

**ALTITUDE AND FARMING SYSTEM AS DRIVERS FOR OCCURRENCE OF
BIOLOGICAL CONTROL AGENTS AND YIELD IN COFFEE FIELDS
OF MOUNT ELGON REGION IN UGANDA**

BY

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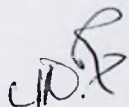
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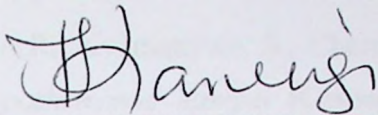
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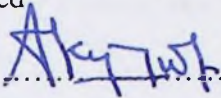


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The articles below, were drafted from different thesis chapters

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DEDICATION

This work is dedicated to PhD fellows, friends and family members for the good support you all accorded me; socially, technically and morally during the challenging and joyful moments of my academic journey.

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ABSTRACT

The Mount Elgon coffee farmlands exist in mosaical patterns with banana, annual crops, and semi natural vegetation with a hierarchy of bio-physical characteristics conferred by altitudinal positioning and cropping intensity. Insect pests are one of the key challenges in coffee production, further exacerbated by the rising temperatures that are known to favor the coffee berry borer (*Hypothenemus hampei*), a key pest. It is not yet clear to what extent such abiotic factors, which drive insect pests' dynamics are influenced by the existent farming systems, altitudinal positioning, and dynamics of associated natural biological control agents.

The objectives of this study were to: i) To determine the effect of altitude and farming system, on the occurrence of the parasitoid complex of the coffee berry borer in the mount Elgon Region (MER), ii) To determine the effect of farming system and altitude on occurrence and distribution of the predatory Carabidae, and the association to the coffee aphids (*Toxoptera aurantii*) in the MER, and iii) To determine the most suitable farming system for high coffee foliage and coffee bean yield performance at the different altitudes in the MER.

The study was set up in Kapchorwa and Sironko, districts of the MER. The selected coffee fields in the study were delineated by two factors: altitude at three levels: lower (1400-1499 m.a.s.l); mid (1500-1679); and high (1680-2100); and coffee farming system at four levels: Coffee monocrop; Coffee+annual crop; Coffee+banana; and Coffee+banana+shade trees with three replications of each farming system. A total of 72 coffee fields were sampled in the longitudinal study for two years.

With regard to the key natural enemies (parasitoids) of the coffee berry borer, results revealed highly significant interactions between altitude and farming system in influencing *H. hampei* field infestation ($F_{df\ 6;\ 2146} = 20.39$; $P < 0.001$) and the abundance of the four parasitoids recorded namely: *Phymastichus coffea* ($F_{df\ 6;\ 130} = 11.48$; $P < 0.001$); *Cephalonomia stephanoderis* ($F_{df\ 6;\ 130} = 0.96$; $P < 0.001$); *Prorops nasuta* ($F_{df\ 6;\ 130} = 5.67$; $P < 0.001$) and *Heterospilus coffeicola* ($F_{df\ 6;\ 130} = 3.6$; $P = 0.002$). Highest level of *P. nasuta* emergence from the reared berries was at high altitude within the Coffee + banana system (78 ± 7.1); *C. stephanoderis* emergence (73 ± 3.5) was highest in the mid altitudes within Coffee + banana+shade tree system; *P. coffea* (58.3 ± 3) in the

mid altitudes within the Coffee+banana farming system; and *H. coffeicola* (13.0 ± 0.9) in the high altitudes within the Coffee+annual crop.

Microclimate and semi natural vegetations had specific and significant relationships with the abundance of parasitoids. Of the four parasitoids, *C. stephanoderis* had a positive relationship to semi-natural vegetation species counts ($t=2.778$, $SE=0.093$, $P=0.006$); *P. coffea* had a negative relationship with temperature ($t=-4.209$, $SE=0.015$, $P<0.000$); *P. nasuta* had a negative relationship with temperature ($t=-2.620$, $SE=0.013$, $P=0.010$); *H. coffeicola* had a positive relationship to light intensity ($t=2.389$, $SE=0.000$, $P=0.018$) and a negative relationship to temperature ($t=-2.707$, $SE=0.011$, $P=0.008$). These relationships contrasted that of *H. hampei*, which was positively related to temperature ($t=5.503$, $SE=0.057$, $P<0.000$); negatively related to light intensity ($t=-1.984$, $SE=0.001$, $P=0.049$) but with no significant relationship to vegetative species counts. *P. coffea* caused the highest parasitism rates for the coffee berry borer in the Coffee + banana farming system (54%); *C. stephanoderis* (52%) achieved highest parasitism at mid altitude in the Coffee + banana system+ shade trees systems.

The predatory Carabidae beetles revealed highly significant interactive effects of altitude and farming systems on the occurrence of three genera: *Anisodactylus*, *Chlaenius*, and *Harpalus*. The abundance of *Harpalus* spp. were highest at lower altitudes in Coffee monocropped farming systems (165 ± 4); *Anisodactylus* spp. were more abundant at higher altitudes in Coffee+annual crop systems (144 ± 2); while *Chlaenius* spp. were highest in the Coffee+banana+shade tree system at mid altitudes (22 ± 0.5). *Anisodactylus* spp. had a significant positive relationship to soil moisture ($t=2.58^{**}$, $SE=1.5$); *Harpalus* spp. had a significant positive relationship to soil EC ($t=5.30^{***}$, $SE=1.27$) while *Chlaenius* spp. had a significant negative relationship to soil pH ($t=-2.19^{*}$, $SE=0.133$). It was only *Chlaenius* spp. which had a significant positive relationship with the semi natural vegetation ($t=2.37^{*}$, $SE=0.176$). In the predator-pest relationship with the coffee aphid *Toxoptera aurantii*, a biplot showed that the aphid correlated highly and negatively to all the three Carabidae (*Anisodactylus* spp. *Chlaenius* spp. and *Harpalus* spp.).

For the effect of farming system on coffee foliage and coffee bean yield performance, the highest number of coffee leaves/branch were on farms with Coffee+annual cropping. Coffee bean yields were highest in the Coffee+banana+shade trees, specifically at low altitude. PCA results revealed

a strong relationship of temperature, and relative humidity with the clean coffee bean yield and leaves per branch.

This study recommends that: i) to reduce infestation of the coffee berry borer and promote the occurrence of the Hymenopteran parasitoids that regulate the pest, growers should embrace the Coffee+banana+shade trees system farming systems that buffer rising temperatures. This is especially relevant for farmers in the range of 1400-1499 m.a.s.l; ii) to promote the generalist predatory Carabidae beetles especially *Anisodactylus*, *Harpalus* and *Chlaenius* species, which regulate the coffee aphid and other hemipteran pests on coffee, growers should adopt practices that enhance soil moisture retention through maintaining good ground cover and/or inclusion of shade trees+banana in their fields; and iii) Growers are urged to embrace innovative ways of introducing semi natural vegetation in their coffee fields/proximity to promote biological control agents like the Carabidae beetles and the parasitic wasps so as to increase the unit productivity/yields of coffee farms. Semi natural vegetation can be incorporated in form of diverse hedges, borders, road reserves, and if possible, by letting adjacent plots to fallow in some periods.

CHAPTER ONE

INTRODUCTION

1.1 Background

Coffee (*Coffea* spp.) is the world's most important beverage that is grown as a cash crop in seventy tropical and subtropical countries worldwide (Rutherford & Phiri, 2006; Uganda Coffee Trade Federation, 2011). Over seventy percent of its production is done by small scale farmers on land parcels of 1-2 acres (Baker, 2002; Rutherford & Phiri, 2006). Uganda is the second largest coffee producer and exporter in Africa, next to Ethiopia (UCTF, 2011). Coffee production contributes a lot to Uganda's economy with close to four million Ugandan households engaged in coffee production. It plays a significant role in foreign exchange earnings, bringing in over 192 million dollars annually (UCTF, 2011).

There is a growing demand for Uganda's specialty coffee, and the country is striving to intensify its coffee production to attain export volumes of 25 million bags with earnings above 853 million dollars per annum by 2025 (Uganda Coffee Development Authority, 2019). However, the biggest challenge to the industry is the stagnating coffee yields, which are mainly due to coffee pests and diseases. Among the key pests are the coffee berry borer, the white stem borer (Jonsson *et al.*, 2014); and a complex of sucking pests (Karungi *et al.*, 2015).

The coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Scolytidae), is a key pest in coffee farming, causing devastation of coffee plantations with huge yield losses since it affects the harvestable product (Baker, 2002; Rutherford & Phiri, 2006; Jaramillo *et al.*, 2010; Jaramillo, 2012). Control measures are challenged by its feeding habits and the nature of its life cycle, which is confined inside the coffee berries (Baker, 2002). Previously effective chemical control measures using organochlorine insecticides such as endosulfan have been frustrated by bans due to their residual effects in the environment (Rutherford & Phiri, 2006). Chemical use is also challenged as it kills off natural enemies and exposes coffee to damage due to secondary pests (Rutherford & Phiri, 2006).

Toxoptera aurantii (Hemiptera: Aphidadae) is an emerging pest of coffee adding to the sucking pest complex of coffee that includes scales, antestia bugs, and mealybugs (Karungi *et al.*, 2015;

Deng *et al.*, 2019). It causes leaf loss and general loss in coffee vigour (Ogunrinde & Adebajo, 2007; Guidolin & Consoli, 2018). The pest has high preference for warmer conditions and its continued presence on crops contributes to high crop losses (Ogunrinde & Adebajo, 2007). Instituted control measures are challenged by rapid reproduction rates for every surviving individual (Ogunrinde & Adebajo, 2007).

Due to the lucrative nature of coffee, especially specialty coffee, strategies that manage important coffee pests with a focus on manipulation of agroecology can offer the best scenario for increasing production and export promotion (UCDA, 2015; 2019). Increased coffee productivity can be made sustainable with clear insights to its farming environment. Altitude, proximity to natural vegetation, and farming system are key factors in Arabica coffee agro ecologies that are attracting attention (Liebig *et al.*, 2016; Karungi *et al.*, 2018).

Altitude designates coffee production in Uganda into two types, namely Robusta coffee (*Coffea canephora*) which is grown at low to mid-level altitudes (1000-1400 m.a.s.l), and, Arabica coffee (*Coffea arabica*), which predominates the slopes above 1500 m.a.sl. (Geleta *et al.*, 2012; Gitonga *et al.*, 2014). Arabica coffee is majorly produced on the mountain slopes of Mt. Elgon (1300-2200 m.a.s.l) in eastern Uganda; where it is grown as a monocrop or in mixed crop farming systems comprising of annual crops or banana and shade trees in different intensities and inclusions (Liebig *et al.*, 2016; Karungi *et al.*, 2018). Coffee density in the Mount Elgon region (MER) is quantified at 2255 plants per hectare in unshaded systems; 2094 coffee plants and 1496 banana plants per hectare in banana shaded systems (Liebig *et al.*, 2016). Inclusions of shade tree species helps modify soil quality and microclimate; and these in turn reduce plant stress and improve partitioning for grain filling (Rao *et al.*, 2000; Varon *et al.*, 2007). Annual crops that are usually intercropped with Arabica coffee include beans, groundnuts, maize, onions, cassava, potatoes and some leafy vegetables (Bamutaze, 2010; Ayanu *et al.*, 2015).

In addition to shade trees, there are parcels of semi natural/natural vegetation within coffee farming systems that include fields under fallow, live hedges/fences, grass borders and tree lots. Semi natural vegetations contribute natural habitats for biological control agents such as the hymenopteran parasitoids (parasitic wasps) and generalist predators such as the Carabidae ground beetles (Bianchi & van der, 2004; Bianchi *et al.*, 2006). Abundance, diversity and efficacy of the natural insect regulators can be influenced by the micro conditions as a result of

quantities and quality of semi natural vegetation in the vicinity of cropped land (Bianchi & van der, 2004; Bianchi *et al.*, 2006). Existing portions of semi natural vegetations in a coffee environment act as modifiers of micro conditions which favor the breeding cycles of the biological control agents (Bianchi & van der, 2004; Bianchi *et al.*, 2006). Semi natural vegetations contribute to increased floral diversity for increased pollination services, soil erosion control and soil moisture availability for increased coffee yields. Therefore, increased physical presence of natural and semi natural vegetation ensures favorable conditions for the success of biological control interventions and better yields. Retaining bigger portions and better quality of the semi natural vegetation is a factor of anthropogenic and awareness aspects (Erbaugh *et al.*, 2006; Eco Trust, 2012; Andersson, 2014; National Population and housing report, 2014).

1.2 Problem statement

The mount Elgon region in Uganda is faced with shortages of food, and land degradation due to an ever-increasing population spanning over 526 persons/km² (National Population and housing report, 2014). There is a steady loss of natural vegetation in favor of food and coffee benefits. The area records 72% loss in grassland, 63% in wood land and 41% in tree cover (EcoTrust, 2012; Andersson, 2014). These have progressively been replaced by small holder farmlands up the slopes of the mountain with no clear rejuvenating plans for effective vegetative cover (EcoTrust, 2012; Andersson, 2014; National Population and housing report, 2014). The incessant replacement of natural vegetation with coffee dominated farmlands to a level up to 2500 m.a.s.l. (Erbaugh *et al.*, 2006; EcoTrust, 2012; Andersson, 2014; National Population and housing report, 2014.) is reported to cause a loss in natural enemy diversity and such losses exacerbates insect pest problems in coffee (Bianchi & van der, 2004; Bianchi *et al.*, 2006). Levels of pest damage on coffee by specific insects are high in the MER with cases in point including leaf miners (Jassogne *et al.*, 2013), the white coffee stem borer, coffee berry borer (Jonsson *et al.*, 2014), and of the hemipteran complex (Karungi *et al.*, 2015). The coffee farming systems and their interactions with altitude and how they influence pest infestations and microclimate is not well understood and should be investigated.

A number of studies, notably, Jonsson *et al.* (2014) and Karungi *et al.* (2015) have reported that temperature could be playing a role in the changes in pest dynamics. Jonsson *et al.* (2014) reported a 17 percent increase in *Hypothenemus hampei* (Coffee berry borer) incidence per every

degree drop of altitude and increase in temperatures in the MER. What is not yet clear is how higher temperature conditions can be modified by the coffee farming system used in the MER.

On the other hand, the high pest occurrence and damage may be a result of inadequate natural control brought about by disturbances in the natural vegetation system. It is indeed reported that loss in natural vegetation to arable cropland eliminates habitats of natural control agents with subsequential narrowing of biodiversity and biological control services (Tscharntke *et al.*, 2005; Bianchi *et al.*, 2006). In the MER, there has been documentation of existing multiple parasitic wasps (Hymenoptera) of the coffee berry borer *H. hampei* (Ijala, 2015). What is not yet understood is how the coffee farming systems in the MER is influencing effectiveness of the Hymenopteran parasitoid complex. How does the choice of a coffee farming system at different altitudes on the mountain slopes influence the bio-physical environment, abundance and diversity of the Hymenopteran parasitoid complex?

For insect pests that do not have documented effective parasitoid complex, predators are often the biological control agent of emphasis. Carabidae beetles have been shown to contribute greatly to hemipteran pest management (Edwards *et al.*, 1979; Loughridge & Luff 1983; Chiverton, 1987; Lovei & Sunderland, 1996; Ogunrinde & Adebajo, 2007) but at the same time are believed to be sensitive to microclimate (Lindroth, 1969; Bassett, 2009). In the MER and Uganda in general, there are several outstanding gaps in the knowledge of the biological insect pest control agents such as Carabidae beetles. Also, it is not clear whether they exist in optimal populations in the coffee farmlands in the MER and which species are present in the MER. In addition, what is the distribution of the Carabidae beetles with respect to altitude and Farming systems?

Pest control notwithstanding, there is a need to promote higher coffee bean yields and coffee quality in the MER. Other than anecdotal reports, it is not well known which of the prevailing coffee farming systems produce higher and quality coffee berries.

Therefore, to make recommendations for sustainability of the Arabica coffee farmlands in MER and Uganda in general, there is need to understand which coffee system is suitable for which altitude and also which one offers greater productivity and stability for agents of biological control services, and higher coffee yields.

1.3 Objectives of the study

1.3.1 Main Objective

The main objective of this study was to contribute to the development of sustainable approaches for improved productivity of smallholder Arabica coffee systems through generation of knowledge on how microclimate; occurrence and effectiveness of biological control agents, and yield are influenced by the biophysical environment created by the interaction of altitude and farming system.

