 0.80c | 1.89 ± 0.10a |
| | 25 | 10 | – | – | 1.40 ± 0.40a | 4.02 ± 0.60b | 3.27 ± 0.14ab | 7.34 ± 0.80bc | 3.23 ± 0.20bc |
| | 30 | 10 | – | – | 1.24 ± 0.10a | 2.80 ± 0.76a | 3.03 ± 0.17a | 9.37 ± 0.62b | 6.26 ± 1.11b |
| | 35 | 10 | – | – | 0.91 ± 0.10a | 3.31 ± 0.40b | 3.61 ± 0.21b | 8.82 ± 0.20c | 7.30 ± 0.90c |
| | 40 | 10 | – | – | 3.30 ± 0.22a | 6.00 ± 1.36a | 4.10 ± 0.72a | 11.08 ± 0.57b | 7.72 ± 1.31ab |

Mean ± SE along the same row with no identical lowercase letter(s) indicate significantly different following a generalized linear model with a negative binomial distribution ($GLM_{nb}$) and Tukey HSD test ($P < 0.005$). The parenthesis – placed in Nymphs 1 and 2 under the 6-day old prey age trials indicate that both nymphal stages of *Rhynocoris bicolor* could not successfully attack and kill *Spodoptera frugiperda* at this age.

### 4.3.2 Functional response of *Rhynocoris bicolor*

Logistic regression between the initial larvae of *S. frugiperda* densities offered and the proportion of the larvae consumed (i.e. *Na*/*No*) by *R. bicolor* showed all significantly negative values of the linear coefficients $P_1$, thus indicating a Type II functional response across all life-stages of *R. bicolor* (Table 4.11).

**Table 4.11:** Logistic regression analysis of the proportion of host age of *Spodoptera frugiperda* predated by all life-stages of *Rhynocoris bicolor* in the R environment for statistical computing (version 4.00)

| Host age | Predator Life-stage | Parameter | Estimates | SE | Z-value | *Pr* (z) |
|---|---|---|---|---|---|---|
| NE | Nymph I | Intercept | 0.0353572 | 0.0238694 | 1.4813 | 0.1385 |
| | | Linear | -0.0391489 | 0.0063396 | -6.1753 | $6.603 \times 10^{-4}$ |
| | | Quadratic | 2.0709460 | 0.2806277 | 7.3797 | $1.587 \times 10^{-13}$ |
| | | Cubic | 0.0260787 | 0.0008358 | 31.2020 | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| | Nymph II | Intercept | 3.2770914 | 0.3521140 | 9.3069 | $< 2.2 \times 10^{-16}$ |
| | | Linear | -0.0324812 | 0.0064666 | -5.0229 | $5.089 \times 10^{-7}$ |
| | | Quadratic | 2.0847423 | 0.2983712 | 6.7830 | < 0.001 |
| | | Cubic | 0.0099134 | 0.0016895 | 5.8676 | $4.421 \times 10^{-9}$ |
| | | | | | | |
| | Nymph III | Intercept | 0.65311692 | 0.33679552 | 1.9392 | 0.05248 |
| | | Linear | -0.0932540 | 0.0088098 | -10.585 | $< 2.2 \times 10^{-16}$ |
| | | Quadratic | 1.19791335 | 0.21900027 | 5.4699 | $4.502 \times 10^{-8}$ |
| | | Cubic | 0.02156417 | 0.00064311 | 33.5311 | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| | Nymph IV | Intercept | 0.77885693 | 0.41401268 | 0. 1.8812 | 0.05994 |
| | | Linear | -0.1043499 | 0.0093187 | -11.748 | $< 2.2 \times 10^{-16}$ |
| | | Quadratic | 1.20854712 | 0.22872269 | 5.2839 | $1.265 \times 10^{-7}$ |
| | | Cubic | 0.02167834 | 0.00060794 | 35.6589 | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| | Nymph V | Intercept | 1.72198494 | 0.96279538 | 1.7885 | 0.0736911 |
| | | Linear | -0.099052 | 0.008845 | -11.199 | $< 2.2 \times 10^{-16}$ |
| | | Quadratic | 0.84118653 | 0.23951978 | 3.5120 | 0.0004448 |
| | | Cubic | 0.02204261 | 0.00079026 | 27.8929 | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| | Male | Intercept | 0.9847333 | 0.2784345 | 0.8784 | 0.7320 |
| | | Linear | -0.018955 | 0.0167494 | -2.9943 | 0.0224 |
| | | Quadratic | 0.629230 | 0.3548909 | 0.8723 | 0.9009 |
| | | Cubic | 0.749334 | 0.0184031 | 2.2202 | 0.0311 |
| | | | | | | |
| | Female | Intercept | 8.6359783 | 0.0040067 | 2155.3832 | $< 2.2 \times 10^{-16}$ |
| | | Linear | -0.110111 | 0.013045 | -8.4407 | $< 2.2 \times 10^{-16}$ |
| | | Quadratic | 0.2563790 | 0.0872962 | 2.9369 | 0.003315 |
| | | Cubic | 0.0214992 | 0.0011849 | 18.1443 | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| 2-day old | Nymph I | Intercept | 1.2495373 | 0.3397621 | 3.6777 | 0.0002354 |
| | | Linear | -0.0183401 | 0.0065187 | -2.8134 | 0.004901 |
| | | Quadratic | 2.1764392 | 0.2673939 | 7.04733 | < 0.001 |
| | | Cubic | 0.0388799 | 0.0093551 | 4.1560 | $3.239 \times 10^{-5}$ |
| | | | | | | |
| | Nymph II | Intercept | 2.931924 | 0.861494 | 3.4033 | 0.0006658 |
| | | Linear | -0.017021 | 0.005883 | -2.8932 | 0.003813 |
| | | Quadratic | 2.198973 | 0.367281 | 6.56373 | < 0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Cubic | 0.028778 | 0.005024 | 5.7280 | $1.016 \times 10^{-8}$ |
| | | | | | | |
| | Nymph III | Intercept | 4.013617 | 0.908294 | 4.4189 | $9.923 \times 10^{-6}$ |
| | | Linear | -0.0296673 | 0.0059161 | -5.0146 | $5.313 \times 10^{-7}$ |
| | | Quadratic | 1.087833 | 0.2092784 | 5.76231 | < 0.001 |
| | | Cubic | 0.028853 | 0.003100 | 9.3075 < | $< 2.2 \times 10^{-16}$ |
| | | | | | | |
| | Nymph IV | Intercept | 1.3403073 | 0.6976868 | 1.9211 | 0.05472 |
| | | Linear | -0.042917 | 0.007142 | -6.0091 | $1.865 \times 10^{-9}$ |
| | | Quadratic | 0.5254356 | 0.2136905 | 2.4589 | 0.01394 |
| | | Cubic | 0.0159362 | 0.0015834 | 10.0647 | $< 2 \times 10^{-16}$ |
| | | | | | | |
| | Nymph V | Intercept | 3.3062909 | 0.4424043 | 7.4735 | $7.811 \times 10^{-14}$ |
| | | Linear | -0.0289991 | 0.0062136 | -4.6671 | $3.055 \times 10^{-6}$ |
| | | Quadratic | 0.5738934 | 0.2783202 | 3.2837 | < 0.001 |
| | | Cubic | 0.0126466 | 0.0020935 | 6.0409 | $1.532 \times 10^{-9}$ |
| | | | | | | |
| | Male | Intercept | 0.6923443 | 0.2849434 | 0.7649 | 0.6954 |
| | | Linear | -0.028952 | 0.0245875 | -2.8955 | 0.0183 |
| | | Quadratic | 0.629230 | 0.5784334 | 0.7344 | 0.8664 |
| | | Cubic | 0.749334 | 0.0193782 | 2.1736 | 0.0281 |
| | | | | | | |
| | Female | Intercept | 4.7298066 | 5.3409506 | 0.8856 | 0.3758 |
| | | Linear | -0.127799 | 0.014365 | -8.8964 | $2.2 \times 10^{-16}$ |
| | | Quadratic | 0.5070169 | 0.4472927 | 1.1335 | 0.2570 |
| | | Cubic | 0.0210068 | 0.0011724 | 17.9181 | $< 2 \times 10^{-16}$ |
| | | | | | | |
| 6-day old | Male | Intercept | 0.352225 | 0.446512 | 0.7888 | 0.43021 |
| | | Linear | -0.020330 | 0.010067 | -2.0195 | 0.04343 |
| | | Quadratic | 0.339877 | 0.591189 | 0.5749 | 0.56536 |
| | | Cubic | 0.056794 | 0.027627 | 2.0557 | 0.03981 |
| | | | | | | |
| | Female | Intercept | 5.73021569 | 2.4235353 | 3 2.3644 | 0.018059 |
| | | Linear | -0.0224938 | 0.0084338 | -2.6671 | 0.007651 |
| | | Quadratic | -0.55881019 | 0.21061438 | -2.6532 | 0.007972 |
| | | Cubic | 0.00011546 | 0.02505211 | 0.0046 | 0.996323 |

Also, the declining consumption with increasing *S. frugiperda* larvae densities confirmed a Type II functional response. Similarly, the monotonically declining proportion of consumption with increased *S. frugiperda* larvae (new-emerged, 2 day-old, and 6 day-old), densities led to further confirmation of Type II functional responses (Figs. 4.5, 4.6, and 4.7).