1.3.2 Specific Objectives

The specific objectives of the study were:

- I. To determine the effect of altitude and farming system on the occurrence of the parasitoid complex of the coffee berry borer (*Hypothenemus hampei*) in the MER
- II. To determine the effect of farming system and altitude on the occurrence and distribution of the predatory Carabidae species, and their association to the coffee aphids (*Toxoptera aurantii*) in the MER
- III. To determine the most suitable farming system for high coffee foliage and bean yields at different altitudes in the MER

1.4 Hypotheses

- I. High temperatures at the lower altitudes are increasing numbers of *Hypothenemus hampei* parasitoids in the cooler, higher altitudes in the MER
- II. Perennial Coffee farming systems with banana/shade trees have higher *Hypothenemus hampei* parasitoids occurrence and parasitism rates than in the often-disturbed coffee-annual crop farming systems
- III. The abundance of hymenopteran parasitoids is more associated with microclimate conditions than semi natural vegetation in the MER
- IV. Coffee fields maintained by grass slashing have higher generalist Carabidae activity than often tilled Coffee+annual crops system

- V. The abundance of *T. aurantii* is more associated to higher Carabidae occurrence in the coffee monocrop fields than in the tree shade coffee fields of the Mount Elgon region (MER)
- VI. Soil properties are more important than the semi-natural vegetation diversity in determining the occurrence of generalist Carabidae in the coffee farm lands of the MER.
- VII. Growing coffee in the lower altitudes can promote higher incidences of coffee pests', coffee foliage and bean yields performance than in the upper altitudes of the mount Elgon farming system

CHAPTER TWO

LITERATURE REVIEW

2.1 Ecological requirements and challenges in coffee production

Coffee trees are glossy leaved evergreen dicotyledons which are adapted to forest conditions (Davis *et al.*, 2006; Waller *et al.*, 2007). It is believed that the two most important species of the genus, *Coffea* (*Coffea arabica* and *Coffea robusta*) are traced and associated to forested landscapes (ASARECA, 2006). Origins of *Coffea arabica* are traced to the area between the Ethiopian highlands adjacent to the Boma plateau, south Eastern Sudan, and Marsabit in Northern Kenya, while *Coffea robusta* is traced to the forested areas of West and Central Africa (Waller *et al.*, 2007). These infer that the forested landscapes and highland areas are key environmental features for coffee growing.

In Uganda, Arabica coffee (*Coffea arabica*) and Robusta coffee (*Coffea canephora*) are produced in the ratio of 1:4. *Coffea robusta* grows well in low to midlevel altitude areas between 1200-1500 meters above sea level, while Arabica coffee grows well in the mountainous slopes of 1500-2300 m above sea level (Rutherford & Phiri, 2006). Arabica coffee requires annual rainfall of 1100-2000 mm with a 3–4month dry spell, on deep friable soils with a pH of around 7 and average temperature of 15-25°C (Chaner & Eskeys, 2004). *Coffea arabica* flowers whenever moisture stress is released, and the coffee ripens within 6-9 months. The best yields are reported under shady, seasonally moist and mulched conditions. Mulch can reduce stress, and induce multiple stem branching for subsequent bearing in the next season (Waller *et al.*, 2007).

In Uganda, Arabica coffee is strategically maintained on the slopes of mount Elgon, Mt. Rwenzori and Mt. Muhabura (UCTF, 2011). The Bugisu coffee is grown by small scale farmers on the slopes of Mt. Elgon making use of natural water gullies and forest cover (UCTF, 2011). Coffee farms are under sunny conditions or are intercropped with different tree species or with food crops such as bananas or annual crops (EcoTrust, 2012; Jonsson *et al.*, 2014, Karungi *et al.*, 2015). Intercrops are believed to increase the coffee productivity for better yields (EcoTrust, 2012).

Arabica coffee productivity in Uganda is constrained by abiotic stress, management consequences, and ravages of pests and diseases (EcoTrust, 2012; UCDA, 2019). That notwithstanding, there is an ever increasing population of human settlements that is narrowing the available land for production and causing land fragmentations up the slopes. The uncontrollable encroaches into conserved areas reduces seminatural vegetations, increases soil erosion, and causes loss of soil fertility (Staver *et al.*, 2001; Teodoro *et al.*, 2008). Other constraints include unproductive old coffee trees, and low coffee tree plant density.

Among the challenges, losses of Arabica coffee to pests and diseases approximate 30 – 40% annually, in Uganda (Rutherford & Phiri, 2006; Perfecto, 2007; Lin, 2011). Coffee borers, sucking pests and fungal disease complexes have a heavy impact on the coffee yields. The coffee berry borer which affects the harvested economic berries and the emerging complexes of sucking pests like coffee aphid which directly impact on seasonal yield, pose a great threat to the coffee industry (Rutherford & Phiri, 2006; Jonsson *et al.*, 2014, Karungi *et al.*, 2015; Ijala, 2015). Therefore, a deeper understanding of the coffee berry borer, the sucking pests such as the coffee aphid and their natural enemies in the Mount Elgon area is very paramount.

2.2 Biology, ecology and behavior of the coffee berry borer, and its parasitoid complex

The coffee berry borer (CBB) (*Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae) is believed to have originated from Central and Eastern Africa (Ticheler, 1961). In Africa, CBB is a problem in the east, central and west; attacking all the coffee types grown. Coffee berry borer infestation causes premature fall of berries and sometimes total berry loss. In other cases, the berries may still be attached until harvest but with reduced weight, lower quality and impaired flavor (Baker, 2002; Rutherford & Phiri, 2006).

Coffee berry borer is a beetle with less than 2 mm length and 1 mm wide. The adult female bores the light green coffee berries, lays eggs and lives a tiny round entrance holes (1 mm in diameter) close to the apex (tip). Normally, one entrance hole is present per berry. However, when berries are scarce, several holes may be made by more than one female (Rutherford & Phiri, 2006). Over a period of about three weeks, the larvae pass through either two for male or three for female instars before pupating to progress to adults. The development period from egg to larva takes 8-10 days, larva to pupa 14-21 days and pupa to adult 7-8 days (Fig 2.1). Cues such as moisture

levels, high temperature and exhaustion of the endosperm trigger off CBB flights either in the evening or morning hours for better niches (Baker, 2002; Rutherford & Phiri, 2006).

Oviposition on immature berries is often abandoned and those berries may be attacked by bacteria and fungi. Females can lay 31-119 eggs within a single berry and male beetles remain within the berry to mate with females (Barrera, 1994; Rutherford & Phiri, 2006). The adult beetles have a lifespan of up to 282 days (females) and for males 103 days (Rutherford & Phiri, 2006). Ground fallen berries are over wintering places for fresh infestations. The pest utilizes wild coffee trees and pods of some leguminous crops as alternate hosts making it more challenging with regards to its control (Barrera, 1994; Waterhouse & Norris, 1989; Baker, 2002; Rutherford & Phiri, 2006).



Figure 2.1. Life stages of *Hypothenemus hampei* Ferrari; Adult (a), Pupa (b), Larva (c) and (d) Eggs (Rutherford & Phiri, 2006)

Four Hymenopteran wasps are documented to effectively parasitize CBB in MER of Uganda: *Cephalonomia stephanoderis* Betrem (Hymenoptera: Bethyridae), *Prorops nasuta* Waterston (Hymenoptera: Bethyridae), *Heterospilus coffeicola* Schemiedeknecht (Hymenoptera: Braconidae) and *Phymastichus coffea* LaSalle (Hymenoptera: Eulophidae) (Rutherford & Phiri, 2006).

The Bethyrid, *P. nasuta*, first reported in Uganda by Waterston (1923) is an idiobiont solitary ectoparasitoid. It lays its eggs externally on the last instar larva or pupa and feeds on and paralyzes the pupa and the adult stages. Development from egg to adult takes 27 days for females and 30 days for males (Abraham *et al.*, 1990; Infante *et al.*, 2005; Jaramillo *et al.*, 2009). It enters the berry and searches for borers to parasitize and feed on; it kills and uses the dead adult borer to seal the entry hole. Like other Bethyrid parasitoids, *P. nasuta* is also sensitive to

interspecific competition, and this interferes with its parasitism potential (Batchelor *et al.*, 2005; 2006). Proper understanding of the environmental conditions favoring the performance of *P. nasuta* could boost its use in the biological control of CBB.

Another Bethyloid, *C. stephanoderis* is of African origin discovered in Ivory coast (Betrem, 1961; Ticheler, 1961). It is widely distributed in most countries in Africa and America with CBB problems (Infante *et al.*, 1994). The larval-pupal ectoparasitoid is also known to prey/feed on the eggs and the adult beetle. The adult emerges within 23 days and can survive for 4-5 days with or without foodstuff (Abraham *et al.*, 1990; Lauzière *et al.*, 1999; Infante *et al.*, 2005). The efficacy of the parasitoid in the field conditions is often interfered by interspecies competition in the presence of other Bethyloids (Batchelor *et al.*, 2005, 2006).

The most promising parasitoid is an Eulophid, *P. coffea*, which actively searches for the female borer for oviposition before its penetration and causes its impairment. The parasitoid develops and matures within the host in 38 days (Baker, 1999; Feldhege, 1992; Infante *et al.*, 1994). The parasitoid has a good record of lowering CBB in field conditions (Gutierrez *et al.*, 1998). Making use of its earlier successes could inform the control strategy for CBB in the Mt. Elgon area.

The Braconid, *H. coffeicola*, also first reported in Uganda (Hargreaves, 1935) lays one egg per berry and its larvae can consume the eggs and juveniles of *H. hampei*. Earlier studies have reported its population and effectiveness to be more responsive to the quality of the environment (Hargreaves, 1926; Baker, 1999). It has been documented with challenges of survival under laboratory cultures (Murphy *et al.*, 2001; Kucel *et al.*, 2004).

Despite the existence of these parasitoids in East Africa, their spatial locations on the mountains and farming systems of MER have not been very clear and this study attempts to create better understanding of their distribution patterns for optimal agricultural benefits.

2.3 Biology, ecology, behavior and *Toxoptera aurantii*; damage on coffee

Toxoptera aurantii (Boyer de Fonscolombe, 1841; Hemiptera: Aphididae) is an emerging and less studied pest on coffee. It is a small black aphid 2 - 3 mm long. The small dark brown nymphs are similar to adults in color, though adults have a globoid, dark green or black body, with or without wings. The apterous females with a pair of cornicles on the back of the body are

larger (2.0–2.1 mm) than winged ones (1.7–1.8 mm). The male aphids are winged and rarely seen. Mature females reproduce by parthenogenesis and are viviparous. Apterous females may each produce up to 50 female nymphs within seven days and the development from nymph to adult takes six days under favorable temperature of 25°C or thereabouts (Ogunrinde, & Adebajo, 2007). With favorable conditions of temperature and relative humidity, winged females disperse and colonize new plants. They start sucking sap from young shoots immediately after they emerge and the associated damage on developing shoots can be seen.

T. aurantii infests leaves, buds and other tender parts of the coffee plant causing coiled, deformed and curled leaves. Reduced growth, leaf and flower drop may follow (Ogunrinde, & Adebajo, 2007). The aphids normally excrete honeydew which favors the growth of sooty mold fungus (blackish appearance). The honeydew is highly preferred by ants, which guard the aphids from predation/parasitism and transport them to favorable plant parts (Ogunrinde, & Adebajo, 2007). Considerable yield reduction has been reported with severe and prolonged attacks particularly in flowering and fruiting coffee trees (Ogunrinde, & Adebajo, 2007).

Warmer humid conditions have been reported to favor aphids continued presence on crops (Ogunrinde, & Adebajo, 2007; Piron *et al.*, 2019). Relative humidity alone can influence the aphids' physiological development (Tomar, 2010); and the impacts of relative humidity on the vegetative growth of the coffee trees can subject the crop to the likely damage by the aphids (Coste, 1992; Waller *et al.*, 2007; Dosta'lek *et al.*, 2018). So, studies that delve on how microclimate in different Farming systems and different altitudes levels impact on the pest and its natural enemies could throw light on management protocols.

2.4 Biology, Ecology and Behavior of the Carabidae

Ground beetles in the Carabidae family of Coleopteran insects are well documented generalist biological control agents in crop fields, devouring smaller insects that they encounter in their searches on the ground and up the foliage (Lovei & Sunderland, 1996). Carabid beetles exhibit complete metamorphosis (egg, larva, pupa and adult) with one generation per year. The females look for a suitable site (within the soil or plant residue) and singly can deposit up to 600 oval eggs (Lovei & Sunderland, 1996). The young larvae are soft bodied with limited mobility and high vulnerability. Much parental care and egg guarding is often observed in most species that produce small litters (Lovei & Sunderland, 1996). Adults can live up to four years or more

(Lovei & Sunderland, 1996). Most adult ground beetles have functional wings but flight is often for dispersal, living their entire lives on the ground walking with some bits of plant climbing in search of prey.

The beetles are primarily predatory and locate food by random search. A few species are known to detect chemical cues from mollusks and aphids (Lovei & Sunderland, 1996). Both the larvae and adults are predators and prey preferences can change throughout their life cycle depending on their nutritional needs and environmental conditions (Lovei & Sunderland, 1996).

Carabid beetles largely contribute to insect pest regulation as generalists' predators, feeding up to their body weight daily of insect pests (aphids and cutworms), the most destructive pests of coffee seedlings (Lovei & Sunderland, 1996; Kromp, 1999). The Carabidae are capable of reducing damage on crops by aphids by 40% (Kromp, 1999; Tooley & Brust, 2002). Among the Carabidae genus associated with aphid feeding includes *Chlaenius*, *Anisodactylus* and *Harpalus* (Laroche 1990; Menalled *et al.*, 2007; Leslie *et al.*, 2009). These Carabidae are favored by their phenology which enables them to climb and fly on top of plants for aphid searches (Chiverton 1987; Snyder & Ives, 2001).

2.5 Altitude as a driver of occurrence of insect pests and their biological control agents and yield in coffee systems

Microclimatic intensities at specific altitude levels which are constituted by ambient temperatures, relative humidity and light; create selective situations on the insect pests and their biological control agents (Rao *et al.*, 2000; Varon *et al.*, 2007).

2.5.1 The effect of altitude and its microclimates on occurrence of *H. hampei* and its parasitoids

Increasing temperatures acting at specific locations have been reported as the key driver pushing *Hypothenemus hampei* infestations. Jaramillo *et al.* (2011) indicated that a 1-2°C increase in temperature led to an increased number of generations, dispersion and damage by the *H. hampei*. Coffee berry borer population flare ups are exacerbated by increasing trends in temperatures and solar exposures (Jonsson *et al.*, 2014). There is a 1.5-2°C difference in temperature between low and high altitude farms in the MER (Karungi *et al.*, 2018).

Altitudes with high relative humidity result into cooler micro conditions which favor the breeding cycles for the parasitoids with higher parasitism rates of coffee berry borer (Jaramillo *et al.*, 2009). These cooler conditions with high relative humidity have been reported only in mid altitudes (Karungi *et al.*, 2018). How modifications in Farming system along the altitude could influence CBB parasitism by the existing natural enemies amidst the global microclimate changes could be the herald of success of biological control especially in the lower altitudes.

2.5.2 The effect of altitude and it's microclimate on the abundance of Carabidae

Altitude and its abiotic constituents can be very important predictors of Carabid abundance and diversity; and also, can explain species composition (Bassett, 2009). Higher diversity and abundance of Carabids is often reported on the upper elevations. For example, elevation changes affected the ground beetle composition in British Columbia (Bassett, 2009). Levels of altitude influence the degree of slope and the resultant quality and quantity of soil deposition. Soil erosion and leaching which are accelerated by steep levels especially on bare mountains can lead to thin soils. The thickness and quality of top soil which is normally exacerbated by effects of soil erosion can influence the shape and arrangements of human settlements up the mountains. Increased human activity up the hills can lead to intensification and fragmentations. The layout and shape of fragmented fields at a given altitude have been found to affect movements and colonization patterns of herbivores and predators within farm locations (Paoletti & Lorenzoni, 1989; Koivula *et al.*, 1999; Koivula, 2011). Carabids which are very important bio indicators and biological control agents in agro ecosystems normally live on the top soil surface, and prey on a wide range of insects (Welsh, 1990; Aviron *et al.*, 2005; Liu *et al.*, 2015). Local and altitude factors may affect the functional groups of Carabids differently which in turn may determine their efficiency in predation of important coffee pests (Welsh, 1990; Aviron *et al.*, 2005; Liu *et al.*, 2015). Most Carabids disperse within 50m radius and respond to landscape structure at fine spatial scales. It has been reported that large predatory Carabids have a strong association with altitude levels (Welsh, 1990; Aviron *et al.*, 2005; Liu *et al.*, 2015).

2.5.3 Effect of altitude and it's microclimate on coffee foliage and bean yield performance

Altitude with it's abiotic constituents (temperature, relative humidity) play a very crucial role in determining the leaf biomass and the potential yields of coffee. The magnitude of abiotic factors along the altitude can influence chemical and physiological changes that trigger vegetative

growth, flowering, fruiting, deposition in sinks which tantamount to leaf biomass and yield accumulation (Carver, 2007; Anhar *et al.*, 2020). Specific sinks of amino-acids, and sugars. and a complex of secondary repellent compounds are influenced at variable rates along the altitude. These can be exacerbated at extreme altitudes causing implications on coffee yields (Carver, 2007; Anhar *et al.*, 2020). Altitude could specifically influence certain plant parts notably leaf thickness, increased depth and changed composition of the waxy cuticle, altered size of resin ducts and reduced intercellular airspace in the leaf mesophyll which influence the leaf biomass (Hullé *et al.*, 2010; Chemura *et al.*, 2014; Pincebourde *et al.*, 2017; Dosta'lek, 2018). The seasonal volume of active buds, to fresh leaves and flowers can contribute to the final yield outcome (Waller *et al.*, 2007; Jassogne *et al.*, 2013).

In addition, altitude influences soil water balance, geologic deposition, species and biomass production of the native vegetation and cultivated plants (Tan, 2006) which could boost up the nutrient status of mountain ecosystems (Walker *et al.*, 2000); and these can lead to variations in plant quality and quantity. Also, farming in the mountainous areas can cause slopy diversity and heterogeneity, and these can intensify soil erosion (Jiang *et al.*, 2014). The intensity in soil erosion along the altitude affects the soil fertility and the resultant yield outputs (Stenseth & Mysterud, 2002).

Altitude is known to influence mismatches in the rates of vegetative growth and herbivores; and the resultant accumulation of stocks from mismatches can be deposited for fruit bulking (Stenseth & Mysterud, 2002; Hodkinson, 2005). In fact, significant reductions in herbivores could result to better yield outputs (Sase *et al.*, 1998; Suzuki, 1998; Hengxiao *et al.*, 1999). How different altitude levels with complex abiotic effects influence Arabica coffee productivity is not well documented in the MER and this study attempts to point out how coffee productivity responds to altitude and its micro environments.

2.6 Farming system as a driver of occurrence of insect pests and their biological control agents, and yield in the coffee farming systems

Insect herbivores respond differently to cropping complexities (Jonsson *et al.*, 2014; Karungi *et al.*, 2015; 2018). Traditional farming of coffee with management systems described as rustic where 71-100% shade can be provided by a span of shade trees which are normally > 50 trees per acre mimic dense micro conditions (Moguel & Toledo, 1999). This kind of coffee

management system demonstrates particularly high degree of associated diversity. In such a coffee system, important ecological services, such as biodiversity conservation, watershed services, and carbon sequestration are easily achieved (Perfecto & Castineiras, 1998; Pérez-Nieto *et al.*, 2005; Dossa *et al.*, 2008), and a consequent reduction in insect pest damage to crops is very possible (Schroth *et al.*, 2000). The presence of diversity in trees can provide “associational resistance” to crops by modifying the soil quality and microclimate. The abundant nutrient supply from the soil enhances the coffee defense system which in turn distorts the life cycle of the pest; making the coffee trees less susceptible to known pests (Rao *et al.*, 2000; Varon *et al.*, 2007). However, a review on pests and diseases in the shading systems recommends case by case basis (Rutherford & Phiri, 2006). Reviews in coffee production recommend coffee production with better yield under coffee agroforestry systems (Waller *et al.*, 2007). Coffee agroforestry can be achieved under shade systems with different levels of intended plant diversity. The main sources of plant diversity in coffee agroforestry reported in the Neotropics, systems are the shade canopy and the ground cover as these can increase the genetic diversity (Sommarriba *et al.*, 2004).

2.6.1 The effect of farming systems and it's microclimates on occurrence of *H. hampei* and its parasitoids

Most studies examining the effect of shade tree diversity on arthropods have focused on the effects of such tree diversity on insect diversity but the response of coffee insect pests was variable (Staver *et al.*, 2001; Teodoro *et al.*, 2008). Jonsson *et al.* (2014) reported shade reduction of CBB but higher intensity of White coffee stem borer in the Mt. Elgon situations. Insights to the microclimates, the parasitoid complex, and proximities to seminatural vegetations could be the major concern.

Semi natural agricultural farming contributes to checks and balances for the pests' situations such as coffee berry borers, which are coaxed by different vegetative intensities. Physical presence of trees in the farms could cause physical disruption of the borers within the plots or cause enhancement of crop defense system against the pest resulting from modifications in soil quality (Beer *et al.*, 1998; Rao *et al.*, 2000; Varon *et al.*, 2007). More diverse habitats and Farming system diversity are important conservation areas for biological control agents in an agricultural system (Jonsson *et al.*, 2014; Karungi *et al.*, 2015). Parasitoids often experience

longer life span and higher fecundity levels with increased nectar sources (Landis & Haas, 1992; Baggen & Gurr, 1998; Siekmann *et al.*, 2001; Wäckers, 2001; Costamagna *et al.*, 2004, Lee *et al.*, 2004). They make use of extra nectar sources and spread into the surrounding crops more easily (Hickman & Wratten 1996; Freeman *et al.*, 1998; Nicholls *et al.*, 2001). Conservation of natural enemies in such natural habitats (vegetation) would boost coffee yields (Lövei & Sunderland, 1996; Jopp & Reuter, 2005; Rutherford & Phiri, 2006).

The reverse is normally observed in intensively cropped areas. Completely cropped coffee areas are unfavorable for many species of parasitoids (Kruess & Tscharntke, 1994). Areas such as coffee mixed with annual crops are frequently disturbed and are unstable. The solar radiations and temperatures are normally high (Karungi *et al.*, 2018), and they are never conducive for the aggressivity of parasitoids especially at the bottom slopes. These farming systems are reported with very high incidences of CBB (Jonsson *et al.*, 2014).

The situation regarding CBB incidences is not any different with minimum tillage operations in coffee farms. Minimum tillage retains a stable ground cover with adequate moistures for grass levels which are maintained under slash and cut activities. Moguel & Toledo (1999) classified such plantations as unshaded, sun monocultures with no shade tree existence and purely coffee with low grass conditions. Karungi *et al.* (2018) reported relatively high solar radiations, temperatures and low humidity in such coffee mono-cropped plantations. These micro conditions in such coffee plantations offer harsh conditions for parasitoid breeding conditions.

However, the inclusion of banana cultivars into coffee plantations could improve and moderate the microclimates inside the coffee plantations (Karungi *et al.*, 2018) and this could attract certain species of hymenopteran parasitoids. The Mt. Elgon region has Arabica coffee farmlands existing as coffee monocrop, Coffee+annual crop, Coffee+banana and Coffee+banana+shade trees (Liebig *et al.*, 2016; Karungi *et al.*, 2018). However, there is little documentation on such dynamics with regard to *H. hampei* parasitoids. As such, this study provides an understanding of the relationships of farming systems and micro-conditions with *H. hampei* and its parasitoids in the MER.

2.6.2 The effect of farming system and it's microclimates on the occurrence and abundance of the predatory Carabidae

Carabid occurrence, abundance and diversity can be influenced by the quality and quantity of the plant populations at a given location (Bassett, 2009). The quality and quantity of plants determines the availability of prey for the Carabid nutrition (Lindroth, 1974; Bassett, 2009). Habitat and local plant diversity can drive changes in diversity of Carabidae and the functional traits (Bassett, 2009). The dry grasslands are known to act as important regional biodiversity and conservation areas for Carabidae populations (Desender & Bosmans, 1998). Small omnivorous and large predatory Carabid beetles respond variably to patterns of local plant diversity (Liu *et al.*, 2010, 2015). Grassy and less disturbed areas are stable and they are known to retain moderate moist conditions with high soil electric conductivity which are favorable to *Harpalus* spp. (Desender & Bosmans 1998; Sadej *et al.*, 2012; Twardowski *et al.*, 2017). Higher plant complexities attract a greater prey diversity for the Carabids (Bassett, 2009) and predation normally depends on woody habitats (Bianchi & van der, 2004). The replacement of previously cleared forested landscapes with land use forms such as hedgerows, channels, banks, paths, path margins, road margins and agro forestry in connectivity can ease the movement of small organisms (Burel *et al.*, 1998). These connectivity as a landscape property spatially links different parts of the land. Hedge rows have been reported to attract free soil-moving beetles and other macro fauna (Burel *et al.*, 1998). They also act as overwintering grounds and a point of their distribution to established crop fields (Burel *et al.*, 1998).

These semi natural agricultural farming systems contribute to checks and balances for the pests' situations such as aphids. Moreso, diverse habitats and Farming system diversity are very important in the conservation of natural enemies for biological control in an agricultural system (Jonsson *et al.*, 2014; Karungi *et al.*, 2015). The agroforestry systems experience high litter deposition which results into high humus accumulation with slightly lower soil pH. The accumulated humus with continuous deposition of litter on top provides cool and poor solar radiations which are the best breeding and thriving conditions for the Carabidae species and *Chlaenius* spp. is particularly reported to favor such conditions (Hance 2002; Baranova *et al.*, 2018).

Much as highly cropped areas harbor high pest complexes, an in-depth study of these micro environments provides a fuller understanding of how best the crop habitat may be modified to attract certain Carabidae species. Carabidae are known to build and multiply to larger numbers in the presence of prey (Bassett, 2009). A combination of intensively managed wheat / maize double-cropping fields with orchards was reported to preserve a greater Carabid diversity. Aphids which are the preferred prey for the Carabidae are known to thrive on other alternative crops notably Rutaceae, Proteaceae, Theaceae, Anacardiaceae, Lythraceae, Ficeae and Asteracea in the absence of favorable coffee conditions (Deng *et al.*, 2019). Certain Carabidae genera like *Anisodactylus* spp. have high associations to intensively cultivated arable land with moderately moist conditions (Tscharntke *et al.*, 2005; Liu *et al.*, 2012; Eo *et al.*, 2016; Qodri & Noerdjito, 2016). Modifications in the coffee agro ecologies to conserve *Anisodactylus* spp. could be the ideal for biological control interests.

2.6.3 Effect of farming system and it's microclimates on the coffee leaf foliage and the coffee bean yield performance

Coffee plants with heat-stressed growing environments can receive a boost from increased crop diversity (Jezeer *et al.*, 2018). Increased diversity is associated with important ecological services, such as biodiversity conservation, watershed services, carbon sequestration, Nitrogen mineralization (Perfecto & Castineiras, 1998; Dossa *et al.*, 2008; Von Lutzow & Kogel-KNabner, 2009) and a reduction in herbivore damage to crops (Schroth *et al.*, 2000). Reduced existence of herbivores creates yield advantage. These can be seen in coffee which grows from the forest understory in the Ethiopian highlands which has always received better coffee yields due to its association with shady tree conditions (Waller *et al.*, 2007). Cooling conditions created in shady conditions could facilitate longer maturation period allowing for increased berry filling which contributes to better coffee yields (Guyot *et al.*, 1996). Shade grown coffee is known to bulk to larger bean size with greater weight accumulation for increased yields (Perfecto *et al.*, 2005; Vaast *et al.*, 2006; Cherukut, 2019).

In addition, increased crop diversity in coffee can ensure “associational resistance” to crops by modifying the soil quality and microclimate. Modified soil conditions to coffee, improves the coffee tolerance to adverse climatic conditions. Resiliency in coffee trees is known stabilize coffee productivity (Rao *et al.*, 2000; Varon *et al.*, 2007; Jezeer *et al.*, 2018). Also, the increased

crop diversity in coffee could provide a variety of pollen for extra advantages associated with pollination in Arabica coffee. Indeed, pollinators have been shown to contribute to higher coffee yields (Perfecto *et al.*, 2007).

Conversely, the situation in the coffee monocrop and Coffee+annual farming system is very different. These farming systems experience higher solar exposures and high temperatures (Karungi *et al.*, 2018) which promote faster maturity and inadequate grain filling (Perfecto *et al.*, 2005; Vaast *et al.*, 2006; Perfecto *et al.*, 2007). They often result into less coffee weights. Cherukut (2019) reported that Coffee+annual and Coffee monocrop systems have low vegetative growth, shorter branches, fewer number of fruiting nodes and berries per branch.

Introductions of banana plants to the coffee plantations comes with benefits that range from mulching material for water conservation, weed reduction and to reduced surface runoff. Such farms have a potential in improving coffee yields. Coffee+banana systems with reduced solar radiation and temperatures can reduce abiotic stress on the coffee trees (Karungi *et al.*, 2018). Cherukut (2019) reported longer branches and higher number of fruiting internodes in Coffee+banana farming systems. Indeed, coffee fields with moderate solar radiation (35 – 65 %) have been found to give better yields (Perfecto *et al.*, 2005).

In the Mount Elgon region, knowledge on the influence of farming system, occurrence of CBB and its parasitoids; and *T. aurantii* and Carabidae beetles as well as coffee foliage and coffee bean productivity at different altitude levels is not well documented and this study documented this evidence.

CHAPTER THREE

EFFECT OF ALTITUDE AND FARMING SYSTEM ON THE OCCURRENCE OF A PARASITOID COMPLEX OF THE COFFEE BERRY BORER, IN THE MOUNT ELGON REGION

3.1 Introduction

Hypothenemus hampei (Ferrari) (Coleoptera: Curculionidae: Scolytinae) is an important pest causing devastation of coffee plantations in the sub-Saharan Africa, especially in East Africa (Jaramillo *et al.*, 2010; 2012). Population flareups are exacerbated by increasing trends in temperatures and solar exposures (Jonsson *et al.*, 2014). Among the possible control measures, biological control of *H. hampei* offers great potential and reports of existing natural enemies, notably, *Cephalonomia stephanoderis* Betrem (Hymenoptera: Bethyridae), *Prorops nasuta* Waterston (Hymenoptera: Bethyridae), *Heterospilus coffeicola* Schemiedeknecht (Hymenoptera: Braconidae), and *Phymastichus coffea* LaSalle (Hymenoptera: Eulophidae) are available (Rutherford & Phiri, 2006; Jaramillo *et al.*, 2010; Jaramillo, 2012). However, the pest continues to be of economic importance in the Mt. Elgon farming system in Uganda (Jonsson *et al.*, 2014). The lack of impact of the natural enemies could be embedded in direct and indirect effects of biophysical factors in the coffee farming systems in the region.

Altitude can interfere with insect pest regulation vertically (Jonsson *et al.*, 2014) or horizontally through its effects on the microclimates, which directly affect the natural enemies (Ayal, 1994; Siemann, 1998; Bianchi *et al.*, 2006; Patrick *et al.*, 2008; Skalski *et al.*, 2011). Jonsson *et al.* (2014) reported increasing trends of abundance of *H. hampei* down the slope with warming temperatures. The changing thermal temperature trends due to global changes and anthropogenic interference create changes in micro conditions at specific locations which distort natural habitats for insect natural enemies (Jason *et al.*, 2005; Jaramillo *et al.*, 2010, 2011, 2013; Seymoure, 2018).

Prevailing farming systems at specific locations create conditions of temperatures, humidity and light intensity, which have a selective effect on the herbivorous insect pests and their natural enemies (Rao *et al.*, 2000; Varon *et al.*, 2007). The Mt. Elgon region has Arabica coffee farmlands with varying cropping intensities and semi natural vegetation that exist in mosaical

patterns under variable habitat management approaches within different altitudes (Liebig *et al.*, 2016; Karungi *et al.*, 2018). There are reports of response of specific insect herbivores and soil macro organisms to cropping complexities in the region (Jonsson *et al.*, 2014; Karungi *et al.*, 2015, 2018). However, there is no documentation on such dynamics with regard to *H. hampei* parasitoids. As such, this study aimed to provide an understanding of the relationships between altitude, farming systems and their microclimate with occurrence of *H. hampei* and its parasitoids in the region.

3.2 Materials and methods

3.2.1 Study sites description

The study was conducted in the Arabica coffee growing areas of Mt. Elgon region of Uganda within the districts of Kapchorwa and Sironko (Figure 3.1). Within these districts exists varying levels of human population (Kapchorwa=104,580 total households and Sironko =246,638 total households; Uganda Government National Population Census, 2014); and mosaical patterns of semi natural vegetation and Arabica coffee (*Coffea arabica*) farm lands. The coffee farmland in this region ranges from 1200-3500 m.a.s.l. This study area lies within 1°8'43''N-1°23'04''N and 34°22'26''E-34°26'29''E; with a bimodal rainfall pattern (March – May; September - November). The average annual precipitation ranges from 1200 to 2200 mm (NEMA, 2010). Coffee is often intercropped with other crops on the same field, notably *Zea mays*, *Solanum tuberosum*, *Phaseolus vulgaris*, *Arachis hypogaea*, highland cooking banana and assorted shade trees. The annual crops are planted bi-annually while the coffee and banana are maintained as established plantations. The soils have been described as Nitisols (International Union of Soil Science, 2007) developed on basaltic outflows (De Bauw *et al.*, 2016).