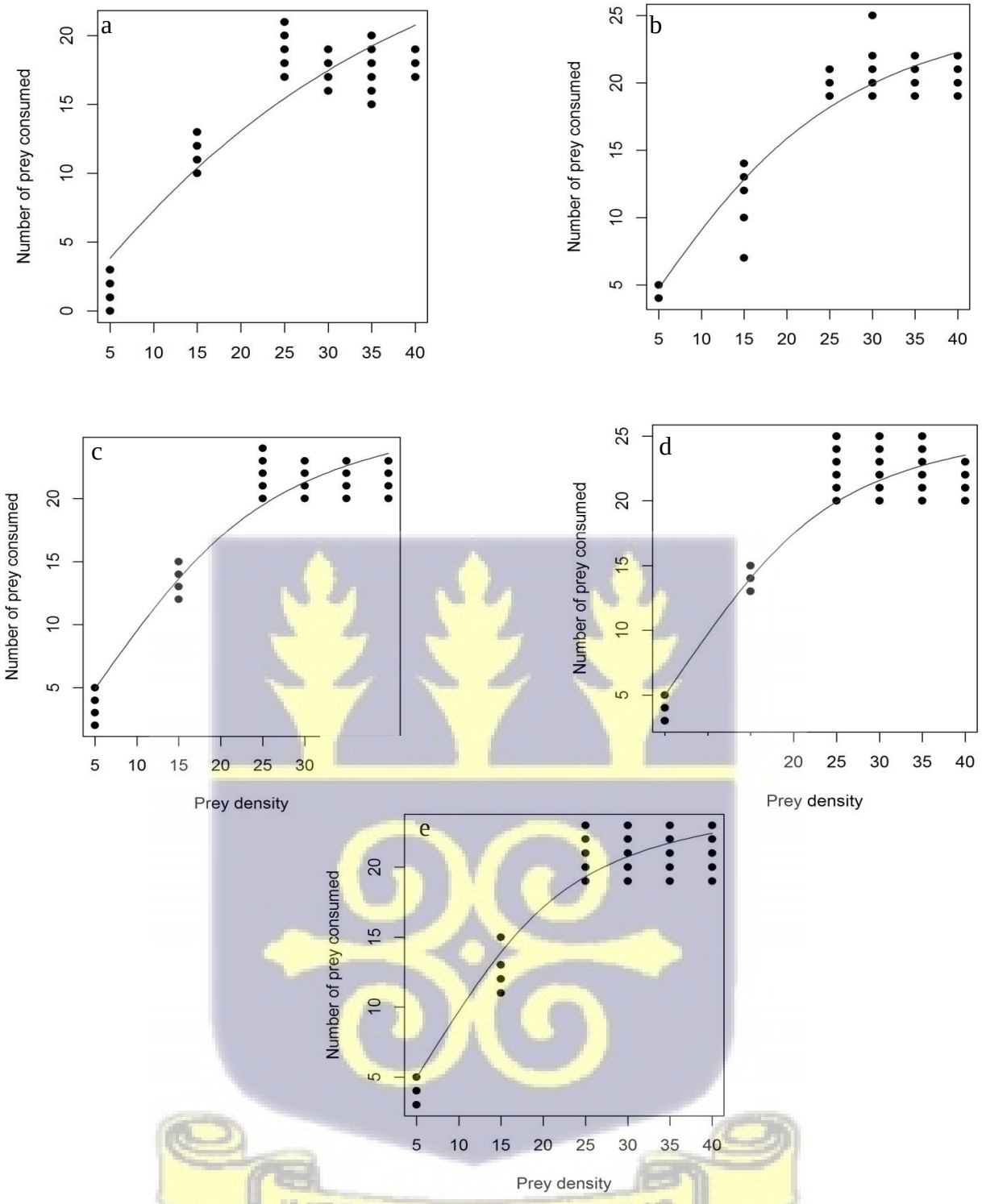


**Figure 4.5:** Type II functional response curves fitted by Rogers decreasing prey function random predator equation *Rhynocoris bicolor* nymphs (a) I, (b) II, (c) III, (d) IV, and (e) V, preying on newly-emerged (< 1 day old) *Spodoptera frugiperda* larvae in a 6-hour period.

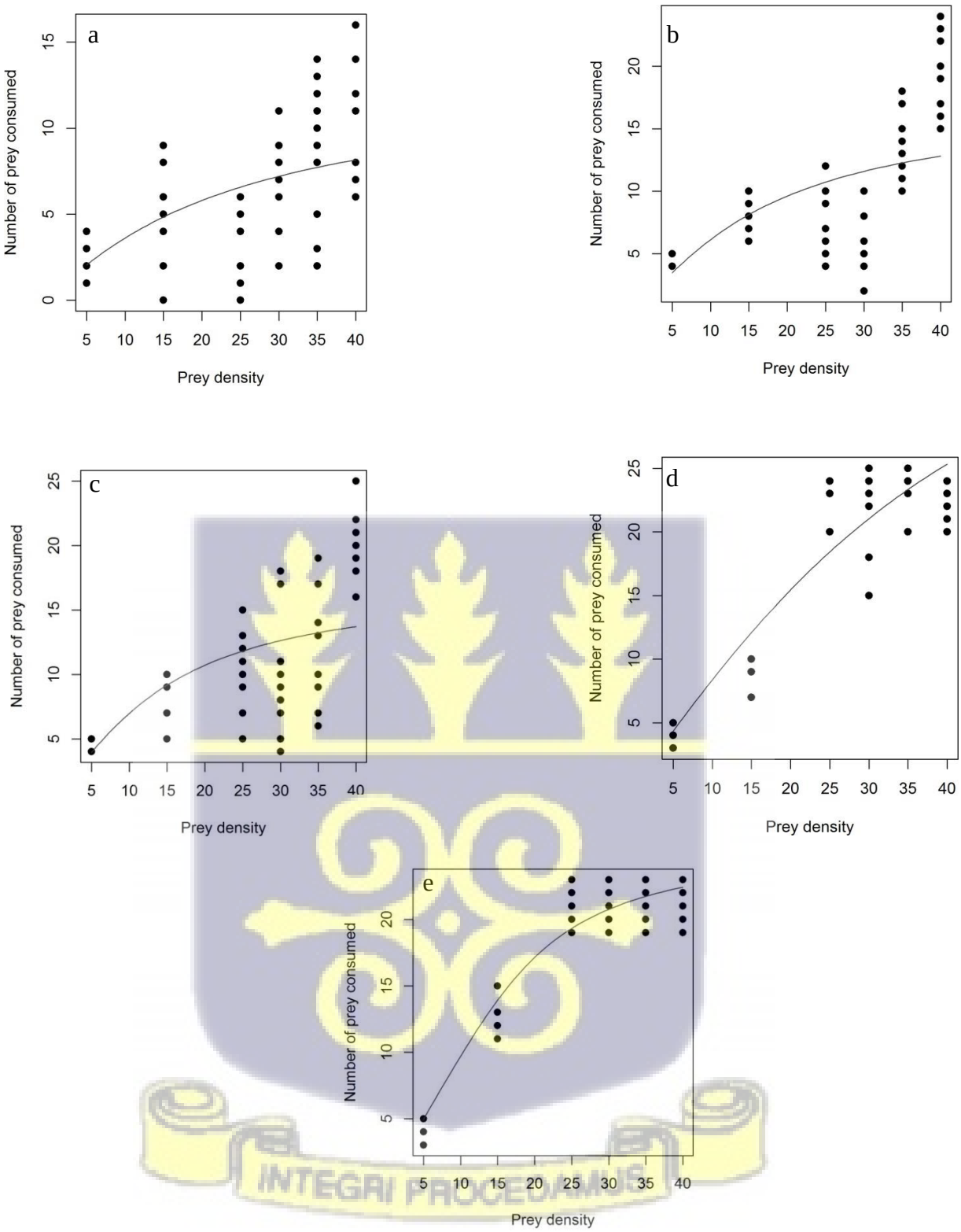


**Figure 4.6:** Type II functional response curves fitted by Rogers decreasing prey function random predator equation *Rhynocoris bicolor* nymphs (a) I, (b) II, (c) III, (d) IV, and (e) V, preying on 2-day old *Spodoptera frugiperda* larvae in a 6-hour period.