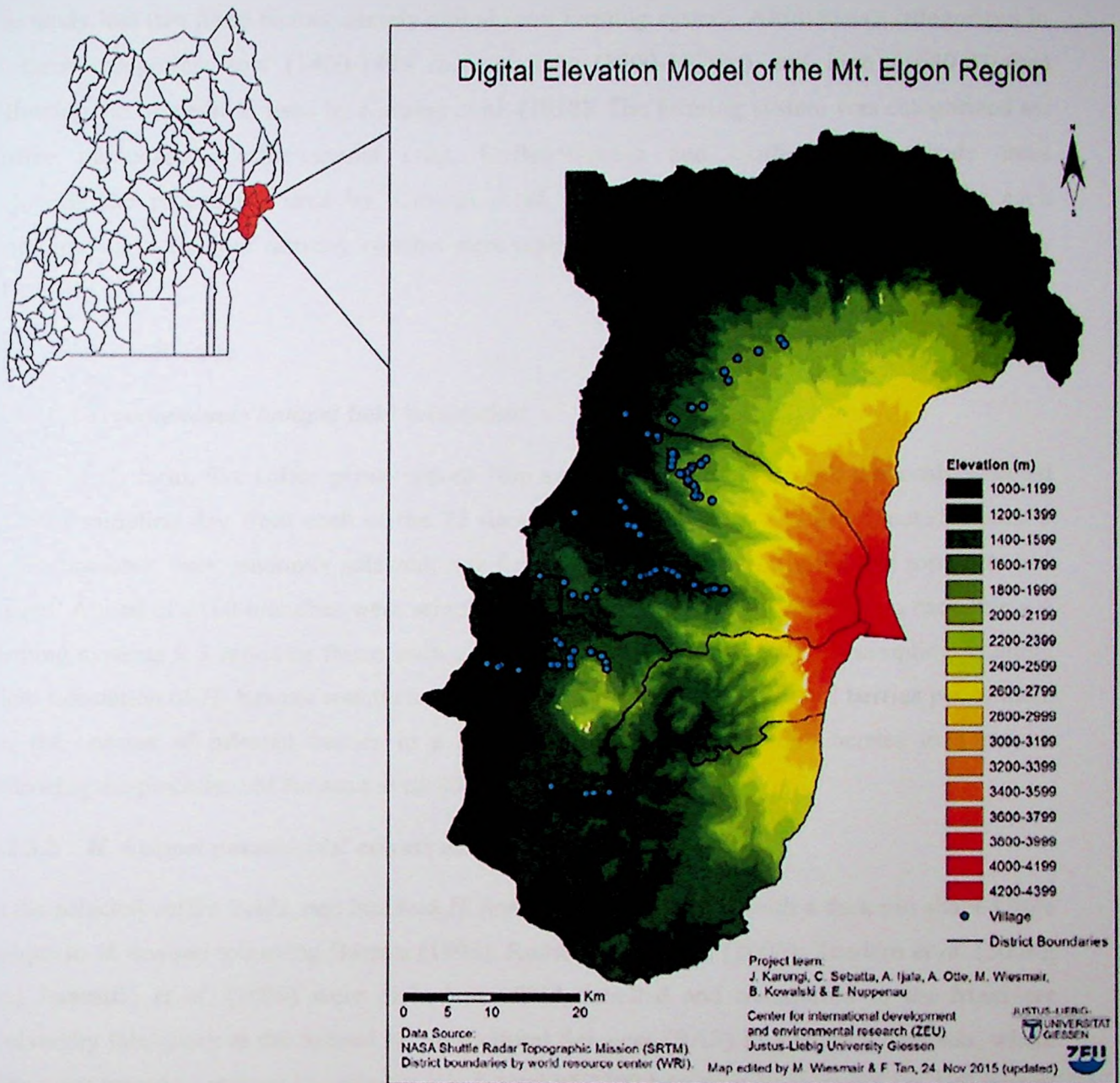


Figure 3.1a Map of the Mount Elgon region showing altitudinal demarcations (courtesy of the Coffee project #89 365)

3.2.2 Research Design

The study had two fixed factors namely altitude and farming system. Altitude was categorized in to three categories: low (1400-1499 m.a.s.l), mid (1500-1679m) and high (1680-2100m) following the procedures used by Karungi *et al.* (2018). The farming system was categorized as: Coffee monocrop, Coffee+annual crop, Coffee+banana and Coffee+banana+shade trees following the procedures used by Karungi *et al.* (2018). Within each district and for each altitudinal class, the four farming systems were replicated three times making a total of 72 study farmlands.

3.2.3 Data collection

3.2.3.1 *Hypothenemus hampei* field infestation

In each study farm, five coffee plants spaced 10m away from each other were randomly selected on each sampling day from each of the 72 sites in the two districts. On the selected plants, 3 coffee branches were randomly selected; one from each of the lower, middle and top parts and tagged. A total of 2160 branches were sampled (ie 5 coffee trees x 3 branches from each tree x 4 farming systems x 3 replicate farms each x 3 altitude levels x 2 districts x 2 sampling rounds). Field infestation of *H. hampei* was then calculated as a proportion of infested berries per branch, i.e, the number of infested berries in a branch/ total number of coffee berries in a branch following the procedure of Jonsson *et al.* (2014).

3.2.3.2 *H. hampei* parasitoids' counts and parasitism

In the selected coffee fields, one hundred *H. hampei* infested berries with a dark pin shaped hole unique to *H. hampei* following Barrera (1994); Rutherford & Phiri (2006); Toedero *et al.* (2008); and Jaramillo *et al.* (2009) were picked per field, labelled and transferred to the Makerere University laboratory at the School of Agricultural Sciences (SAS) in Kampala, Uganda, where they were reared to recover the parasitoids. A total of 7200 berries in each round i.e.,100 berries by 4 farming systems by 3 replicate farms by 3 altitude levels by 2 districts were collected. The 100 berries per site were maintained in a round bottom jar (500ml) under laboratory conditions to await emergence of parasitoids (n=72 jars for one round). The bottom of the jar was lined with absorbent materials (2 parts of charcoal dust: 2 parts paper paste: 10 parts of crane filler) to avoid rotting of the berries and the top cover covered with a thin cloth mesh (< 1mm pore size) to

prevent insects escape following Toedero *et al.* (2008) and Jaramillo *et al.* (2009). The jars were moistened per day with droplets from a water bottle to maintain the humidity at $70\% \pm 5\%$ RH and kept at room temperature to avoid berry desiccation following the methodologies of Toedero *et al.* (2008); and Jaramillo *et al.* (2009). Each rearing round was maintained for three months to allow for daily and complete emergence of all the parasitoids and data collected following the methodologies of Toedero *et al.* (2008); and Jaramillo *et al.* (2009). The laboratory rearing was done twice, i.e., for year one and year two (N=144 jars) at the Makerere University research laboratory of School of Agricultural Sciences. The morphological identification of the parasitoids was done with technical support from the Coffee berry borer laboratories of ICIPE, Nairobi, Kenya following the guiding comparative morphological descriptions by notable studies such as: For *P. coffea*, critical observations were made on the head size, antennal segments and forewing expansion (LaSalle, 1990; Feldhege 1992; Vergara-Olaya *et al.*, 2001; Espinoza *et al.*, 2009; Jaramillo, 2012); *C. stephanoderis*, observations on the submarginal veins of the forewing, size and shape of the mouth parts, head, thorax, abdomen, and flagellum (Betrem , 1961; Infante *et al.*, 1994; Jaramillo, 2012); *P. nausta*, observations on the head shape, mouth parts, thorax, forelegs and forewings (Waterston, 1923; Jaramillo *et al.*, 2009; Jaramillo, 2012); *H. coffeicola*, observations on the forewing expansion, shape of the abdomen, thorax, and head (Hargreaves, 1935; Baker, 1999; Murphy *et al.*, 2001; Jaramillo, 2012).

After the three months, 50 berries from each jar were opened and examined under a stereo microscope (at a magnification of 10x-50x) to count *H. hampei* individuals (dead/alive) and any un-emerged natural enemies. For the emerged parasitoids, proportional parasitism was calculated as: Number of parasitoids of each species/ (Number of parasitoids + the number of *H. hampei*) following the guidelines of Le Pelley (1968); Delgado *et al.* (1990); Echeverry-Arias (1999); Infante *et al.* (2013).



Figure 3.1b Ijala working on Parasitoid identification in the Laboratory

3.2.3.3 Microclimate data

To obtain data on microclimatic variables of temperature, relative humidity and light intensity (summarized in Table 3.1), readings were taken on each insect sampling date along the diagonal in each study site and done three times per site per day; and data collection period using a thermo-hygrometer pen (Model 3402) for temperature and relative humidity whereas a foot candle meter (Model 3413F) was used for light intensity following the techniques of Dunning (2009); Jonsson *et al.* (2014) and Karungi *et al.* (2018).

3.2.4 Data analysis

The effect of fixed factors (altitude and farming system) on the response variables (insect/parasitoid abundance and parasitism) was assessed using the generalized linear mixed models (GLMM) of GenStat version 19, making use of a binomial distribution and logit for data on proportions of *H. hampei* field infestation and parasitism; poisson distribution with logarithm for parasitoid and *H. hampei* counts from collected berries. For parasitoid and *H. hampei* counts, the random factor was farm and for field infestation, the random factor was the branch. Means were separated using pairwise multiple comparison by Fisher's protected least significant difference test to test for differences between and among the means.

To establish the relationships between parasitoid/pest numbers and microclimate, and vegetation species, a general linear regression was carried out. This was done on transformed data ($X=0.5$)^{1/2}. Relative humidity was not included in the regression model as it was found to be auto-correlated to temperature.

3.3 Results

The localized mean microclimate conditions readings within altitudes and farming systems are shown in Table 3.1. On the selected study sites, semi-natural vegetation, which included grasses, weeds, bushes, trees, shrubs, field margins and hedgerows, in and outside (5m) the plot were scored and recorded as species counts (Table 3. 1). Light intensity was recorded highest at high altitudes with Coffee monocrop fields; relative humidity was highest at mid altitudes within Coffee+banana+ shade trees system; Temperature was highest at low altitudes within the Coffee+annual system; Semi natural vegetation counts were recorded highest at low altitudes within the Coffee+banana+ shade trees system; and the Shannon's H diversity index was highest at high altitudes within Coffee monocrop fields (Table 3.1).

Table 3.1. Parameters (means) of microclimate and semi natural vegetation species in the study fields

Altitude	Farming system	Semi natural vegetation species counts	Shannon's H for semi-natural vegetation	Temperature (°C)	Relative humidity (%)	Light intensity (foot candles)
Low	Coffee monocrop	10	1.785	26.56	58.83	187.7
	Coffee+annual	10	1.895	27.28	55.36	217.78
	Coffee+banana	10	1.815	26.68	60.28	187.95
	Coffee+banana+ shade trees	20	1.700	25.08	64.71	39.83
Mean		12.5	1.799	26.4	59.795	158.315
Mid	Coffee monocrop	11	1.930	23.78	67.4	217.97
	Coffee+annual	11	1.930	25.08	64.13	180.81
	Coffee+banana	9	1.740	24.02	65.03	160.75
	Coffee+banana+ shade trees	12	1.845	22.55	69.98	19.92
Mean		10.75	1.861	23.858	66.635	144.863
High	Coffee monocrop	13	2.100	24.39	56.15	281.64
	Coffee+annual	10	1.925	24.27	59.10	223.67
	Coffee+banana	10	1.855	23.84	60.38	221.89
	Coffee+banana+ shade trees	17	1.820	23.01	62.45	48.440
Mean		12.50	1.925	23.876	59.520	193.910

3.3.1 Effect of altitude and farming system on occurrence of Parasitoids and *H. hampei*

The parasitoid emergence studies yielded four parasitoid species associated with *H. hampei*: *Cephalonomia stephanoderis* (Bethyridae), *Phymastichus coffea* (Eulophidae), *Prorops nasuta* (Bethyridae), and *Heterospilus coffeicola* (Braconidae). Parasitoids' emergence was significantly influenced by altitude, farming system; and the interaction of altitude and farming systems from which the berries had been picked (*C. stephanoderis*, Altitude $F_{df\ 2; 130} = 18.92$; $P < 0.001$; Farming system $F_{df\ 3; 130} = 2.09$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 130} = 0.96$; $P < 0.001$; *H. coffeicola*, Altitude $F_{df\ 2; 130} = 3.53$; $P = 0.032$; Farming system $F_{df\ 3; 130} = 4.02$; $P = 0.009$; Altitude*Farming system $F_{df\ 6; 130} = 3.6$; $P = 0.002$; *P. coffea*, Altitude $F_{df\ 2; 130} = 26.72$; $P < 0.001$; Farming system $F_{df\ 3; 130} = 16.08$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 130} = 11.48$; $P < 0.001$; *P. nasuta*, Altitude $F_{df\ 2; 130} = 3.79$; $P = 0.025$; Farming system $F_{df\ 3; 130} = 6.54$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 130} = 5.67$; $P < 0.001$).

3.3.2.1 Parasitoid emergence counts across altitude and farming systems

(i) *Cephalonomia stephanoderis*:

The emergence of *C. stephanoderis* differed significantly with changes in altitude and farming system (Table 3.2). Within the low altitude, the mean emergence of *C. stephanoderis* was significantly highest in the Coffee+banana+shade trees, whereas the rest were not significantly different. At mid altitude, the highest *C. stephanoderis* emergence was still in the Coffee+banana+shade trees systems followed by the Coffee monocrop, whereas emergence in Coffee+annual crop and Coffee+banana farming systems, were not significantly different. The emergence in the Coffee+banana+shade trees system was still highest at high altitude with the lowest emergence recorded in the Coffee+annual crop; Emergence in the Coffee monocrop and Coffee+banana did not differ significantly.

Within the Coffee monocrop farming system, *C. stephanoderis* emergence was significantly highest in the mid altitudes, followed by high and then low altitude. In the Coffee+annual crop system, emergence at mid altitude was the highest, whereas high and low altitudes did not differ significantly. For the Coffee+banana system, emergence at low altitude was significantly the lowest while that at mid and high altitudes did not significantly differ. Within the

Coffee+banana+shade trees systems, emergence at mid altitudes was highest followed by high altitude and then low altitude (Table 3.2).

Table 3.2. Mean emergence of *Cephalonomia stephanoderis* counts from coffee berries at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+ Banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	2.33±0.4a ^A	0.0a ^A	2.33±0.4a ^A	17.33±1.4b ^A	5.5	3
Mid	21.00±1.5b ^C	8.67±1a ^B	12.00±1a ^B	73.00±3.5c ^C	29	13
High	9.67±0.8b ^B	2.33±0.5a ^A	8.33±0.8b ^B	20.33±2.7c ^B	10	3.2
Farming system mean	11	4	8	37		
SE	5.4	2.6	2.8	18		

Mean counts followed by the same letter within the row (lower letter case- farming system); and means followed by the same letter within the column in (upper letter case- altitude) do not differ significantly at P<0.05

(ii) *Phymastichus coffea*

Emergence of *Phymastichus coffea* also differed significantly as a result of changes in both altitude and farming system (Table 3.3). At the low altitude, emergence of Coffee+banana+shade tree system was highest while the other farming systems did not differ significantly. In the mid altitude, the Coffee+banana farming system had the highest emergence of *P. coffea* followed by the Coffee+banana+shade trees. Emergence was still highest in the Coffee+banana at high altitudes while the lowest was in Coffee+banana+shade trees farming system; emergence did not differ significantly between Coffee monocrop and Coffee+annual crop farming systems.

Within the Coffee monocrop farming system, *P. coffea* had no emergence at the low altitude whereas mid and high altitudes did not differ significantly. Coffee+annual crop system had the lowest emergence in the low altitude. For Coffee+banana, emergence was highest in the mid altitudes followed by that at the high altitude, and then low altitude. As for the Coffee+banana+shade trees system, emergence was highest in the mid altitude followed by that at the low altitude and then high altitude.

Table 3.3. Mean emergence of *Phymastichus coffea* counts from coffee berries at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	0.0a ^A	4.0±0.4a ^A	2.33±0.3a ^A	7.0±0.7b ^B	3.3	1.3
Mid	6.7±0.7a ^B	7.3±0.7a ^B	58.30±3c ^C	19.0±1.2b ^C	23	11
High	7.3±0.6b ^B	7.3±0.7b ^B	13.67±1.3b ^B	5.7±0.4a ^A	8.5	1.5
Farming system mean	5	6.2	25	11		
SE	2.3	1.2	17	4.4		

Mean counts followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case- Altitude) do not differ significantly at $P<0.05$

(iii) *Prorops nasuta*

The emergence of *P. nasuta* varied as the farming systems and altitudes changed (Table 3.4). Within the low altitude, the Coffee+banana+shade trees system had the highest emergence for *P. nasuta* while Coffee monocrop had the lowest emergence. Whereas the other did not differ significantly. At mid altitude, the Coffee monocrop had the highest emergence of *P. nasuta* followed by Coffee+banana, then Coffee+banana+shade trees while for Coffee+annual system, had no emergence of *P. nasuta*. At high altitude, Coffee+banana system had the highest emergence followed by Coffee+banana+shade trees, then Coffee monocrop, and still Coffee+annual crops system did not have any emergence of *P. nasuta*.