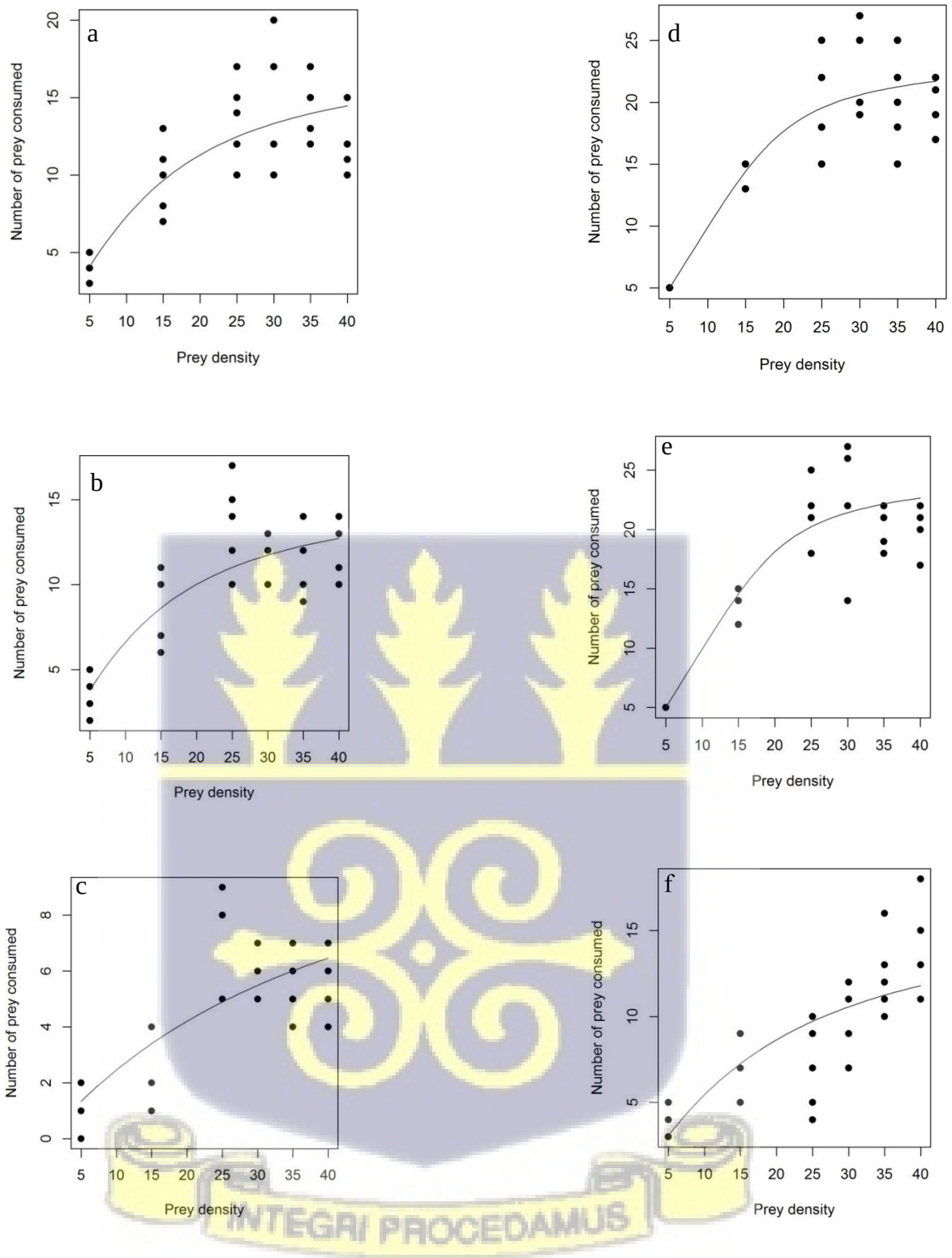


**Figure 4.7:** Type II functional response curves fitted by Rogers decreasing prey function random predator equation for *Rhynocoris bicolor* males preying on (a) newly-emerged, (b) 2-day old, (c) 6-day old *Spodoptera frugiperda* larvae and females preying on (d) newly-emerged, (e) 2-day old, and (f) 6-day old *S. frugiperda* larvae in a 6-hour period.

Estimates of functional response parameters, determined through fits to the Rogers random predator model, revealed significant differences in the attack rates (*a*) and handling time (*Th*), between the different life-stages of *R. bicolor*. The Females exhibited a significantly higher attack rate, the shortest handling time, and maximum predation rate (T/*Th*) than nymphs and males. The first two nymph stages (i.e. nymph 1 and 2) had similar attack rates and handling time, but differed significantly from that of the three other nymphs and males. However, handling time of the nymphs and males did not differ significantly, except in the fifth instar nymph, which had a shorter handling time (Table 4.12).

**Table 4.12:** Functional response estimates of *a* = attack rate and *Th* = handling time during the considered time interval (6 hours) of the five nymphs and adults of *Rhynocoris bicolor*, and the 95% CI = confidence interval

| | ***a*** | **CI** | ***Th*** | **CI** |
|---|---|---|---|---|
| Nymph 1 | 1.25 ± 0.02a | 1.100 – 1.812 | $4.02 \times 10^{-2}$ a | $1.072 – 7.259 \times 10^{-2}$ |
| Nymph 2 | 2.93 ± 0.11a | 2.436 – 3.149 | $3.00 \times 10^{-2}$ a | $1.338 – 9.026 \times 10^{-2}$ |
| Nymph 3 | 4.01 ± 0.60b | 4.071 – 4.173 | $3.00 \times 10^{-2}$a | $1.051 – 5.109 \times 10^{-2}$ |
| Nymph 4 | 4.44 ± 1.10b | 4.265 – 4.824 | $3.00 \times 10^{-2}$ a | $1.163 – 4.391 \times 10^{-2}$ |
| Nymph 5 | 3.30 ± 0.77b | 3.181 – 3.828 | $2.70 \times 10^{-1}$ b | $8.844 \times 10^{-2} – 1.674 \times 10^{-1}$ |
| Female | 7.79 ± 1.01c | 7.349 – 8.077 | $1.17 \times 10^{-1}$c | $9.175 \times 10^{-2} – 1.430 \times 10^{-1}$ |
| Male | 2.46 ± 0.83b | 2.315 – 2.925 | $3.00 \times 10^{-2}$a | $1.146 – 8.211 \times 10^{-2}$ |

# CHAPTER FIVE

# DISCUSSION

## 5.1 Diversity and abundance of general arthropod communities associated with maize agroecosystems

The role of biodiversity in maintaining ecosystem functions is of great importance (Reiss *et al.*, 2009). Biodiversity is particularly important because the loss of only one species may result in critical changes to ecological processes, with potential adverse ramifications for the broader functioning of an ecosystem. Understanding the drivers of ecological change and the resultant effects thereof on the abundance, distribution, and diversity of species is paramount to environmental health. Arthropod diversity represents the bedrock of all levels of ecosystems (Cardinale *et al.*, 2006). They play significant roles as herbivores, detritivores, and carnivores for nutrient cycles and energy flow in terrestrial ecosystems. Also, they proffer numerous ecosystem services, including pollination, organic matter decomposition, seeds dispersal, regulation of the populations of other species, such as pests, and maintaining soil structure and fertility (Babin-fenske and Anand, 2010). Amongst these arthropods, insects, especially those that feed on dead trees or wood and other decaying organic matter, play a crucial role in nutrient cycling and substantial roles in pest management. Insect predators, in most cases, are more effective than many synthetic chemical pesticides used in controlling economically damaging pests (Purslow, 2004).

Generally, insects are considered bioindicators that determine the stability of agroecosystems (Majeed *et al.*, 2019; Naseem *et al.*, 2020). However, several factors such as climate change and anthropogenic-mediated activities, encompassing intensifications of landscapes for agriculture, especially monocultures, facilitate the extinction of many arthropod species (Balasubramanian *et*

*al*., 2005; Khadijah *et al*., 2013; Balakrishnan *et al*., 2014). In virtually all cases, following the invasion of an alien pest in novel environments, the amounts of chemical inputs applied as control are often far above the recommended doses due to the impacts of the pest (Desneux *et al*., 2021). In Ghana, for example, following *S. frugiperda* invasion, management has relied mainly on the procurement and distribution of pesticides. However, reliance and overuse of these pesticides may result in substantial disruption of the structure and function of arthropod communities. In most cases, pesticides eliminate both the target pest and beneficial/non-target species such as predators, parasitoids, and pathogens (Theiling and Croft 1988; Bengsston *et al*., 2005; Attwood *et al*., 2008; Flores-Gutiérrez *et al*., 2020), thus resulting in the loss of important ecosystem services that native predators and parasitoids provide (Losey and Vaughan, 2006; Desneux *et al*., 2007; Zhang *et al*., 2007; Chapin *et al*., 2000;). Hence, the rationale for investigating the effects of the pesticides used for the control of *S. frugiperda* in Ghana on the arthropod communities in maize agroecosystems.