Looking at the farming systems, the *P. nasuta* emergence within the Coffee+annual system, was significantly highest in the mid altitude, whereas the other altitudes did not differ. Within the Coffee+annual crop, no emergence was observed in the mid and high altitudes whereas in low altitude it was recorded highest. For the Coffee+banana, the emergence followed the order of high>mid>low altitude. Within the Coffee+banana+shade trees, the emergence of *P. nasuta* was recorded lowest at mid altitude, whereas low and high altitudes did not differ significantly.

Table 3.4. Mean emergence of *Prorops nasuta* counts from the coffee berries at different altitudes and Farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+banana	Coffee+banana+s shade trees	Altitude mean	SE
Low	3.3±0.5a ^A	5±0.7b ^B	7.0±0.9b ^A	11±1.5c ^B	7	1.4
Mid	26.0±0.4d ^B	0.0a ^A	15.0±1.7c ^B	5.0±0.8b ^A	12	5
High	3.3±0.5a ^A	0.0a ^A	78.3±7.1c ^C	14±1.8b ^B	24	16
Farming system mean	11	1.7	33.4	10		
SE	8	1.7	23	3		

Mean counts followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P<0.05$

(iv) *Heterospilus coffeicola*

Emergence of *Heterospilus coffeicola* was uniquely different at the different altitude and farming system, and also had the least emergence (13.0 ± 0.9) of all the parasitoids (Table 3.5). Within the low altitude, emergence was significantly highest in the Coffee monocrop, followed by Coffee+banana, whereas emergence in the Coffee+banana+shade trees and Coffee+annual did not differ. Within the mid altitudes, *H. coffeicola* emergence was not recorded in the Coffee monocrop and Coffee+banana+shade trees systems, whereas it was recorded highest in the Coffee+annual crop system. As within the high altitude, the emergence was again highest in the Coffee+annual crop system followed by Coffee monocrop. Coffee+banana and Coffee+banana+shade trees were not significantly different.

As regards the farming system, the emergence within the Coffee monocrop was significantly recorded highest in the low altitudes followed by high altitude. The mid altitude recorded no emergence of *H. coffeicola* within the Coffee+annual crop system, the emergence was in the order of high>mid>low. The emergence within the Coffee+banana farming system was highest at the low altitude whereas mid and high altitudes did not differ significantly. For the *H. coffeicola* emergence within the Coffee+banana+shade trees, mid altitude recorded zero counts but were still not significantly different from others (Table 3.5).

Table 3.5. Mean emergence of *Heterospilus coffeicola* counts from the coffee berries at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	8.3±0.6c ^C	2.0±0.4a ^A	3.7±0.5b ^B	2.0±0.6a ^A	4	1.3
Mid	0.00a ^A	4.3±0.8b ^B	2.3±0.4a ^A	0.00a ^A	1.7	0.9
High	4.7±0.6b ^B	13.0±0.9c ^C	1.3±0.2a ^A	2±0.4a ^A	5.3	2.3
Farming system mean	4.3	6.4	2.4	1.3		
SE	2.4	3.3	0.7	0.7		

Mean counts followed by the same letter within the row (lower letter case-Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P<0.05$

Hypothenemus hampei

Analysis of numbers of (*H. hampei*) abundance recovered from the dissected berries revealed that, only the main effect of altitude, had a significant effect (Altitude $F_{df\ 2; 130} = 18.92$; $P<0.001$) but not the Farming system ($F_{df\ 3; 130} = 2.09$; $P=0.104$); or (Altitude*Farming system $F_{df\ 6; 130} = 0.96$; $P=0.453$). Thus, counts of *H. hampei* recoveries across farming systems were pooled together by altitude in the analysis (Fig. 3.2). The highest abundance of *H. hampei* recoveries were found in berries at low altitude areas and the lowest in the high altitude areas (Fig. 3.2).

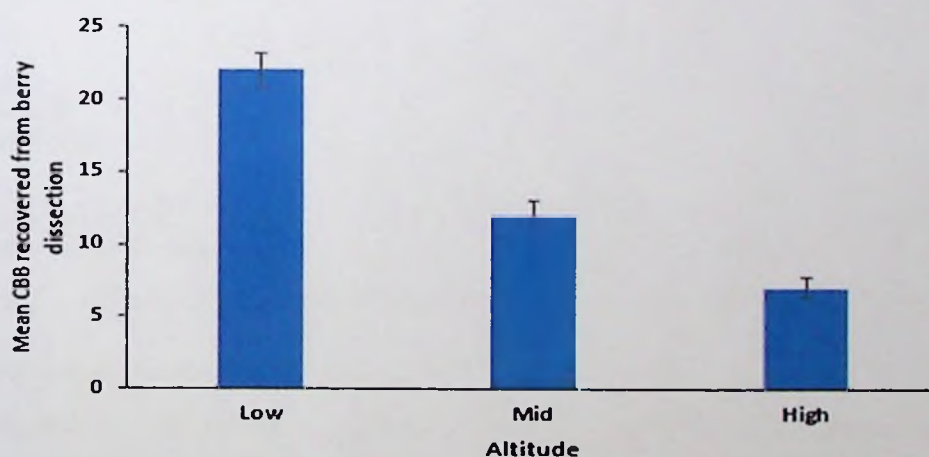


Figure 3.2. *H. hampei* mean counts ± SE recovered from berries dissected at different altitudes

On the other hand, the proportional field infestation of coffee berries by *H. hampei* was highly significant for the main effects of altitude, and farming system, as well as the interactions of altitude and farming system (Altitude $F_{df\ 2; 2146} = 11.53$; $P<0.001$; Farming system $F_{df\ 3; 2146}$

=11.15; $P=0.001$; Altitude*Farming system $F_{df\ 6;\ 2146}=20.39$; $P<0.001$. Within the low altitude, field infestation was highest in the Coffee monocrop system followed by Coffee+annual crop; while the rest of the farming systems did not differ significantly. As within the mid altitude, the infestation was significantly the lowest in the Coffee monocrop system, and the rest of the farming systems did not have clear differences. The field infestation within the high altitude did not show any clear differences among the farming systems (Table 3.6).

Within the farming systems, field infestation by *H. hampei* also varied with altitude. Within the Coffee monocrop system, the infestation was highest in the low altitude, whereas mid and high altitudes were not significantly different. As within the Coffee+annual crop, the infestation was significantly lowest in the high altitude, while mid and low altitudes were not significantly different. For the Coffee+banana systems, the infestation was not significantly different. Within the Coffee+banana+shade trees system, the infestation was highest in at mid altitude, whereas low and high altitudes were not significantly different (Table 3.6).

Table 3.6. *H. hampei* proportional field infestation at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude means	SE
Low	0.24±0.003d ^C	0.07±0.001c ^C	0.05±0.009ab ^{AB}	0.03±0.006a ^A	0.1	0.04
Mid	0.05±0.0001ab ^{AB}	0.09±0.02c ^C	0.08±0.0001c ^C	0.07±0.0001c ^C	0.07	0.01
High	0.04±0.001ab ^{AB}	0.05±0.007ab ^{AB}	0.06±0.009abc ^{ABC}	0.05±0.001ab ^{AB}	0.05	0.004
Farming system mean	0.11	0.07	0.06	0.05		
SE	0.07	0.01	0.008	0.01		

Mean proportions followed by the same letter within the row (lower letter case-Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P<0.05$

3.3.2 Effect of altitude and farming system on parasitism of *H. hampei*

The parasitism of the *H. hampei* by *C. stephanoderis* varied significantly with altitude (Fig. 3.3 A), and the farming system (Fig. 3.3 B) but not with the interactions of the altitude and the farming system (Altitude*Farming system: $F_{df\ 6;\ 2130}=1.79$; $P=0.106$). The mean proportional parasitism of *H. hampei* by *C. stephanoderis* was highest in the mid altitudes and lowest in the low altitudes (Fig 3.3A; $P<0.05$). Looking at the effect of the farming system, the parasitism of *H. hampei* by *C. stephanoderis* was recorded highest in the Coffee+ banana+shade trees and the lowest in the Coffee+annual crop (Fig. 3.3B; $P<0.05$).

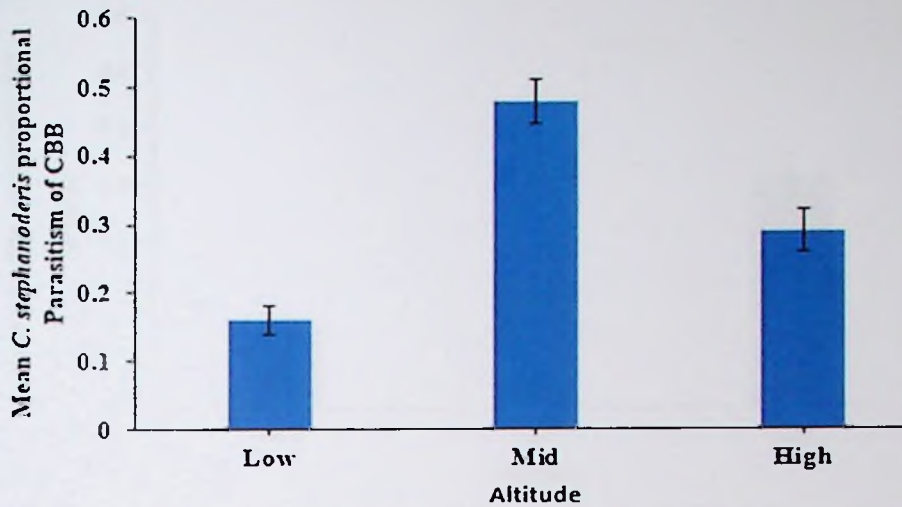


Figure 3.3A. Mean *C. stephanoderis* proportional parasitism of *H. hampei* as affected by altitude

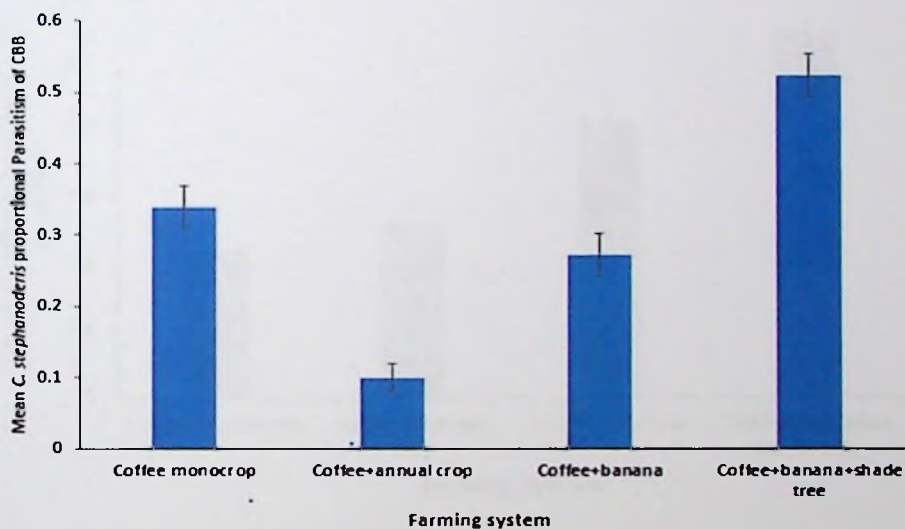


Figure 3.3B. Mean $\pm$ SE *C. stephanoderis* proportional parasitism of *H. hampei* as affected by farming system

Similarly, *P. coffea* parasitism of *H. hampei* was significantly influenced by altitude (Fig. 3.3C), and the farming system (Fig. 3.3D), but not with the interactions of altitude*farming system (Altitude*Farming system; $F_{df\ 6; 2130} = 1.39$; $P = 0.224$). The mean proportional parasitism of *H. hampei* by *P. coffea* was lowest in the low altitude and highest in the mid altitude (Fig 3.3C, $P < 0.05$). As for the farming system, the mean parasitism was significantly highest in the Coffee+banana+shade trees system followed by the Coffee+ banana (Fig. 3.3 D; $P < 0.05$).

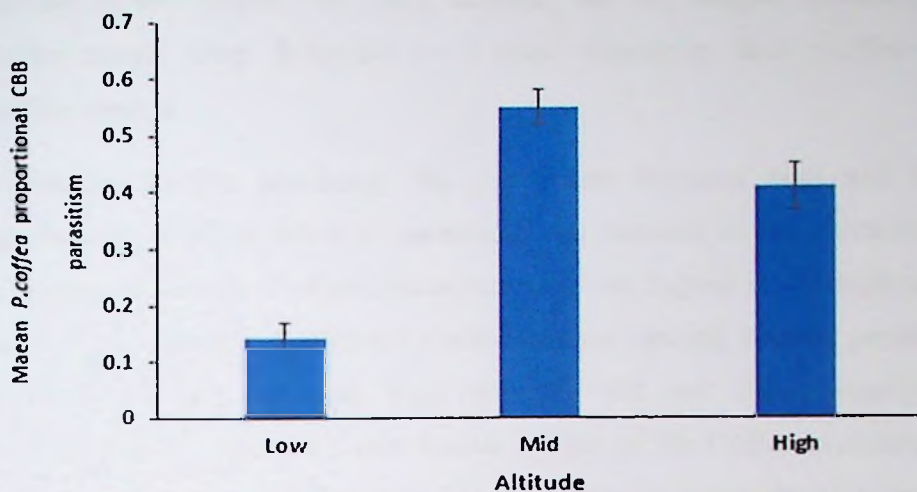


Figure 3.3C mean $\pm$ SE *P. coffea* proportional parasitism of *H. hampei* as affected by altitude

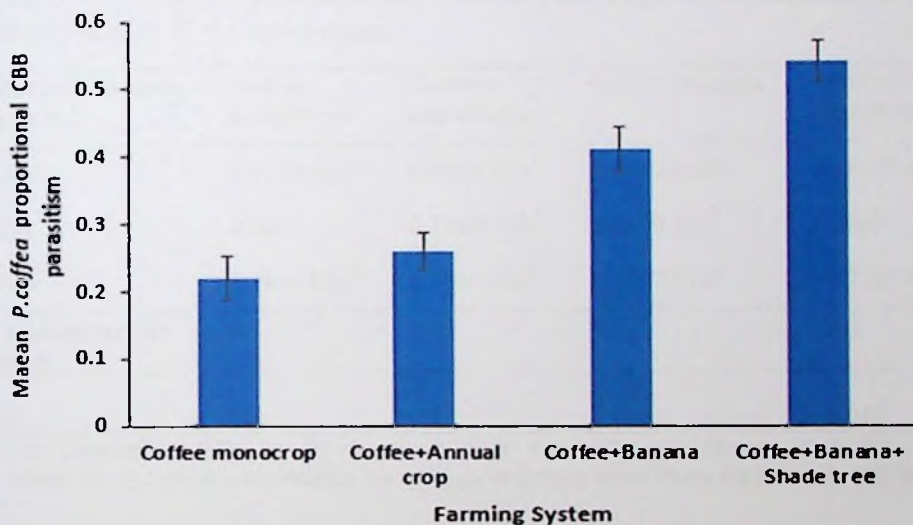


Figure 3.3D mean $\pm$ SE *P. coffea* proportional parasitism of *H. hampei* as affected by farming system

With regard to *H. coffeicola* parasitism of *H. hampei*, there were significant effects of the altitude, and the altitude*farming system interaction; whereas the main effect of farming system alone was not significant (Altitude: $F_{df\ 2; 2130} = 5.82$; $P = 0.004$; Farming system: $F_{df\ 3; 2130} = 1.87$; $P = 0.138$; Altitude*Farming system: $F_{df\ 6; 2130} = 1.39$; $P = 0.027$). The mean separations recorded differences by altitude and farming systems (Table 3.7). Within the low altitude, *H. coffeicola* parasitism was highest in the Coffee monocrop farming system, whereas it was lowest in the Coffee+annual crop system. As for *H. coffeicola* parasitism of *H. hampei* within the mid

altitudes, it was highest in the Coffee+annual farming system and the rest of the farming systems did not differ. Within the high altitude, the *H. hampei* parasitism was highest in the Coffee+annual crop followed by Coffee monocrop then Coffee+banana+shade trees > Coffee+banana.

Within the Coffee monocrop, the parasitisms between high and low altitudes were not significantly different, while no parasitism was recorded at mid altitude. As for the parasitism of *H. hampei* within the Coffee+annual crop, it was highest in the high altitude followed by mid and then low altitude. Within the Coffee+banana farming system, parasitism was highest at low altitude, whereas mid and high altitudes did not differ significantly. The trend for Coffee+banana+shade trees was similar to that of the Coffee monocrop with no parasitism at mid, and no significant difference of *H. hampei* at the rest of the altitudes (Table 3.7).