Results of the investigations of pesticide application effects on arthropod communities in an agroecosystem in Ghana revealed that the application of insecticides had significant adverse effects on arthropod communities, especially their abundance in the maize agroecosystem. In the major maize cropping season, the control plots – with no treatment applied – recorded significantly more individual arthropods than MFP treatment plots, in which an insecticide was applied. A similar trend was observed in the minor maize cropping season in which the control plots also recorded more individual arthropods than the MFP treatment plots, thus an apparent indication of the adverse effects of chemical pesticides on the arthropod communities. This finding was not unexpected because agricultural activities, notably the direct application of insecticides, may have

subtstantial adverse effects on arthropod communities (De Snoo and De Wit 1998, Cilgi and Jepson 1995, Bundschuh *et al*., 2014).

On the diversity of the arthropod communities, the control plots had a higher Shannon-Wiener diversity index value and species equitability/evenness than the MFP plots in the major maize cropping season and a similar trend also occurred in the minor maize cropping season. This implies that the pesticides used by farmers, for the control of S. *frugiperda* in maize agroecosystems, in a typical maize growing season in Ghana, significantly reduces the abundance of arthropods and the communities do not remain stable in diversity and evenness. Overall, *Oecophylla longinoda was* the most prevalent/abundant arthropod species recorded in the control and MFP plots both in the major and minor cropping seasons. Prior reports of *Oecophylla* sp. suggest that these species are often effective in controlling several insect pest species (Way and Khoo, 1992.,Van Mele, 2008., Offenberg, 2015), and augmentative releases are, in some cases, linked to improve crop yields (Delabie, 2001; Blüthgen *et al*., 2006). For example, the potential effectiveness of the genus *Oecophylla* as a biological control agent has been carried out on pests of citrus (Afreh-Nuamah *et al*., 2012), mango (Van Mele and Vayssières, 2007), and cashew (Dwomoh *et al*., 2009) in Africa, Asia, and Australia (Huang and Yang, 1987).

**5.2 Diversity and abundance of predators and *Spodoptera frugiperda* infestation levels**

A total of seven predatory arthropods: *Crematogaster striatula* (Emery), *Cosmolestes pictus* (Klug), *Haematochares obscuripennis* (Stal), *Hediocoris tibialis* (Stal), *Rhynocoris* sp. *Sphedanolestes picturellus* (Schouteden), and *Misumenops* sp. were confirmed predators of *S. frugiperda* after laboratory tests. More predatory arthropods were recorded in the major cropping

season than in the minor cropping season. In both cropping seasons, the control plots had the highest abundance of predator species than the BCM (i.e., plots where the parasitoid, *T. remus* were released) and MFP treatment plots and this was also reflected in the weekly variations in the abundance of predators. Across all six sampling weeks, the number of predators was higher in the control and BCM plots than the MFP plots in the major and minor cropping seasons. This pattern suggests that chemical insecticides are not only affecting the arthropod communities, but also the abundance of predators. The application of pesticides reduced the abundance of predators in the MFP plots, thus articulating one of the deleterious ecological consequences of pesticides (Desneux *et al*., 2021). Similarly, pesticides also negatively affected the diversity of the predator populations in the agroecosystem, as reflected in both the Shannon-Wiener diversity index. However, the species evenness was similar in all plots. Thus, implying that the diversity of predators in the maize agroecosystems declines when pesticides are applied and biocontrol services are reduced due to the significant reductions in the abundance of predators. The infestation levels of *S. frugiperda* in the major cropping season validated this hypothesis. Here, egg batches of the pest were significantly more in the control and MFP plots than in the BCM plots, despite the application of pesticides in the MFP plots, clearly elucidating why farmers suffer devastating losses in maize despite the high inputs of pesticides applied. It further demonstrates the importance and needs for IPM because pesticides are not effective alone to manage *S. frugiperda* but rather increase management costs.

Overall, the major cropping season had a higher infestation level of *S. frugiperda* than the minor cropping season. However, bioclimatic parameters such as temperature and rainfall did not significantly influence the infestation levels of *S. frugiperda* or the abundance and diversity of

arthropods including the predatory species due to the similarities of both parameters during the major and minor cropping seasons.

### 5.3 Predation rate and functional response of *Rhynocoris bicolor*, a potential biological control agent of *Spodoptera frugiperda*

The functional response of predators represents the number of prey successfully attacked as a function of prey density (Solomon, 1949; Holling, 1959). It articulates the response of a predatory species to prey densities (Solomon, 1949). Holling (1959) underscores three functional response types. Type I highlights the occurrence of a linear relationship between the maximum numbers of prey killed and prey density. Type II, however, elucidates a monotonic decline in prey proportion consumed by a predator in increasing prey density. A sigmoid relationship occurs in Type III and a positively density-dependent relationship between prey density and proportion consumed occurs (Holling, 1959). A dome-shaped variant is possible in each of these three types, where the consumption rate does not monotonically increase with prey density but instead declines at high densities. Fundamentally, functional response models facilitate the evaluation of two crucial parameters: handling time (i.e., the time a predator requires to successfully attack, consume, and digest a prey) and attack rate, also regarded as the searching efficiency of a predator (i.e., the searching capacity or speed a predator uses for for finding prey).

In applied ecology, natural enemies are limited in experimental arenas in functional reponse tests and more than one prey species are seldom supplied. However, in natural ecological scenarios, these limitations are diminished or do not occur, as predators can freely attack several prey species (Xiao and Fadamiro, 2010). Many predators that have been released for biological control of pests

show or demsonstrate the type II rfunctional response (Xiao and Fadamiro, 2010). For example, the earwig *Doru lineare* Eschscholtz (Dermaptera: Forficulidae) can attack both eggs and larvae of *S. frugiperda* until it attains satiation at 39.4 *S. frugiperda* larvae (Sueldo et al., 2010). In the Neotropics, *Podisus nigrispinus* (Dallas) (Heteroptera: Pentatomidae) has been reported as a potential biocontrol agent of *S. frugiperda* and exhibits a type II functional response.

Similarly, in this study, the functional response tests, under laboratory conditions, revealed that *R. bicolor* exhibits type II functional response, with *S. frugiperda* as prey. All five nymphal stages and adult (male and female) of the *R. bicolor* sucesssfully attacked and fed on newly-emerged (i.e., 1-and-2-day old) larvae. However, the early nymphal instars (i.e., 1 and 2) were not able to attack or feed on older larvae such as six-day old larvae, but late nymphal instars (3, 4, and 5) and adults successfully attacked and fed on the older larvae (i.e the sizes of the predatoy species correspond to the sizes of *S. frugiperda* larvae they can feed on). Although the five nymphal stages and males of *R. bicolor* had a relatively high attack rate and handling time, females of *R. bicolor*, however, had the highest attack rate and shortest handling time across all age groups (i.e., newly-emerged, 2-day old, and 6-day old) of the pest. In the context of biological control, these results suggest that *R. bicolor* can significantly reduce the density of early infestation by *S. frugiperda*, thus reducing the density and infestation level of the pest in a typical maize agroecosystem. Therefore mass-rearing and periodic or intermittent augmentative releases of *R. bicolor* should be used for the control of *S. frugiperda* in Ghana, albeit in combination with other IPM strategies that are effective and environmentally safe such as entomopathogens, parasitoids, and other predators.

Generally, predators with higher searching efficiency (i.e., attack rate) and lower handling time are considered the most effective agents. This indicates that predators exhibiting the type III response are efficient biocontrol agents. However, there is evidence that many of the predators that are considered successful biocontrol agents show type II functional response on their prey (Xiao and Fadamiro, 2010). The functional response curve, showing the high predation rate of *R. bicolor*, prior to satiation lends credence to these reports.

# CHAPTER SIX

# CONCLUSION AND RECOMMENDATIONS

## 6.1 Conclusion

This thesis documented that the conventional control method (i.e., the application of pesticides) used for the control *of S. frugiperda* by maize farmers in Ghana significantly reduced the diversity and abundance of arthropod. Thus, altering the structure and function of the agroecosystem. Similarly, the same adverse effects of pesticides were observed on the abundance and diversity of predators, and did not significantly reduce the infestation levels of the pest. Most likely because the pest has evolved resistance to most synthetic chemical pesticides. Overall, the control plots conserved the integrity of the fauna in the maize agroecosystem as it recorded more arthropod communities including predators. A total of seven predatory species were confirmed as predators of *S. frugiperda*. Laboratory assessment on *R. bicolor* considered it as a potentially effective biological control agent for the control of *S. frugiperda* due to its high predation rate under laboratory environmental conditions. *R. bicolor* exhibited a type II functional response. This thesis is the first report of *R. bicolor* as a promising biological control candidate of *S. frugiperda*.

### 6.2 Recommendations

Recommendations and subsequent studies should include the following:

1. Pesticides should not be used as the main control option of *S. frugiperda* because it is harmful to beneficial/non-target species, as reflected in the low abundance of predators in MFP plots in this study.
2. Further, pesticides did not suffice in reducing the infestation levels of the pests below critical damage levels. Instead, a more comprehensive approach, involving integrated pest management (IPM), should be adopted because IPM aims to reduce and suppress the population of a pest below thresholds of economic importance through an integrated approach that adopts different methodologies that are environmentally safe and not harmful to non-target species.
3. The integration of natural enemies such as predators, parasitoids, and pathogens with environmentally friendly pesticides (bio-pesticides) should be tested and applied.
4. The functional response tests revealed *R. bicolor* as a potential biocontrol agent of *S. frugiperda*. Therefore, mass-rearing and augmentative releases of the predator is recommended in maize agroecosystems in Ghana.
5. This study was time limited. The biocontrol potential of the seven recorded predators was not investigated. Therefore, further studies should investigate the predatory potential of these predators on *S. frugiperda* and the possibility of combining them with other natural enemies such as parasitoids for increased biological control.

# REFERENCES

**Abrahams P, Bateman M, Beale T, Clottey V, Cock M, Colmenarez Y, Corniani N, Day R, Early R, Godwin J, et al. (2017).** Fall Armyworm: Impacts and Implications for Africa. Evidence Note (2), September 2017. Report to DFID. Wallingford: CABI.

**Adeye, A. T., Sikirou, R., Boukari, S., Aboudou, M., Amagnide, G. Y. G. A., Idrissou, B. S., ... and Zocli, B. (2018).** Protection de la culture de maïs contre *Spodoptera frugiperda* avec les insecticides Plantneem, Lambdace 25 EC et Viper 46 EC et reduction de pertes de rendement au Benin. *Journal de la Recherche Scientifique de l'Université de Lomé*, *20*(2), 53-65.

**Afreh-Nuamah, K., Billah, M. K., and Obeng-Ofori, D. (2012).** Weaver ant, *Oecophylla longinoda* (Latreille) (Hymenoptera: Formicidae) activity reduces fruit fly damage in citrus orchards. *Journal of Agricultural Science and Technology A*, *2*, 449-458.

**Agboyi, L. K., Goergen, G., Beseh, P., Mensah, S. A., Clottey, V. A., Glikpo, R., ... and Kenis, M. (2020).** Parasitoid complex of fall armyworm, *Spodoptera frugiperda*, in Ghana and Benin. *Insects*, *11*(2), 68.

**Agboyi, L. K., Mensah, S. A., Clottey, V. A., Beseh, P., Glikpo, R., Rwomushana, I., ... and Kenis, M. (2019).** Evidence of leaf consumption rate decrease in fall armyworm, *Spodoptera frugiperda*, larvae parasitized by *Coccygidium luteum*. *Insects*, *10*(11), 410.

**Akramov, K., and Malek, M. (2012).** Analyzing profitability of maize, rice, and soybean production in Ghana: Results of PAM and DEA analysis. *Ghana Strategy Support Program (GSSP) Working*, *28*.

**Akutse, K. S., Kimemia, J. W., Ekesi, S., Khamis, F. M., Ombura, O. L., and Subramanian, S. (2019).** Ovicidal effects of entomopathogenic fungal isolates on the invasive fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Applied Entomology*, *143*(6), 626-634.

**Amadou, L. A. O. U. A. L. I., Baoua, I., Ba, M. N., Karimoune, L. A. O. U. A. L. I., and Muniappan, R. A. N. G. A. S. W. A. M. Y. (2018).** Native parasitoids recruited by the invaded fall armyworm in Niger. *Indian Journal of Entomology*, 1253-1254.

**Ambrose, D. P. (2003).** Biocontrol potential of assassin bugs (Hemiptera: Reduviidae). *Journal of Experimental Zoology*, *6*(1), 1-44.

**Arya, M., and Tiwari, R. (2013).** Efficacy of plant and animal origin bioproducts against lesser grain borer, *Rhyzopertha dominica* (Fab.) in stored wheat. *International Journal of Recent Scientific Research*, *4*(5), 649-653.

**Assefa, F., and Ayalew, D. (2019).** Status and control measures of fall armyworm (*Spodoptera frugiperda*) infestations in maize fields in Ethiopia: A review. *Cogent Food and Agriculture*, *5*(1), 1641902.

**Attwood, S. J., Maron, M., House, A. P. N., and Zammit, C. (2008).** Do arthropod assemblages display globally consistent responses to intensified agricultural land use and management?. *Global Ecology and Biogeography*, 17(5), 585-599.

**Babin-Fenske, J., and Anand, M. (2010).** Terrestrial insect communities and the restoration of an industrially perturbed landscape: assessing success and surrogacy. *Restoration Ecology*, *18*, 73-84.

**Badu-Apraku, B., and Fakorede, M. A. B. (2017).** Maize in Sub-Saharan Africa: importance and production constraints. In *Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa* (pp. 3-10). Springer, Cham.

**Balakrishnan, S., Srinivasan, M., and Mohanraj, J. (2014).** Diversity of some insect fauna in different coastal habitats of Tamil Nadu, southeast coast of *Journal of Asia-Pacific Biodiversity*, *7*(4), 408-414.

**Balasubramanian, K., Srinivasan, M., and Kathiresan, K. (2005).** Insects. In: Proceedings of coastal biodiversity in mangrove ecosystems: UNU-INWEH-UNESCO, International Training Course. 359-363.

**Baloch, M. N., Fan, J., Haseeb, M., and Zhang, R. (2020).** Mapping potential distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in central Asia. *Insects*, *11*(3), 172.

**Bartlett, M. S. (1937).** Properties of sufficiency and statistical tests. *Proceedings of the Royal Society of London. Series A-Mathematical and Physical Sciences*, *160*(901), 268-282.

**Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., ... and Sattin, M. (2015).** Eight principles of integrated pest management. *Agronomy for Sustainable development*, *35*(4), 1199-1215.

**Bateman, M. L., Day, R. K., Luke, B., Edgington, S., Kuhlmann, U., and Cock, M. J. (2018).** Assessment of potential biopesticide options for managing fall armyworm (*Spodoptera frugiperda*) in Africa. *Journal of Applied Entomology*, *142*(9), 805-819.

**Behle, R. W., and Popham, H. J. (2012).** Laboratory and field evaluations of the efficacy of a fast-killing baculovirus isolate from *Spodoptera frugiperda*. *Journal of Invertebrate Pathology*, *109*(2), 194-200.

**Bengtsson, J., Ahnström, J., and WEIBULL, A. C. (2005).** The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology*, *42*(2), 261-269.

**Beserra, E. B., and Parra, J. R. P. (2005).** Impact of the number of *Spodoptera frugiperda* egg layers on parasitism by *Trichogramma atopovirilia*. *Scientia Agricola*, *62*, 190-193.

**Blüthgen, N., Mezger, D., and Linsenmair, K. E. (2006).** Ant-hemipteran trophobioses in a Bornean rainforest–diversity, specificity and monopolisation. *Insectes Sociaux*, *53*(2), 194-203.

**Britz, C. (2020).** *Relationship between Spodoptera frugiperda (Lepidoptera: Noctuidae) damage and yield loss in maize* (Doctoral dissertation, North-West University (South Africa)).

**Bundschuh, M., Goedkoop, W., and Kreuger, J. (2014).** Evaluation of pesticide monitoring strategies in agricultural streams based on the toxic-unit concept—experiences from long-term measurements. *Science of the Total Environment*, *484*, 84-91.

**CABI. (2017).** New report reveals cost of fall armyworm to farmers in Africa, provides recommendation for control. CABI, Wallingford, United Kingdom.

**CABI. (2019).** "*Spodoptera frugiperda* (Fall Armyworm). (Original Text by Ivan Rwomushana)." In *Invasive Species Compendium*. Wallingford UK: CABI International. www.cabi.org.isc. Accessed January 2020.

**Capinera, J. L. (2000).** Fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Insecta: Lepidoptera: Noctuidae). The University of Florida, Institute of Food and Agricultural Sciences. (UF/IFAS), Gainesville, Florida.

**Capinera, J. L. (2017).** Fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Insecta: Lepidoptera: Noctuidae). http://edis.ifas.ufl.edu/in255.

**Cardinale, B. J., Srivastava, D. S., Duffy, J. E., Wright, J. P., Downing, A. L., Sankaran, M., and Jouseau, C. (2006).** Effects of biodiversity on the functioning of trophic groups and ecosystems. *Nature*, *443*(7114), 989-992.

**Carvalho, R. A., Omoto, C., Field, L. M., Williamson, M. S., and Bass, C. (2013).** Investigating the molecular mechanisms of organophosphate and pyrethroid resistance in the fall armyworm *Spodoptera frugiperda*. *PLoS One*, *8*(4), e62268.

**Casmuz, A., Juarez, M. L., Socias, M. G., Murua, M. G., Prieto, S., Medina, S., ... and Gastaminza, G. (2010).** Review of the host plants of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Revista de la Sociedad Entomológica Argentina*, *69*(3-4).

**Chapin Iii, F. S., Zavaleta, E. S., Eviner, V. T., Naylor, R. L., Vitousek, P. M., Reynolds, H. L., ... and Díaz, S. (2000).** Consequences of changing biodiversity. *Nature*, *405*(6783), 234-242.