Table 3.7. Mean proportions for *Heterospilus coffeicola* parasitism of *H. hampei* at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	0.32±0.02c ^B	0.07±0.01a ^A	0.12±0.02b ^B	0.15±0.03b ^B	0.17	0.05
Mid	0.0a ^A	0.13±0.02b ^B	0.09±0.02a ^A	0.0a ^A	0.06	0.02
High	0.28±0.03c ^B	0.50±0.03d ^C	0.08±0.01a ^A	0.17±0.03b ^B	0.3	0.08
Farming system mean	0.2	0.23	0.1	0.1		
SE	0.1	0.13	0.013	0.054		

Mean proportions followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case- Altitude) do not differ significantly at P<0.05

P. nasuta parasitism of *H. hampei* showed no significant main effects of altitude, but farming system, and the altitude*farming systems had a significant influence (Altitude: $F_{df\ 2; 2130} = 0.32$; $P = 0.726$; Farming system: $F_{df\ 3; 2130} = 4.42$; $P = 0.005$; Altitude*Farming system: $F_{df\ 6; 2130} = 2.47$; $P = 0.027$). Within the low altitude, *P. nasuta* had the highest parasitism in the Coffee+banana+shade trees farming system and the rest of the farming systems did not differ. Within the mid altitudes, the parasitism was higher in Coffee monocrop and Coffee+banana systems than that in the Coffee+banana+shade trees and Coffee+annual systems. As within the high altitude, the parasitism at Coffee+banana system was highest followed by that in the

Coffee+banana+shade trees, whereas the parasitism at Coffee+annual and Coffee monocrop did not differ significantly.

Looking at the farming systems, within the Coffee monocrop, parasitism was significantly highest in the mid altitude; whereas parasitism in the rest of the altitudes did not differ significantly. Within the Coffee+annual crop system, there were no differences in parasitism. For the Coffee+banana system, parasitism was lowest in the low altitude whereas mid and high altitudes did not differ significantly. Within the Coffee+banana+shade trees, parasitism was lowest in the mid altitude whereas high and low did not differ (Table.3.8).

Table 3.8. Mean proportions for *P. nasuta* parasitism of *H. hampei* at different altitudes and Farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	0.11±0.02a ^A	0.17±0.02a ^A	0.18±0.02a ^A	0.27±0.03b ^B	0.2	0.03
Mid	0.42±0.03c ^C	0.0a ^A	0.36±0.03c ^C	0.16±0.03a ^A	0.23	0.08
High	0.07±0.01a ^A	0.0a ^A	0.48±0.03c ^C	0.27±0.03b ^B	0.21	0.09
Farming system mean	0.2	0.057	0.34	0.23		
SE	0.1	0.05	0.09	0.037		

Mean proportions followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at P<0.05

3.3.3 Relationships between parasitoid/pest numbers with microclimate variables and semi natural vegetation species

The linear regression showed a significant negative relationship between *C. stephanoderis* and ambient temperature, and a positive one with vegetative species counts but no discernible relationship with light intensity (Table 3.9). *P. coffea* had a similar negative relationship with temperature but vegetative species counts were not a significant predictor for it. For *P. nasuta*, only temperature had a significant negative relationship. Though *H. coffeicola* was also negatively related to ambient temperature as all the other parasitoids, it had a positive relationship with light intensity (Table 3.9). The real contrast was with *H. hampei*, the pest, it

had a positive relationship with ambient temperature and a negative one with light intensity and no discernible relationship with vegetative species counts (Table 3.9).

Table 3.9. Regression coefficients for microclimate variables and semi natural vegetation species occurrence as predictors of parasitoid and *H. hampei* numbers in collected berries

Parameter	Coefficients	SE	t	p value
<i>H. hampei</i> (pest)				
(Constant)	-4.117	1.831	-2.249	0.026
Vegetation species	-0.059	0.353	-0.168	0.867
Temperature	0.311	0.057	5.503	0.000
Light intensity	-0.003	0.001	-1.984	0.049
<i>P. coffea</i>				
(Constant)	2.257	0.493	4.575	0.000
Vegetation species	-0.065	0.095	-0.679	0.498
Temperature	-0.064	0.015	-4.209	0.000
Light intensity	0.000	0.000	0.106	0.916
<i>C. stephanoderis</i>				
(Constant)	0.738	0.481	1.535	0.127
Vegetation species	0.257	0.093	2.778	0.006
Temperature	-0.047	0.015	-3.185	0.002
Light intensity	0.000	0.000	-0.757	0.450
<i>P. nasuta</i>				
(Constant)	0.696	0.433	1.605	0.111
Vegetation species	0.125	0.084	1.501	0.136
Temperature	-0.035	0.013	-2.620	0.010
Light intensity	0.000	0.000	.180	0.858
<i>H. coffeicola</i>				
(Constant)	0.759	0.362	2.096	0.038
Vegetation species	0.023	0.070	0.336	0.737
Temperature	-0.030	0.011	-2.707	0.008
Light intensity	0.001	0.000	2.389	0.018

Values significant at $P < 0.05$

3.4. Discussion

These results on parasitoid occurrence and parasitism give credence to the stated hypothesis that prevailing microclimate conditions may be accelerating the movement of *H. hampei* parasitoids to the higher altitudes. *C. stephanoderis* and *P. coffea* were most abundant at mid altitude and *P.*

nasuta and *H. coffeicola* at high altitude. These trends can be explained by microclimate prevailing at plot level as all four parasitoids had a negative relationship with ambient temperature, which was notably lower at mid and higher altitudes. This has implications on future regulation of *H. hampei* by the natural control agents due to the contrasting response of the parasitoids and pest to microclimate, especially ambient temperature. Theoretical models have shown that host-parasitoid relationships can be altered by environmental change. Temperature increase, for example, may differentially affect developmental cues and rates of hosts and parasitoids (van Nouhuys & Lei, 2004). Furthermore, any climate related changes in the development rate of the host may affect their window of vulnerability to parasitism (Klapwijk *et al.*, 2010). The resulting synchrony can alter the fitness of both partners (Stenseth & Mysterud, 2002; Voigt *et al.*, 2003; van Asch & Visser, 2007). Jaramillo *et al.* (2011) indicated that the tolerance temperature range for *H. hampei* is 15-32 °C and optimum growth occurs at 20-30 °C. Other studies of Jaramillo *et al.* (2013) showed that a 1-2°C increase in temperature from the lower thresholds could lead to an increased number of generations, dispersion and damage by the coffee berry borer (*H. hampei*); whereas a rise in temperature of 2°C and above could lead to shifts in altitudinal and latitudinal distribution of the pest. Yet, the results of this study show that the opposite would be true for the parasitoids. The decoupling of the coffee berry borer and its natural enemies could result in higher pest numbers or more serious outbreaks (Stireman *et al.*, 2005; Hance *et al.*, 2007; Walther, 2010).

The situation at low altitude is dire for *H. hampei* parasitoids if no effort is made to buffer temperature. The results showed that including banana and/or shade trees in coffee could indeed ameliorate conditions at low altitude, and increase occurrence of *C. stephanoderis*, *P. coffea* and *P. nasuta*. It has been reported that wooded and herbaceous vegetation's provide moderate micro climates for parasitoids that would experience considerable shorter life spans at high temperatures (Rahim *et al.*, 1991; Hailemichael & Smith, 1994) in addition to offering increased sources of pollen and nectar (Baggen & Gurr, 1998). The shade trees and banana provide both benefits and should be emphasized, especially at low altitudes.

The expectation was for the semi natural vegetation to play the key role in parasitoid occurrence as Bianchi *et al.* (2006) reported greater natural enemy populations in fields associated with herbaceous habitats. In this study, it was only *C. stephanoderis* for which presence of vegetation

was crucial. This shows that in the Elgon region, microclimate, especially ambient temperature was very critical in the occurrence of *H. hampei* and its parasitoids. The populations of the *C. stephanoderis* were higher in the mid altitudes and the farming system of Coffee+banana+shade tree, with an average temperature recording of 23⁰C. Other studies reported *C. stephanoderis* with better field performance at temperature ranges of 18 - 27 °C (Infante *et al.*, 1992; Kumar, *et al.*, 2014).

H. coffeicola was uniquely the only parasitoid with preference for Coffee+ annual farming system with field conditions that were described with an average temperature of 24.27⁰C and light conditions of 223.67foot candles; and overall, not as suitable to the other parasitoids. This could be explained by its preference for high light intensity, which was relatively high in this system. This could also explain why *H. coffeicola* is challenging to culture under laboratory conditions (Murphy *et al.*, 2001; Kucel *et al.*, 2004).

In terms of parasitism, *P. coffea* was more effective among the parasitoids with an average of 54%; compared to *C. stephanoderis*, the runner up, with 52%. *P. coffea* in this study was more abundant in mid altitudes and Coffee+ banana system which were described with an average temperature of 24.02⁰C. Other studies reported better field performance of *P. coffea* at temperature ranges of 24-27⁰C (Feldhege, 1992; Infante *et al.*, 1994; Lopez *et al.*, 1997). The parasitism of *H. hampei* in this study is in line with the earlier reports showing *P. coffea* with a very high capability of lowering *H. hampei* populations in the field (Gutiérrez *et al.*, 1998).

P. nasuta though occurring in relatively adequate numbers displayed the lowest parasitism levels. The activity temperature ranges for *P. nasuta* have been reported at 18-30 °C (Barrera *et al.*, 1991; Infante *et al.*, 2005) and maximum performance at 18-22 °C (Infante, 2000), beyond this, the field efficacy is slowed down. As in this study, more field populations were recorded in the higher altitudes and Coffee+ banana farming systems with an average field temperature of 23.84⁰C. Other studies by Rahim *et al.* (1991) and Hailemichael & Smith (1994) report shorter life spans and ineffectiveness of parasitoids under conditions of higher temperatures. Other poor field performance of the Bethyloid parasitoids have been associated with very high levels of interspecific competition, which interferes with their parasitism potential (Batchelor *et al.*, 2005, 2006). This could also have implications on its inconsistent parasitism rates.

As such *P. coffea* and *C. stephanoderis* show potential for regulation of CBB and efforts should be made to provide conditions that promote their occurrence and effectiveness. From the results of this study and drawing on recommendations from other studies (Altieri, 1999; Lin 2011; Jaramillo *et al.*, 2011; Jonsson *et al.*, 2014), the study strongly recommends introduction of shade trees and/or banana intercrop as they have been confirmed to buffer microclimate and also provide additional benefits like nectar and nesting nooks that are essential for survival of parasitoids.

3.5. Conclusion

In the coffee farm lands of the Mt. Elgon region, there are four Hymenopteran parasitoids that collectively could regulate infestation of *H. hampei*. An increase in parasitoid occurrence could be discerned from the lower to mid and high levels. Ambient temperatures were more influential than semi natural vegetation which was earlier on expected to influence the parasitoid occurrences. Including banana and/or shade trees in coffee farming systems at lower altitudinal levels can buffer microclimate, and consequently promote the parasitoids much more than in the often-disturbed Coffee +annual crop farming systems. These insights best inform the needs for use of parasitoids for biological of *H. hampei* in the coffee farms.

CHAPTER FOUR

THE EFFECT OF FARMING SYSTEM AND ALTITUDE ON DIVERSITY AND ABUNDANCE OF THE PREDATORY CARABIDAE, AND THEIR RELATIONSHIP TO THE COFFEE APHID, IN COFFEE FIELDS IN THE MOUNT ELGON REGION

4.1 Introduction

Ground beetles (Coleoptera: Carabidae) are usually diverse and highly abundant in nature, and agroecosystems; where they offer crop protection services as biological control agents of insect pests (Laroche, 1990; Kromp, 1999; Sunderland, 2002; French *et al.*, 2004; Menalled *et al.*, 2007; Leslie *et al.*, 2009; Traugott *et al.*, 2012; Evans, 2016; Adhikari & Menalled, 2018). Among the notable Carabids genera, *Harpalus* spp., *Chlaenius* spp., *Anisodactylus* spp., *Bembidion* spp., and *Pterostichus* spp. have often been reported within agricultural ecologies (Edwards *et al.*, 1979, Loughridge & Luff, 1983; Kromp, 1999; Tooley & Brust, 2002; Milius *et al.*, 2006). These Carabidae have known predatory behavior on insect pests in the reported agricultural ecologies. They have been reported to be commonly associated with particular habitats in the agroecologies and they always search for better niches for their continuity (Thiele, 1977; Desender & Bosmans 1998; Goulet, 2003; Merivee *et al.*, 2004; 2006; Milius *et al.*, 2006; Ogunrinde & Adebajo, 2007; Koivula *et al.*, 2011; Sadej *et al.*, 2012).

The MER of Uganda has coffee farms distributed along the slopes of the mountain (1400-2300 meters above sea level) in patches of differing crop combinations and seminatural vegetation. The varying altitude and cropping/vegetation intensity create parcels of microclimate that may affect insect functional groups differently. Indeed, altitude has been reported to moderate soil properties and vegetative physical presence causing direct and/or indirect impacts on Carabidae aggregations (Siemann, 1998; Yüsek *et al.*, 2013; Park *et al.*, 2015; Nietupski *et al.*, 2015; Twardowski *et al.*, 2017). The parameters of soil that have been reported to influence Carabidae populations are soil acidity, soil salts, and soil moisture (Goulet, 2003; Sadej *et al.*, 2012).

Farming systems with unique styles of vegetative inclusions such as intercropping, agroforestry, hedgerows, road reserves, fallows, tree strips, contour tillage, and minimum tillage are also reported to modify below-ground microclimates leading to variable Carabidae occupations (Welsh, 1990; Siemann, 1998; Desender & Bosmans, 1998; Holland & Luff, 2000; Szyszko *et*

al., 2000; Aviron *et al.*, 2005; Skalski *et al.*, 2011; Liu *et al.*, 2015; Nietupski *et al.*, 2015; Twardowski *et al.*, 2017; Li *et al.*, 2017).

The unique biophysical parcels in the coffee farmland mosaics of the MER were found to have distinct effects on soil macrofauna and the Hemipteran pest complex associated with the coffee tree (Karungi *et al.*, 2015, 2018). The hemipteran pests such as aphids have showed high preference for warmer conditions and their continued presence on crops contributes to high crop losses (Ogunrinde, & Adebajo, 2007). They live in association with ants, which interfere with the efficacy of biological control, especially by the parasitoids, hence exacerbating other pest situations (Ogunrinde & Adebajo, 2007; Abedeta *et al.*, 2011). A case in point is *Toxoptera aurantii*, an important pest of coffee in the tropics and subtropics (Deng *et al.*, 2019), which sucks sap from leaves, stems, flowers and fruits of coffee and may cause falling off of leaves and flowers (Ogunrinde & Adebajo, 2007). Besides sap feeding, it injects toxic saliva into the plant tissue causing phytotoxicity and stunting in seedlings (Guidolin & Consoli, 2018). The pest also secretes honeydew when sap-feeding, and sooty molds frequently grow on the honeydew, which hinders photosynthetic activity (Sevim *et al.*, 2012).

Toxoptera aurantii existence in the mount Elgon Arabica coffee was reported by Karungi *et al.* (2015) and is known to thrive on various alternative crops in the absence of favorable coffee conditions; notably, Rutaceae, Proteaceae, Theaceae, Anacardiaceae, Lythraceae, Ficeae and Asteracea (Deng *et al.*, 2019) and its biological control by natural enemies would be the most ideal. Biological control of insect pests by generalist predators in major farming systems has been documented (Lovei & Sunderland, 1996; Ogunrinde & Adebajo, 2007), especially of aphid species (Edwards *et al.*, 1979, Chiverton, 1987; Loughridge & Luff, 1983, Ogunrinde & Adebajo, 2007). Therefore, the studies on the occurrence, specific preferences of the Carabidae and genus association with *T. aurantii* could add to the existing information for the MER and provide insights that would boost biological control measures in the coffee farmlands as a whole.

4.2 Materials and methods

The study on Carabidae and their relationship to the aphid *T. aurantii* in the Mount Elgon region was carried out using the coffee farmlands and the study design as described in sections 3.2.1-3.2.2 in chapter three.

4.2.1 Abundance of Carabidae

In each study field, ten pitfall traps were established in a zig-zag pattern below the canopies of the coffee trees, spaced at least 10m apart for monthly monitoring of Carabids following the guidelines of Dauber *et al.* (2003, 2005), Qodri & Noerdjito (2016), Mwambala *et al.* (2019), and Allema *et al.* (2019). This was a longitudinal study over a period of two years. Every month, a total of 720 pitfall traps (10 traps for each field; by 4 farming systems X 3 replicates; by 3 altitude levels; by 2 districts) were processed. The pitfall traps were made of 500 ml plastic cups (diameter 85 mm) filled with approximately 170 ml of ethanol-glycerine solution (2:1) and a detergent added in to reduce surface tension. Rain covers (metallic sheets, 250 mm) were placed approximately 10 cm above each trap to prevent flooding by rain following the guidelines of Dauber *et al.* (2003); Liu *et al.* (2015); Baranová *et al.* (2018); and Allema *et al.* (2019). The trapped insects were collected into 300ml bottles containing 70% ethanol. All the bottles were precisely labelled by farm code, farming system, altitude and dataset.