**Chapman, J. W., Williams, T., Escribano, A., Caballero, P., Cave, R. D., and Goulson, D. (1999).** Fitness consequences of cannibalism in the fall armyworm, *Spodoptera frugiperda*. *Behavioral Ecology*, *10*(3), 298-303.

**Chimweta, M., Nyakudya, I. W., Jimu, L., and Bray Mashingaidze, A. (2019).** Fall armyworm (*Spodoptera frugiperda* (J.E. Smith)) damage in maize: management options for flood-recession cropping smallholder farmers. *International Journal of Pest Management*, *66*(2), 142-154.

**Chinwada, P. (2018).** Fall Armyworm Prevalence Assessment in Madagascar. *FAO Mission Report*.

**Çilgi, T., and Jepson, P. C. (1995).** The risks posed by deltamethrin drift to hedgerow butterflies. *Environmental Pollution*, *87*(1), 1-9.

**Cock, M. J., Beseh, P. K., Buddie, A. G., Cafá, G., and Crozier, J. (2017**). Molecular methods to detect *Spodoptera frugiperda* in Ghana, and implications for monitoring the spread of invasive species in developing countries. *Scientific Reports*, *7*(1), 1-10.

**Cruz I. (1992).** Flutuação populacional dodepredador Doru luteipes, agente de controle biológico de *Spodoptera frugiperda* e *Helicoverpa zea*. In: Relatorio técnico anual do centro Nacional de Pesquisa de milho e sorgo 1988-1991. pp. 5-76

**Cruz I. (1995).** A lagarta do cartucho na cultura do milho. *EMBRAPA-CNPMS Circular técnica* 21: 1-45.

**Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., ... and Witt, A. (2017).** Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management*, *28*(5), 196-201.

**De Groote, H., Dema, G., Sonda, G. B., and Gitonga, Z. M. (2013).** Maize for food and feed in East Africa—The farmers' perspective. *Field Crops Research*, *153*, 22-36.

**de Snoo, G. R., and de Wit, P. J. (1998).** Buffer zones for reducing pesticide drift to ditches and risks to aquatic organisms. *Ecotoxicology and Environmental Safety*, *41*(1), 112-118.

**Delabie, J. H. (2001).** Trophobiosis between Formicidae and Hemiptera (Sternorrhyncha and Auchenorrhyncha): an overview. *Neotropical Entomology*, *30*, 501-516.

**Desneux, N., Decourtye, A., and Delpuech, J. M. (2007).** The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, *52*, 81-106.

**Desneux, N., Han, P., Mansour, R., Arnó, J., Brévault, T., Campos, M. R., ... and Biondi, A. (2021).** Integrated pest management of *Tuta absoluta*: practical implementations across different world regions. *Journal of Pest Science*, 1-23.

**Dwomoh, E. A., Afun, J. V., Ackonor, J. B., and Agene, V. N. (2009).** Investigations on *Oecophylla longinoda* (Latreille) (Hymenoptera: Formicidae) as a biocontrol agent in the protection of cashew plantations. *Pest Management Science: Formerly Pesticide Science*, *65*(1), 41-46.

**Early, R., González-Moreno, P., Murphy, S. T., and Day, R. (2018).** Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm.

**Eilenberg, J., Hajek, A., and Lomer, C. (2001).** Suggestions for unifying the terminology in biological control. *BioControl*, *46*(4), 387-400.

**EPPO. (2018).** European and Mediterranean Plant global database. EPPO, Paris, France. https://gd.eppo.int/. Accessed July 5th 2021.

**FAO. (2018).** Integrated management of the Fall Armyworm on Maize; A guide for Farmer Field School in Africa. Accessed April 7th 2021.

**FAO. (2018a).** integrsted management of Fall Armyworm: A guide for farmer Field Schools in AFRica ". Food and Agriculture (FAO) of the United Nations. Accessed July 3rd 2021. http://www.fao.org/3/I8665EN/i8665en.pdf.

**FAO. (2019).** Briefing Note of FAO Actions on Fall Armyworm in Africa: http://www.fao.org/3/a-bs183e.pdf. Accessed July 2nd 2021.

**FAOSTAT. (2021).** Statistical databases and data-sets of the Food and Agriculture Organization of the United Nations. FAO, Rome. http://www.fao.org/faosta. Acessed July 5th 2021.

**Fast, R. B., and Caldwell, E. F. (2000)**. Breakfast cereals and how they are made (No. Ed. 2). American Association of cereal chemists.

**Fatoretto, J. C., Michel, A. P., Silva Filho, M. C., and Silva, N. (2017).** Adaptive potential of fall armyworm (Lepidoptera: Noctuidae) limits Bt trait durability in Brazil. *Journal of Integrated Pest Management*, *8*(1), 17.

**Fening, K. O., MacCarthy, D. S., and Tegbe, R. E. (2020).** Effect of intercropping and soil amendment on the population dynamics of major pests and natural enemies of white cabbage. *West African Journal of Applied Ecology*, *28*(1), 96-112.

**Flagel, L., Lee, Y. W., Wanjugi, H., Swarup, S., Brown, A., Wang, J., ... and Head, G. (2018).** Mutational disruption of the ABCC2 gene in fall armyworm, Spodoptera frugiperda, confers resistance to the Cry1Fa and Cry1A. 105 insecticidal proteins. *Scientific Reports*, *8*(1), 1-11.

**Flores-Gutierrez, A. M., Mora, F., Avila-Cabadilla, L. D., Boege, K., and del-Val, E. (2020).** Assessing the cascading effects of management and landscape on the arthropod guilds occurring in papaya plantations. *Agriculture, Ecosystems and Environment*, *293*, 106836.

**Ge, S. S., He, L. M., Wei, H. E., Ran, Y. A. N., Wyckhuys, K. A., and WU, K. M. (2021).** Laboratory-based flight performance of the fall armyworm, *Spodoptera frugiperda*. *Journal of Integrative Agriculture*, *20*(3), 707-714.

**Goergen, G., Kumar, P. L., Sankung, S. B., Togola, A., and Tamò, M. (2016).** First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PloS one*, *11*(10), e0165632.

**Gómez, J., Guevara, J., Cuartas, P., Espinel, C., and Villamizar, L. (2013).** Microencapsulated *Spodoptera frugiperda* nucleopolyhedrovirus: insecticidal activity and effect on arthropod populations in maize. *Biocontrol Science and Technology*, *23*(7), 829-846.

**Haase, S., Sciocco-Cap, A., and Romanowski, V. (2015).** Baculovirus insecticides in Latin America: historical overview, current status and future perspectives. *Viruses*, *7*(5), 2230-2267.

**Haftay, G., and Fissiha, G. (2020).** Effect of integrating night-time light trap and push-pull method on monitoring and deterring adult fall armyworm (*Spodoptera frugiperda*). *Journal of Entomology Research*, *5*(1), 28-32.

**Harrison, R. D., Thierfelder, C., Baudron, F., Chinmwada, P., Midega, C., Schaffner, U., and Van Den Berg, J. (2019).** Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Mangement, 243, 18-330.*

**Hassell, M. P. (2000).** Host–parasitoid population dynamics. *Journal of Animal Ecology*, *69*(4), 543-566.

**Holling, C. S. (1959).** The components of predation as revealed by a study of small-mammal predation of the European Pine Sawfly1. *The Canadian Entomologist*, *91*(5), 293-320.

**Houngbo, S., Zannou, A., Aoudji, A., Sossou, H. C., Sinzogan, A., Sikirou, R., ... and Ahanchédé, A. (2020).** Farmers' Knowledge and Management Practices of Fall Armyworm, *Spodoptera frugiperda* (JE Smith) in Benin, West Africa. *Agriculture*, *10*(10), 430.

**Hruska, A. (2019).** Fall armyworm (*Spodoptera frugiperda*) management by smallholders. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 14: 1–11.

**Huang, H. T., and Yang, P. (1987).** The ancient cultured citrus ant. *BioScience*, *37*(9), 665-671.

**IFPRI (2014).** International Food Policy Research Institute (Ghana Strategy Support Program, GSSP). Ghana Agricultural News Digest – September 8, 2014. New GSSP policy note prepared by Arhin, B.G.

**International Institute of tropical agriculture (IITA), 2018**. Maize. Available at https://www.iita.org/crops/maize/. Accessed July 4th 2021.

**Jakka, S. R., Shrestha, R. B., and Gassmann, A. J. (2016).** Broad-spectrum resistance to Bacillus thuringiensis toxins by western corn rootworm (*Diabrotica virgifera virgifera*). *Scientific reports*, *6*(1), 1-9.

**Jirnmci, E. (2013).** Efficacy of botanical extracts against termites, macrotermes spp.,(Lsoptera: Termiticlae) under laboratory conditions. Retrived from http:// docsdrive.com/pdfs/academicjournals/ijar/0000/ 57223-57223.pdf.

**Johnson, S. J. (1987).** Migration and the life history strategy of the fall armyworm, *Spodoptera frugiperda* in the western hemisphere. *International Journal of Tropical Insect Science*, *8*(4-5-6), 543-549.

**Jones, R. W., Gilstrap, F. E., and Andrews, K. L. (1988).** Biology and life tables for the predaceous earwig, *Doru taeniatum* (Derm.: Forficulidae). *Entomophaga*, *33*(1), 43-54.

**Jourdie, V., Alvarez, N., Turlings, T. C., and Franck, P. (2009).** Isolation and characterization of polymorphic microsatellite loci in two primary parasitoids of the noctuid *Spodoptera frugiperda*: *Chelonus insularis* and *Campoletis sonorensis* (Hymenoptera). *Molecular Ecology Resources*, *9*(1), 171-173.

**Juliano, S. A. (2001).** Nonlinear curve fitting: predation and functional response curves. *Design and Analysis of Ecological Experiments*, *2*, 178-196.

**Kansiime, M. K., Mugambi, I., Rwomushana, I., Nunda, W., Lamontagne-Godwin, J., Rware, H., ... and Day, R. (2019).** Farmer perception of fall armyworm (*Spodoptera frugiderda* JE Smith) and farm-level management practices in Zambia. *Pest Management Science*, *75*(10), 2840-2850.

**Kassie, M., Wossen, T., De Groote, H., Tefera, T., Sevgan, S., and Balew, S. (2020).** Economic impacts of fall armyworm and its management strategies: evidence from southern Ethiopia. *European Review of Agricultural Economics*, *47*(4), 1473-1501.

**Kenis, M., Du Plessis, H., Van den Berg, J., Ba, M. N., Goergen, G., Kwadjo, K. E., ... and Polaszek, A. (2019).** *Telenomus remus*, a candidate parasitoid for the biological control of *Spodoptera frugiperda* in Africa, is already present on the continent. *Insects*, *10*(4), 92.

**Khadijah, A. R., Azidah, A. A., and Meor, S. R. (2013).** Diversity and abundance of insect species at Kota Damansara community forest reserve, Selangor. *Scientific Research and Essays*, *8*(9), 359-374.

**Klun, J. A., Potts, W. J., and Oliver, J. E. (1996).** Four species of noctuid moths degrade sex pheromone by a common antennal metabolic pathway. *Journal of Entomological Science*, *31*(4), 404-413.

**Koffi, D., Kyerematen, R., Eziah, V. Y., Agboka, K., Adom, M., Goergen, G., and Meagher, R. L. (2020).** Natural enemies of the fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) in Ghana. *Florida Entomologist*, *103*(1), 85-90.

**Kumela, T., Simiyu, J., Sisay, B., Likhayo, P., Mendesil, E., Gohole, L., and Tefera, T. (2019).** Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management*, *65*(1), 1-9.

**Lanza Reis L, Jacob Oliveira L, Cruz I. (1988).** Biologia e potencial de *Doru luteipes* no controle de *Spodoptera frugiperda*. *Pesquisa agropecuaria Brasileira* 23(4): 333-342.

**Lastres Schindler, M. L. (1990).** The role of two predators, *Doru taeniatum* Dorhn and *Solenopsis geminata* F., as control agents of *Spodoptera frugiperda* in Honduras (No. Thesis L349r). Texas AandM University, Austin, TX (EUA).

**Losey, J. E., and Vaughan, M. (2006).** The economic value of ecological services provided by insects. *Bioscience*, *56*(4), 311-323.

**Luginbill, P. (1928).** *The fall armyworm* (No. 34). US Department of Agriculture.

**Maino, J. L., Schouten, R., Overton, K., Day, R., Ekesi, S., Bett, B., ... and Reynolds, O. L. (2021).** Regional and seasonal activity predictions for fall armyworm in Australia. *Current Research in Insect Science*, *1*, 100010.

**Majeed, W., N. Rana, S.U.R. Qamar, S. Nargis, I.A. Raja, S. Kanwal and R. Naseem. (2019**). Diversity of foliage insects around different canal territories: A case study of Dingroo and Kamal Pur canal, Faisalabad, Pakistan. *GSC Biological and Pharmaceutical Sciences*, *6*(1), 07-015.

**Martínez, A. M., Aguado-Pedraza, A. J., Viñuela, E., Rodríguez-Enríquez, C. L., Lobit, P., Gómez, B., and Pineda, S. (2017).** Effects of ethanolic extracts of *Argemone ochroleuca* (Papaveraceae) on the food consumption and development of *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Florida Entomologist*, *100*(2), 339-345.

**Mathenge, M. K., Smale, M., and Olwande, J. (2014).** The impacts of hybrid maize seed on the welfare of farming households in Kenya. *Food Policy*, *44*, 262-271.

**McCord Jr, E., and Yu, S. J. (1987).** The mechanisms of carbaryl resistance in the fall armyworm, *Spodoptera frugiperda* (JE Smith). *Pesticide Biochemistry and Physiology*, *27*(1), 114-122.

**Midega, C. A., Pittchar, J. O., Pickett, J. A., Hailu, G. W., and Khan, Z. R. (2018).** A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (JE Smith), in maize in East Africa. *Crop Protection*, *105*, 10-15.

**Ministry of Food and Agriculture (MoFA). (2017).** *Ghana maize strategy document and investment opportunities or the private sector*. Statistics, Research and Information Directorate (SRID), Accra, Ghana.

**Molina-Ochoa, J., Carpenter, J. E., Heinrichs, E. A., and Foster, J. E. (2003).** Parasitoids and parasites of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas and Caribbean Basin: an inventory. *Florida Entomologist*, *86*(3), 254-289.

**Monnerat, R., Martins, E., Macedo, C., Queiroz, P., Praça, L., Soares, C. M., ... and Bravo, A. (2015).** Evidence of field-evolved resistance of *Spodoptera frugiperda* to Bt corn expressing Cry1F in Brazil that is still sensitive to modified Bt toxins. *PLoS one*, *10*(4), e0119544.

**Montezano, D. G., Sosa-Gómez, D. R., Specht, A., Roque-Specht, V. F., Sousa-Silva, J. C., Paula-Moraes, S. D., ... and Hunt, T. E. (2018).** Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. *African Entomology*, *26*(2), 286-300.

**Nagoshi, R. N., Meagher, R. L., and Hay-Roe, M. (2012).** Inferring the annual migration patterns of fall armyworm (Lepidoptera: Noctuidae) in the United States from mitochondrial haplotypes. *Ecology and Evolution*, *2*(7), 1458-1467.

**Naharki, K., Regmi, S., and Shrestha, N. (2020).** A Review on invasion and management of fall armyworm (*Spodoptera frugiperda*) in Nepal. *Reviews in Food and Agriculture*, 1(1), 6-11.

**Naseem, R., N. Rana, E.B.A. Koch, W. Majeed and S. Nargis. (2020).** Abundance and diversity of foliage insects among different Olericulture Crops. *GSC Biological and Pharmaceutical Sciences*, *10*, 62-69.

**Offenberg, J. (2015).** Ants as tools in sustainable agriculture. *Journal of Applied Ecology*, *52*(5), 1197-1205.

**Oliver, A. D., and Chapin, J. B. (1981).** Biology and illustrated key for the identification of twenty species of economically important noctuid pests (Louisiana agriculture). *Bulletin-Louisiana Agricultural Experiment Station (USA)*.

**Orr, A. (2003).** Integrated pest management for resource-poor African farmers: Is the emperor naked?. *World Development*, *31*(5), 831-845.

**Otim, M. H., Tay, W. T., Walsh, T. K., Kanyesigye, D., Adumo, S., Abongosi, J., ... and Agona, A. (2018).** Detection of sister-species in invasive populations of the fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) from Uganda. *PloS one*, *13*(4), e0194571.

**Oyewo, I. O. (2011).** Technical efficiency of maize production in Oyo State. *Journal of Economics and International Finance*, *3*(4), 211.

**Pannuti, L. E. R., Baldin, E. L. L., Hunt, T. E., and Paula-Moraes, S. V. (2016**). On-plant larval movement and feeding behavior of fall armyworm (Lepidoptera: Noctuidae) on reproductive corn stages. *Environmental Entomology*, *45*(1), 192-200.

**Perfecto, I. (1989).** Ants as biological control agents in the maize agroecosystem in Nicaragua (Doctoral dissertation, University of Michigan).

**Pitre, H. N., and Hogg, D. B. (1983).** Development of the fall armyworm on cotton, soybean and corn (*Spodoptera frugiperda*). *Journal of the Georgia Entomological Society*.

**Pomari, A. F., Bueno, A. D. F., Bueno, R. C. O. D. F., Menezes Junior, A. D. O., and Fonseca, A. C. P. F. (2013).** Releasing number of *Telenomus remus* (Nixon) (Hymenoptera: Platygastridae) against *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in corn, cotton and soybean. *Ciência Rural*, *43*(3), 377-382.

**Prasanna, B. M., Huesing, J. E., Eddy, R., and Peschke, V. M. (2018).** Fall armyworm in Africa: a guide for integrated pest management. Feed the Future Research Program on Maize, 1-120.