The insects were first sorted into major groups such as beetles, ants, centipedes and millipedes. The beetles were further sorted into distinct groupings using their external morphological features. Since there was no record of Carabidae species in coffee systems in the region for reference, procedures for identification into family, subfamily, genera, and species level using comparative morphological identification keys were instituted at the Kenya National Museum in Nairobi following the guidelines of a Lindroth (1974) handbook. Thirteen representatives of these samples were sent to the CABI Plantwise diagnostic and advisory services in the United Kingdom where they were confirmed by morphological identification and sequencing (inquiry No CABI 002-18). Only 4 of the 13 representatives of Coleoptera were confirmed to belong to the family Carabidae. Of the remaining 9; 2 were identified as Nitidulidae, 3 as Scarabaeidae, 1 as Rhopalidae, and 3 were not identified. All the representatives of the thirteen (subsamples) were deposited at CABI with the inquiry No CABI 002-18.

The four which were confirmed as belonging to the Carabidae family were identified to genus and/or species from the Kenya National Museum (*Anisodactylus australis* Per; *Anisodactylus* sp.; *Harpalus crotonathoides* Gat, *Harpalus asemus* Bas; *Chlaenius discopictus* Frm; and *Chlaenius* sp) with the reference number NMK/SIZ-IC 103. In the bulk of the analysis,

it is only data of the three identified Carabidae genera that was used. Information on the trap collections is summarized in Table 4.1.

Table 4.1. Insect groups, total number of insects and percentage trap collections using pitfall traps

Insect Group	Insect Total Numbers	% Trap collection
Carabidae	9780	54.4
Nitidulidae	1078	6.1
Scarabaeidae	2451	13.6
Rhopalidae	987	5.4
Un-identified Coleoptera	3693	20.5
Grand Total	17989	100



Figure 4.1 Ijala working from the National Museum of Kenya on morphological identification of Carabidae

4.2.2 Abundance of *Toxoptera aurantii*

Five coffee trees, spaced 10m away from each other, were randomly selected for this purpose. For each selected trees, 3 coffee branches were randomly selected (one for each of the positions at Low, Middle and Top), for leaf count and examination for *T. aurantii* occurrence. The study trees and branches were tagged using ribbons. The total number of leaves on each branch, aphid infested leaves (discolored and with aphids) were counted. The numbers of aphids on each of the infested leaves were counted with aid of a magnifying lens, following the procedures of Sudiono *et al.* (2017).

Data were collected in 12 rounds, in two years, covering the major and minor coffee production cycles (5 trees x 3 branches x 4 coffee farming systems x 3 altitude levels x 12 rounds= 2160). Proportions were calculated for the pest infestation intensity in each data collection round, following Sudiono *et al.* (2017).

4.2.3 Above ground and below ground soil microclimate, and soil properties

Data on above ground microclimate parameters of ambient temperature, relative humidity and light intensity as well as vegetation diversity were collected as in Section 3.2.3.3 and Table 3.1 in Chapter three.

The data on soil properties were obtained *in-situ* at each farm level. Data was collected on soil temperature ($\pm 1^{\circ}\text{C}$), soil moisture ($\pm 3\%$ VWC), and soil electrical conductivity (EC) $\pm 5\%$ from 0 to 5 dS/m using Procheck sensor (GS3 model) and soil pH using a pH meter following the technology of Wadsworth (2015). All the measurements were taken from a soil depth of 0 – 15 cm. The soil organic matter was determined from a composite sample using laboratory procedures of Okalebo *et al.* (2002). A checklist was used to collect data on soil management practices and categorized as 1= organic-intensive, 2= inorganic-intensive, and 3= no management. The data on soil variables were used in establishing relationships (correlations and regression) with Carabidae occurrence following guidelines of Karungi *et al.* (2018). Mean soil microclimate parameters designated as below ground microclimate parameters and rain/dry season for the studied farmlands are shown in Table 4.2.

Table 4.2. Below ground microclimate variables of different farming systems at different altitudes and seasons

Altitude	Farming system	Season	Soil moisture (m ³ /m ³)	Soil EC (dS/m)	Soil pH
Low	Coffee+banana+ shade trees	Dry	0.41	0.3	6.29
		Rainy	0.35	0.2	7.81
	Coffee+banana	Dry	0.35	0.2	6.29
		Rainy	0.39	0.2	7.84
	Coffee monocrop	Dry	0.41	0.3	6.21
		Rainy	0.37	0.2	7.23
	Coffee+annual	Dry	0.36	0.2	6.32
		Rainy	0.43	0.2	7.41
	Coffee+banana+ shade trees	Dry	0.4	0.2	6.43
		Rainy	0.43	0.2	7.18
Mid	Coffee+banana	Dry	0.44	0.3	6.36
		Rainy	0.46	0.1	7.57
	Coffee monocrop	Dry	0.43	0.2	6.61
		Rainy	0.43	0.1	7.29
	Coffee+annual	Dry	0.39	0.1	6.49
		Rainy	0.48	0.3	7.16
High	Coffee+banana+ shade trees	Dry	0.41	0.2	6.41
		Rainy	0.44	0.2	7.1
	Coffee+banana	Dry	0.43	0.2	6.51
		Rainy	0.02	0	7.32
	Coffee monocrop	Dry	0.43	0.2	6.33
		Rainy	0.47	0.3	7.35
	Coffee+annual	Dry	0.39	0.2	6.04
		Rainy	0.48	0.3	6.9

4.2.4 Semi natural vegetation parameters

To establish abundance and diversity of the semi natural vegetation in the coffee fields data on tree vegetation, grasses and weeds within the study sites were collected and summarized in Table 3.1 in Chapter three.

4.3 Data analysis

Data on Carabidae and *Toxoptera aurantii* counts were analyzed using the generalized linear mixed models (GLMM) of GenStat 19 Computer Software. The Poisson distribution with a logarithm link was used with the farm as a random factor with a dispersion of 1 for fixed factors. The Wald tests were generated for tables and back-transformed means were used in the figures. Mean separations were done using Fischer's protected LSD at 5%.

For the data on leaf damage intensity by *T. aurantii*, binomial distribution and logit link were used since the data was on proportions.

As for the relationship of Carabidae with below and above ground microclimates; and semi natural vegetation, the variables for soil properties, above ground microclimate; and semi natural vegetation were used as predictors while transformed $(X=0.5)^{1/2}$ numbers of Carabidae were the response variables in the general linear regression. The auto selection of potentially important predictors was done using a stepwise regression procedure of a generalized linear regression model. In the testing criteria, fixed critical F-values (Test Criterion) were used which were not based on the actual F-distribution. Typically, criterion values of 4.0 were selected in the stepwise methods. The Change model was used to add the predictors and the worst predictors were dropped off from the model (O'Neill, 2010; Gallagher *et al.*, 2011).

To explore the relationship between Carabidae and *T. aurantii* (aphid) i.e, the data on aphid counts and Carabidae counts, a Pearson's two tailed correlation was done to establish a linear relationship between the variables; To remove the general problems of different measurement scales and avoiding the domination of the results by a few variables with large variances, PCA was done on the correlation matrix with standardized variables (mean 0, variance 1) using the extraction method of GenStat 19, with two fixed dimensions. For the biplot, the first two principal component scores were standardized to have equal variance and plotted against one another. All the four standardized variables contributed to the first principal component; likewise, the second (vertical) coordinate of the vectors represented the coefficients of the second principal component.

4.4 Results

4.4.1 The effect of altitude and farming system on Carabidae occurrence

The results of analysis revealed a highly significant effect of altitude, farming system, and altitude*farming system interactions on the occurrence of the Carabidae genera *Anisodactylus* spp., *Chlaenius* spp., and *Harpalus* spp. (*Anisodactylus* spp., Altitude $F_{df\ 2; 778} = 20.28$; $P < 0.001$; Farming system $F_{df\ 3; 778} = 3.36$; $P = 0.019$; Altitude*Farming system $F_{df\ 6; 778} = 3.26$; $P = 0.004$; *Chlaenius* spp., Altitude $F_{df\ 2; 778} = 5.94$; $P = 0.003$; Farming system $F_{df\ 3; 778} = 5.57$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 778} = 3.06$; $P = 0.006$; and *Harpalus* spp., Altitude $F_{df\ 2; 778} = 6.12$; $P = 0.002$; Farming system $F_{df\ 3; 778} = 4.98$; $P = 0.002$; Altitude*Farming system $F_{df\ 6; 778} = 4.97$; $P < 0.001$).

Anisodactylus spp. occurrences varied owing to changes in altitude and farming system (Table 4.3). Within low altitude, the occurrence of *Anisodactylus* spp. was significantly lowest in the Coffee+banana systems, and did not differ significantly in the rest of the farming systems. Whereas there were no differences in occurrence among the farming systems at mid altitude, the occurrence within the Coffee+annual crop, was the highest in high altitude and Coffee monocrop was the lowest.

As regards the farming system, within the Coffee monocrop, occurrence was highest in the mid altitude whereas it was not significantly different between high and low altitudes. Within the Coffee+annual crop, occurrences were highest in high altitude followed by mid altitude, and then low altitude respectively (Table 4.3). Also, in the Coffee+banana, occurrence followed the same pattern as in Coffee+annual crop farming system. The same trend continued within the Coffee+banana+shade trees system.

Table 4.3. Mean occurrence of *Anisodactylus* spp. at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+ Banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	38.2±0.6b ^A	29.09±0.5b ^A	18.06±0.4a ^A	26.67±0.6b ^A	28	3.6
Mid	51.6±0.8a ^B	63.03±1.2a ^B	54.67±1.3a ^B	52.12±0.8a ^B	55.4	2.3
High	37.3±0.6a ^A	144.00±2c ^C	94.79±1.3b ^C	91.15±1.6b ^C	92	19
Farming system mean	42.4	79	56	57		
SE	4.6	34	22	19		

Means followed by the same letter within the row (lower letter case-Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P<0.05$

Chlaenius spp. occurrence differed owing to changes in both altitude and farming systems (Table 4.4). Within low altitude, *Chlaenius* spp. occurrence were only observed in Coffee+annual crop and Coffee+banana; while occurrence was similar for Coffee monocrop and Coffee+banana+shade trees systems farming systems. Within the mid altitude, *Chlaenius* spp. occurrence was highest in Coffee+banana+shade trees whereas, the rest of the farming systems did not differ significantly. Within high altitude, occurrence was significantly highest in Coffee+banana+shade trees followed by Coffee+banana system and the rest of the farming systems did not differ significantly (Table 4.4).

Looking at the farming system, within the Coffee monocrop farming systems, the occurrence of *Chlaenius* spp. was the highest in mid altitude (Table 4.4). Within the Coffee+annual crop, occurrence was not significantly different between low and mid altitudes while there was no occurrence at high altitude. As for the occurrence within the Coffee+banana, they were no significant differences due to altitude. Within the Coffee+banana+shade trees, occurrences did not differ between mid and high altitude while no occurrence was registered at low altitude.

Table 4.4. Mean occurrence of *Chlaenius* spp. at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+banana	Coffee+banana + shade trees	Altitude mean	SE
Low	0.0a ^A	5.94±0.3b ^B	4.85±0.2b ^A	0.0a ^A	3	1.4
Mid	6.67±0.2a ^B	4.61±0.2a ^B	8.12±0.4a ^A	21.58±0.5b ^B	10	3.3
High	2.2 ±0.09a ^A	0.0a ^A	5.21±0.2b ^A	15.15±0.3c ^B	5.6	2.9
Farming system mean	3	3.5	6	12.2		
SE	1.96	1.8	1	6.4		

Means followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at P<0.05

Similarly, *Harpalus* spp. varied with differences in altitude and farming system (Table 4.5). Within low altitude, occurrence of *Harpalus* spp. was significantly highest in the Coffee monocrop followed by Coffee+banana+shade trees, and did not differ significantly in the rest of the farming systems. Within the mid altitude, *Harpalus* spp. occurrence was significantly highest in the Coffee+banana+shade trees and lowest in the Coffee+annual crop (Table 4.5). Within the high altitude the same trend as at mid altitude was exhibited.

Within the Coffee monocrop and Coffee+annual crop farming systems, the occurrence of *Harpalus* spp. was highest in the low altitudes while high and mid altitudes did not differ significantly. There were no significant differences within the Coffee+banana farming systems due to altitude. As for the *Harpalus* spp. occurrence within the Coffee+banana+shade trees, farming system, it was highest at high altitude, and no significant difference existed between mid and low altitude.

Table 4.5. Mean occurrence of *Harpalus* spp. at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+ annual crop	Coffee+banana	Coffee+banana +shade trees	Altitude mean	SE
Low	164.97±4d ^B	23.27±0.7a ^B	19.03±0.5a ^A	39.03±1c ^A	62	31
Mid	15.8±1.1b ^A	5.70±0.2a ^A	14.55±0.6b ^A	31.76±1.3c ^A	17	5
High	13.6±0.4b ^A	3.52±0.2a ^A	17.82±0.9b ^A	61.45±1.6c ^B	24	11
Farming system mean	65	11	17	44.1		
SE	50	0.9	1.3	9		

Means followed by the same letter within the row (lower letter case- farming system); and means followed by the same letter within the column in (upper letter case- Altitude) do not differ significantly at P<0.05

4.4.2. The relationship between Carabidae occurrence and above and below- ground microclimate parameters, and diversity of semi natural vegetation

Linear regression of potentially important predictors for Carabidae occurrence indicated specific significant relationships. Soil moisture, pH, and soil EC were the studied soil properties and formed the below-ground microclimate. For *Anisodactylus* spp., the only significant relationship was with soil moisture, which was positive (Table 4.6a). On the other hand, *Harpalus* spp. had a significant positive relationship with soil EC (Table 4.6a). *Chlaenius* spp. had a significant relationship with soil pH, which was negative (Table 4.6a).

Uniquely, ambient temperature, relative humidity, and light intensity that formed the above-ground microclimate were not significant predictors of Carabidae abundance for any genera in this study (Table 4.6a).

Table 4.6a. Regression parameter estimates, standard error, and T statistic for the relationship of Carabidae counts with below and above ground microclimate parameters

Carabidae genera	Parameter	Estimate	SE	T statistic
<i>Below ground microclimate parameters</i>				
<i>Anisodactylus</i> spp.	Constant	0.242	0.949	0.26
	soil moisture (m ³ /m ³)	3.86	1.500	2.58**
	pH	0.047	0.139	0.34
	soil EC (dS/m)	-1.041	0.989	-1.05
<i>Harpalus</i> spp.	Constant	3.80	1.22	3.12
	soil moisture (m ³ /m ³)	-5.80	1.92	-3.01
	pH	-0.285	0.178	-1.60
	soil EC (dS/m)	6.73	1.27	5.30***
<i>Chlaenius</i> spp.	Constant	2.418	0.912	2.65
	soil moisture (m ³ /m ³)	0.840	1.44	0.58
	pH	-0.292	0.133	-2.19*
	soil EC (dS/m)	-1.753	0.95	-1.84
<i>Above ground microclimate parameters</i>				
Carabidae genera	Parameter	Estimate	SE	T statistic
<i>Anisodactylus</i> spp.	Constant	0.730	1.69	0.43
	%Relative humidity	0.0142	0.025	0.57
	Light intensity (foot candles)	0.0006	0.001	0.43
<i>Harpalus</i> spp.	Constant	0.920	4.63	0.20
	% Relative humidity	0.0305	0.038	0.81
	Temperature (°C)	-0.088	0.113	-0.78
<i>Chlaenius</i> spp. (Parameters were minor to the model and dropped off).				

Values with *** significant at <0.001, ** significant at <0.01, * significant at <0.05

With regard to the relationship with semi-natural vegetation, *Chlaenius* spp. was the only Carabidae genera that showed a significant relationship with semi natural vegetation diversity, which was positive (Table 4.6b).

Table 4.6b. Regression parameter estimates, standard error, and T statistic for the relationship of Carabidae counts and seminatural vegetation diversity

Carabidae genera	Parameter	Estimate	SE	T statistic
<i>Anisodactylus</i> spp.	Constant	5.400	1.560	3.47
	Semi natural vegetation	-0.287	0.456	-0.63
<i>Harpalus</i> spp.	Constant	-0.660	1.400	-0.47
	Semi natural vegetation	0.684	0.410	1.67
<i>Chlaenius</i> spp.	Constant	-0.772	0.599	-1.29
	Semi natural vegetation	0.416	0.176	2.37*

Values with * significant at $P < 0.05$

4.5 Occurrence of the coffee aphid, *T. aurantii* and its relationship with Carabidae

4.5.1 The effect of altitude and farming system on occurrence of the Coffee aphid, *T. aurantii*

Altitude, farming system; and altitude*farming systems interactions significantly influenced occurrence of *T. aurantii* (Altitude: $F_{df\ 2; 2146} = 78.88$; $P < 0.001$; Farming system: $F_{df\ 3; 2146} = 34.39$; $P < 0.001$; Altitude*Farming system: $F_{df\ 6; 2146} = 20.50$; $P < 0.001$). Within the low altitude, the occurrence of *T. aurantii* was not significantly different among the farming systems (Table 4.7). As for the occurrence within the mid altitude, it was highest in the Coffee+banana+shade trees, followed by Coffee+annual crop, then Coffee monocrop, and lowest in the Coffee+banana. There no significant differences among the farming systems within the high altitude (Table 4.7).