**Pritchard, D. W., Paterson, R. A., Bovy, H. C., and Barrios-O'Neill, D. (2017).** Frair: an R package for fitting and comparing consumer functional responses. *Methods in Ecology and Evolution*, *8*(11), 1528-1534.

**Purslow, J. (2004).** Friendly control of bugs. Farmer's Weekly. pp. 140-155.

**Ranum, P., Peña-Rosas, J. P., and Garcia-Casal, M. N. (2014).** Global maize production, utilization, and consumption. *Annals of the New York Academy of Sciences*, *1312*(1), 105-112.

**Reiss, J., Bridle, J. R., Montoya, J. M., and Woodward, G. (2009).** Emerging horizons in biodiversity and ecosystem functioning research. *Trends in Ecology and Evolution*, *24*(9), 505-514.

**Rodríguez–Cabrera, L., Trujillo–Bacallao, D., Borrás–Hidalgo, O., Wright, D. J., and Ayra–Pardo, C. (2010).** RNAi-mediated knockdown of a *Spodoptera frugiperda* trypsin-like serine-protease gene reduces susceptibility to a *Bacillus thuringiensis* Cry1Ca1 protoxin. *Environmental Microbiology*, *12*(11), 2894-2903.

**Rogers, D. (1972).** Random search and insect population models. *The Journal of Animal Ecology*, 369-383.

**Rosegrant, M. R., Ringler, C., Sulser, T. B., Ewing, M., Palazzo, A., Zhu, T., ... and Batka, M. (2009).** Agriculture and food security under global change: Prospects for 2025/2050. *International Food Policy Research Institute, Washington, DC*, 145-178.

**Rwomushana, I., M. Bateman., T. Beale., P. Beseh., K. Cameron., M. Chiluba., V. Clottey., T. Davis., R. Day., R. Early., *et al*., (2018).** Fall armyworm: impacts and implications for Africa: Evidance Note Update. CABI, Wallingford, United Kingdom.

**Shapiro, S. S., and Wilk, M. B. (1965).** An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591-611.

**Sharanabasappa, S., Kalleshwaraswamy, C. M., Poorani, J., Maruthi, M. S., Pavithra, H. B., and Diraviam, J. (2019).** Natural enemies of *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), a recent invasive pest on maize in South India. *The Florida Entomologist*, *102*(3), 619-623.

**Shiferaw, B., Prasanna, B. M., Hellin, J., and Bänziger, M. (2011).** Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, *3*(3), 307-327.

**Shorey, H. H., Summers, C. G., Sisk, C. B., and Gerber, R. G. (1994).** Disruption of pheromone communication in *Spodoptera exigua* (Lepidoptera: Noctuidae) in tomatoes, alfalfa, and cotton. *Environmental Entomology*, *23*(6), 1529-1533.

**Shylesha, A. N., and Sravika, A. (2018).** Natural occurrence of predatory bugs, Eocanthecona furcellata (Wolff) and Andrallus spinidens (Fabr.) on *Spodoptera frugiperda* (Smith) (Hemiptera: Pentatomidae) in maize and their potential in management of fall army worm. *Journal of Biological Control*, *32*(3), 209-211.

**Silva, M. S., Broglio, S. M. F., Trindade, R. C. P., Ferrreira, E. S., Gomes, I. B., and Micheletti, L. B. (2015).** Toxicity and application of neem in fall armyworm. *Comunicata Scientiae*, *6*(3), 359-364.

**Simmons, A. M., and Lynch, R. E. (1990).** Egg production and adult longevity of *Spodoptera frugiperda*, *Helicoverpa zea* (Lepidoptera: Noctuidae), and *Elasmopalpus lignosellus* (Lepidoptera: Pyralidae) on selected adult diets. *Florida Entomologist*, 665-671.

**Sisay, B., Simiyu, J., Malusi, P., Likhayo, P., Mendesil, E., Elibariki, N., ... and Tefera, T. (2018).** First report of the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), natural enemies from Africa. *Journal of Applied Entomology*, *142*(8), 800-804.

**Solomon, M. E. (1949).** The natural control of animal populations. *The Journal of Animal Ecology*, 1-35.

**Sparks, A. N. (1979).** A review of the biology of the fall armyworm. *Florida Entomologist*, 82-87.

**Stern, V. M. R. F., Smith, R., van den Bosch, R., and Hagen, K. (1959).** The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. *Hilgardia*, *29*(2), 81-101.

**Stout, M. J. (2014).** Host-plant resistance in pest management. In: *Integrated pest management* (pp. 1-21). Academic Press.

**Sueldo, M. R., Bruzzone, O. A., and Virla, E. G. (2010).** Characterization of the earwig, *Doru lineare*, as a predator of larvae of the fall armyworm, *Spodoptera frugiperda*: a functional response study. *Journal of Insect Science*, *10*(1), 38.

**Tambo, J. A., Kansiime, M. K., Mugambi, I., Rwomushana, I., Kenis, M., Day, R. K., and Lamontagne-Godwin, J. (2020).** Understanding smallholders' responses to fall armyworm (*Spodoptera frugiperda*) invasion: Evidence from five African countries. *Science of the Total Environment*, *740*, 140015.

**Tendeng, E., Labou, B., Diatte, M., Djiba, S., and Diarra, K. (2019).** The fall armyworm *Spodoptera frugiperda* (JE Smith), a new pest of maize in Africa: Biology and first native natural enemies detected. *International Journal of Biological and Chemical Sciences*, *13*(2), 1011-1026.

**Theiling, K. M., and Croft, B. A. (1988).** Pesticide side-effects on arthropod natural enemies: a database summary. *Agriculture, Ecosystems and Environment*, *21*(3-4), 191-218.

**Thorne, P. J. (2002).** Maize as Food, Feed, and Fertiliser in Intensifying Crop-livestock Systems in East and Southern Africa: An Ex Ante Impact Assessment of Technology Interventions to Improve Smallholder Welfare (Vol. 11). ILRI (aka ILCA and ILRAD).

**UF/IFAS Extension (internet). (2017)** University of Florida's Institute of Food and Agricultural Sciences. This document is EENY098, one of a series of the Department of Entomology and Nematology Retrieved 8th December, 2017 The full report is available at http://edis.ifas.ufl.edu

**Van Mele, P. (2008).** A historical review of research on the weaver ant Oecophylla in biological control. *Agricultural and Forest Entomology*, *10*(1), 13-22.

**Van Mele, P., Vayssières, J. F., Van Tellingen, E., and Vrolijks, J. (2007).** Effects of an African weaver ant, *Oecophylla longinoda*, in controlling mango fruit flies (Diptera: Tephritidae) in Benin. *Journal of Economic Entomology*, *100*(3), 695-701.

**Way, M. J., and Khoo, K. C. (1992).** Role of ants in pest management. *Annual review of Entomology*, *37*(1), 479-503.

**Wyckhuys, K. A., and O'Neil, R. J. (2006).** Population dynamics of *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) and associated arthropod natural enemies in Honduran subsistence maize. *Crop Protection*, *25*(11), 1180-1190.

**Xiao, Y., and Fadamiro, H. Y. (2010).** Functional responses and prey-stage preferences of three species of predacious mites (Acari: Phytoseiidae) on citrus red mite, *Panonychus citri* (Acari: Tetranychidae). *Biological Control*, *53*(3), 345-352.

**Xiao, Y., and Wu, K. (2019).** Recent progress on the interaction between insects and *Bacillus thuringiensis* crops. *Philosophical Transactions of the Royal Society B*, *374*(1767), 20180316.

**Yu, S. J., Nguyen, S. N., and Abo-Elghar, G. E. (2003).** Biochemical characteristics of insecticide resistance in the fall armyworm, *Spodoptera frugiperda* (JE Smith). *Pesticide Biochemistry and Physiology*, *77*(1), 1-11.

**Zeng, G., Zhi, J. R., Zhang, C. R., Zhang, T., Ye, J. Q., Zhou, L., ... and Ye, M. (2021).** *Orius similis* (Hemiptera: Anthocoridae): A Promising Candidate Predator of *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Economic Entomology*, *114*(2), 582-589.

**Zhang, L., Liu, B., Zheng, W., Liu, C., Zhang, D., Zhao, S., ... and Xiao, Y. (2020).** Genetic structure and insecticide resistance characteristics of fall armyworm populations invading China. *Molecular Ecology Resources*, *20*(6), 1682-1696.

**Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., and Swinton, S. M. (2007).** Ecosystem services and dis-services to agriculture. *Ecological Economics*, *64*(2), 253-260.

**Zhu, Y. C., Blanco, C. A., Portilla, M., Adamczyk, J., Luttrell, R., and Huang, F. (2015).** Evidence of multiple/cross resistance to Bt and organophosphate insecticides in Puerto Rico population of the fall armyworm, *Spodoptera frugiperda*. *Pesticide Biochemistry and Physiology*, *122*, 15-21.