As for the farming systems, within the Coffee monocrop, the *T. aurantii* occurrences were significantly lowest in the high altitudes whereas mid and low altitudes were not significantly different. Within the Coffee+annual crop, the highest occurrence was in the mid altitude followed by the low altitude and then lowest in the high altitude. As for the occurrence within the Coffee+banana farming system it was highest in the low altitude whereas no significant differences existed in the mid and high altitudes. Within the Coffee+banana+shade trees, the highest occurrences of *T. aurantii* was in the mid altitudes followed by low, and the lowest was in the high altitude (Table 4.7).

Table 4.7. Mean of occurrence of *T. aurantii* at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana+ shade trees.	Altitude mean	SE
Low	10.6±3a ^B	15.14±1b ^B	14.02±1b ^B	17.43±2b ^B	14.3	1.2
Mid	16.52±3b ^B	24.51±2c ^C	6.44±1a ^A	46.71±4d ^C	24	7.4
High	4.1±0.8a ^A	7.14±1a ^A	6.82±0.8a ^A	4.83±1a ^A	6	0.6
Farming system mean	10.4	16	9.1	23		
SE	4	5	2.4	12.4		

Means followed by the same letter within the row (lower letter case-farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P < 0.05$

4.5.2 The effect of altitude and farming system on the coffee aphid infestation

The proportional leaf damage intensity of Arabica coffee by *T. aurantii* was significantly influenced by altitude and farming system; the interaction of altitude and farming system did not have a significant influence (Altitude $F_{df\ 2; 2146} = 34.35$; $P < 0.001$; Farming system $F_{df\ 3; 2146} = 15.85$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 2146} = 1.28$; $P = 0.264$). Results showed that the Coffee monocrop system had the lowest leaf damage intensity and the Coffee+annual crop had the highest among the farming systems (Fig 4.2A). Looking at the altitude levels, high altitude had the lowest leaf damage intensity and the highest was in the mid altitude (Fig 4.2B).

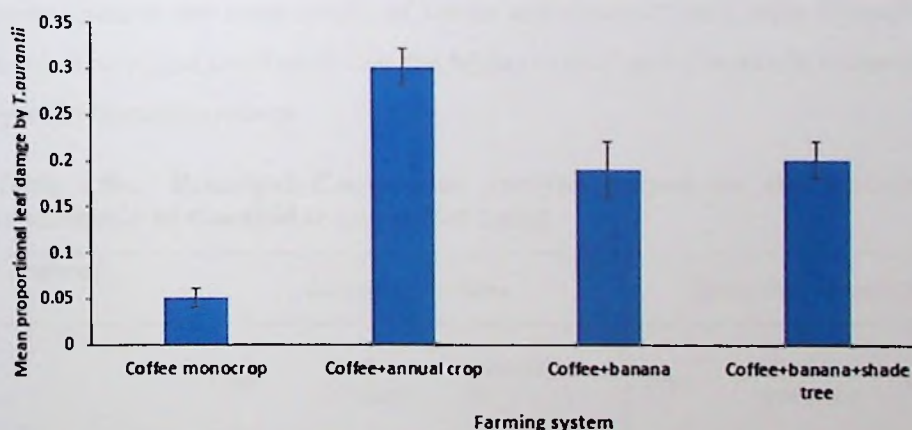


Figure 4.2A. Means of proportional leaf damage of Arabica coffee by *Toxoptera aurantii* with different farming systems in the Mt. Elgon region

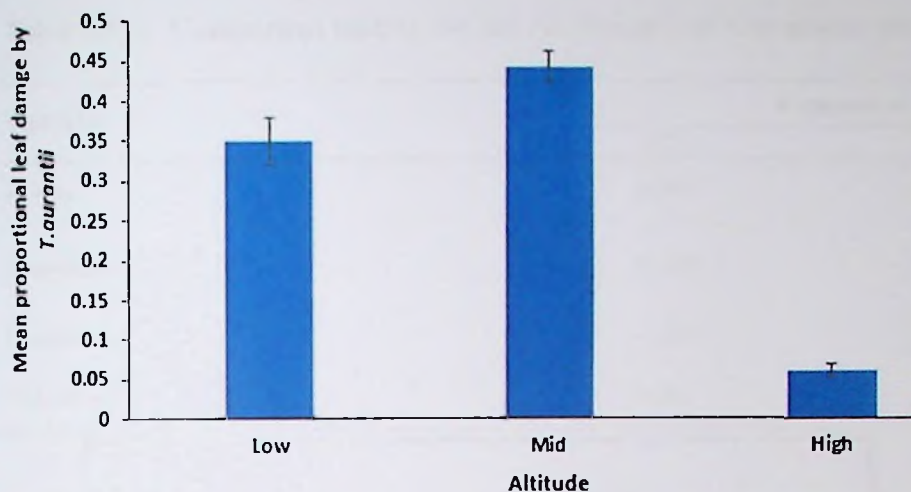


Figure 4.2B. Means of proportional leaf damage/ farm of Arabica coffee by *Toxoptera aurantii* at different altitudes in the Mt. Elgon region

4.5.3 Relationship of Carabidae with *T. aurantii*

Results of the PCA show that the loading for PC1 and PC2 cumulatively accounted for 57.1% of the total variation (Table 4.8a). The biplot shows that the coffee aphid correlated highly and negatively to *Anisodactylus* spp.; *Chlaenius* spp.; and *Harpalus* spp. The length of the vectors indicates the weight of the score for each of the important variables. All the three Carabidae had approximately the same length of vector and shortest being with *Harpalus* spp. (Fig 4.3; Table 4.8b). The biplot confirmed that the highest aphid and Carabiade occurrence were associated to specific farming systems.

Table 4.8a. Principal Component Analysis output for the cumulative variance in the relationship of Carabidae and coffee aphid

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.205	30.129	30.129	1.205	30.129	30.129
2	1.078	26.938	57.067	1.078	26.938	57.067
3	0.958	23.949	81.016			
4	0.759	18.984	100			

Table 4.8b. Component matrix for the relationship of Carabidae and aphids

Variables	Component	
	PC1	PC2
Aphids	0.764	-0.136
<i>Anisodactylus</i> spp.	-0.626	0.514
<i>Harpalus</i> spp.	-0.288	-0.548
<i>Chlaenius</i> spp.	0.382	0.703

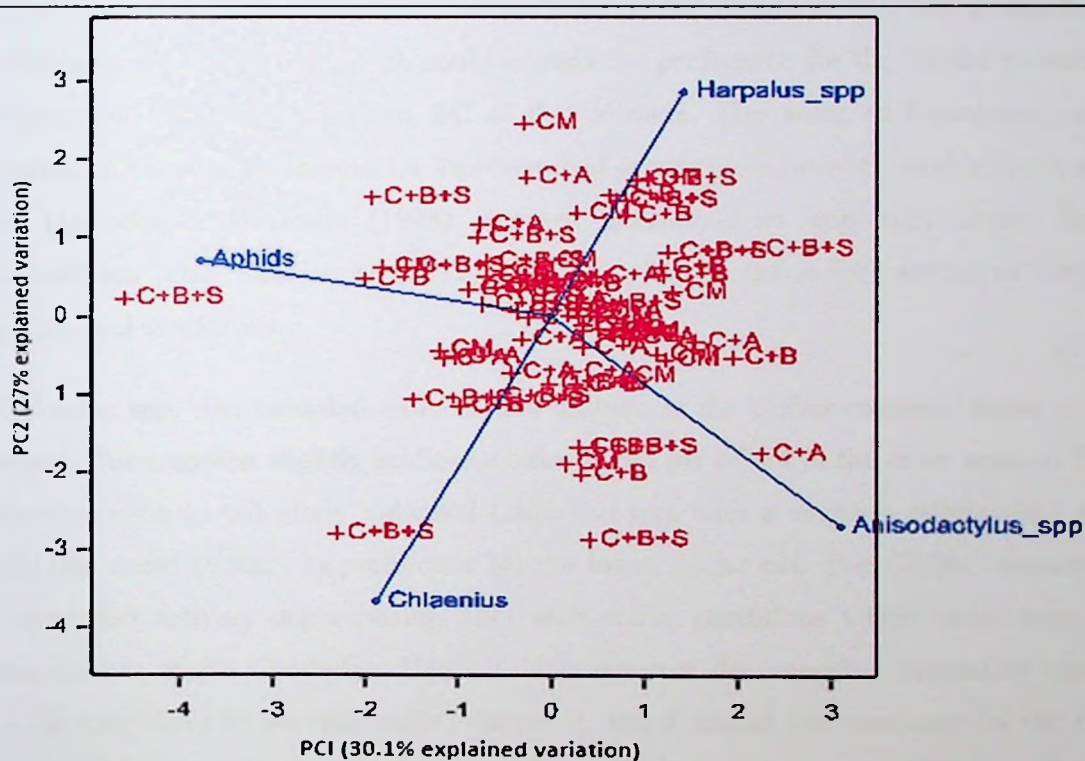


Figure 4.3 PCA biplot for the relationship between Carabidae and the coffee aphid, *T. aurantii*

4.6 Discussion

The occurrences of Carabidae in the Mount Elgon region of Uganda were specific to genus and preferences for certain specific habitats which were created by the altitude and farming system interactions. These specificities of the Carabidae genus could to some extent be explained by the below ground microclimate.

Harpalus spp. were more abundant in the low altitude and Coffee monocrop farming systems and these could be explained by the below ground microclimates. The below ground microclimates under monocropped conditions could be unique to stable soils, soil moisture, and soil salts. The *Harpalus* spp. preference for these systems could indicate the preference to the stable soil conditions with balanced soil electrical conductivity and organic matter. The Coffee monocropped fields in this study were mostly maintained under slashed predominantly grassy undergrowth conditions with no tillage, which could have retained stable soil electrical conductivity levels that favored *Harpalus* spp. In this study, low altitudes and Coffee monocropped with moderate soil EC (mean 0.2 dS/m were found stable during the rainy conditions). Infact the regression analysis showed that *Harpalus* spp. had a significant positive relationship with soil EC, which could explain the preference for the Coffee monocrop farming systems which had the highest EC at that altitude. The work of Twardowski *et al.* (2017) reported Carabidae preference for less disturbed grassy areas (mowed once a year); and the study by Desender & Bosmans (1998) reported grasslands as important niches for Carabidae populations. Also, Sadej *et al.* (2012) indicated a better chance for survival of Carabidae under grassy land conditions.

Chlaenius spp. was recorded more at mid altitude in the Coffee+banana+shade trees system, a system that recorded slightly acidic conditions with pH of 6.4 in the dryer season. The results of the regression in this study indicated *Chlaenius* spp. with a negative relationship with soil pH. and this could explain its preference for the lower acidic pH. The Coffee+banana+shade trees system had actively decomposing litter with acidic conditions which could have favored the occurrences of the Carabidae. Hance (2002) reported decomposing vegetative materials under acidic conditions to provide shelter, breeding, and dispersal environments for the Carabidae. In this study *Chlaenius* spp. also was positive with the semi natural vegetation. The seminatural vegetations could be characterized with high leafy and actively decomposing debris with lightly acidic conditions. Baranova *et al.* (2018) also reported humus accumulation to promote the presence of Carabidae under less acidic conditions.

Anisodactylus spp. showed a marked preference for high altitudes in Coffee+annual farming systems. The Coffee+annual crop systems undergo frequent tillage operations during seasonal additions of the annual crops; which create loosened soil conditions that may favor this genus.

The preference for high altitude could be due to the high soil moisture levels ($0.48\text{m}^3/\text{m}^3$ and in the rainy season), high up on the slopes of the mountain as it showed a significant positive relation with soil moisture. Members of this genus have been reported to exhibit specific preference for habitats /niches with moderately moist conditions and presence of small seeded low crops (Eo *et al.*, 2016; Qodri & Noerdjito, 2016).

Though distinct in effect for the three Carabidae genera, this study provides further evidence of soil moisture, and soil pH as important drivers of Carabidae occurrence. The study adds to the findings of Baguette (1993) who reported that distributions of Carabids were mostly related to the acidity, organic content and water holding capacity of the soils; to Holopainen *et al.* (1995) who ranked soil water content and soil pH as some of the soil factors of importance to Carabidae; to Luff (1996) who reported soil moisture to be the most important environmental factor affecting Carabid assemblages; and more recently, to Vician *et al.* (2015) who reported higher species diversity of Carabid beetles in the plots with a higher pH and humus content. The soil moisture, soil pH, and soil EC found in the studied parcels are a result of prevailing physical and management aspects, in this case the interaction between altitude and farming systems; a fact that is echoed by other studies (Adis, 1998; De Bauw *et al.*, 2016; Baranova *et al.*, 2018; Hiramatsu & Usio, 2018; Allema *et al.*, 2019).

Though some studies have shown Carabidae to prefer more diverse crop habitats (Noordijk *et al.* 2011), in this study *Chlaenius* was the only genus that was positively influenced by increased semi-natural vegetation diversity. Luff & Rushton (1989) found ground beetle communities influenced more by soil parameters than vegetation structure. Tschardtke *et al.* (2005) and Liu *et al.* (2012) showed Carabidae to uniquely prefer intensively cultivated arable land compared to undisturbed or semi-natural habitats. Even in the cultivated habitats, this study has shown that it is not a 'one size fit all' scenario for the Carabidae. From this study, Carabidae occurrence is to some extent shaped by farming practices which are linked to the respective decisions made on the farms, for example, management directly impacting the diversity of the plant communities, and soil and water conservation techniques. This decision can be helpful in designing strategies intending to tap gains from the generalist predators for pest control.

In this study, the Carabidae occurrence and numbers were correlated with aphid numbers using the PCA analysis. Their relationship was negative for all the three genera with the aphids. Increasing the Carabidae numbers (*Harpalus* spp., and *Anisodactylus* spp.), reduced the aphid numbers. This can be explained on one hand by the diverging preferences in farming systems but one can also argue that the Carabidae are able to prey on the aphids. The predatory nature of Carabidae on aphids was reported in the earlier studies done by Loughridge & Luff (1983) and Edwards *et al.* (1979); and recent studies (LaRochelle, 1990; Lovei & Sunderland 1996; Menalled *et al.*, 1999; Ogunrinde & Adebajo, 2007; Sunderland, 2002). Much as the effectiveness of Carabidae in aphid reduction is dependent on higher Carabidae numbers, it is also influenced by other factors such as soil microclimates, and presence or absence of vegetation (Kromp, 1999; Koivula, 2011; Liu *et al.*, 2010, 2015; Qodri, 2016). Nonetheless, the observed negative relationship of Carabidae spp. and aphid numbers in the present study provides insights on possible field management of aphids using generalists' predators. Moreover, critical microclimates in the soil and vegetation play a great role in the assemblage of Carabidae numbers for their efficacy in pest reduction (Kromp, 1999; Park, *et al.*, 2015; Sadej, *et al.*, 2012; De Bauw *et al.*, 2016; Eo *et al.*, 2016; Qodri & Noerdjito, 2016).

4.7. Conclusion

Three Carabidae genera were found with high occurrences in coffee fields of the mount Elgon of Uganda. *Anisodactylus* spp. were more abundant in the high altitudes and the often-tilled Coffee+annual cropped; *Chlaenius* spp. were more abundant in the mid altitudes and Coffee+banana+shade tree farming systems; and *Harpalus* spp. were more abundant in the low altitudes and Coffee monocrop farming systems which were maintained by grass slashing. These specific genera niche preferences were a result of soil properties, and semi-natural vegetation diversity, which stemmed from the farming system and altitudinal placement. The relationship between Carabidae and *T. aurantii* was variable and genus dependent and seemed to be driven by the preferred farming system of the functional group. The negative results observed could be an insight in the aphid field management using the generalists' predators.

CHAPTER FIVE

EFFECT OF FARMING SYSTEM ON COFFEE FOLIAGE AND COFFEE BEAN YIELD PERFORMANCE AT THE DIFFERENT ALTITUDES IN THE MOUNT ELGON REGION OF UGANDA

5.1 Introduction

Coffee grown under increased plant diversity can give better coffee yields which are often associated with subsequential benefits derived from shady tree conditions (Waller *et al.*, 2007). Tree conditions can create lower cooling conditions which facilitate increased berry sets for better coffee yields and longer maturation period (Guyot *et al.*, 1996). The resulting larger berries with slower maturation often receive more in nutrients partitioning (Perfecto *et al.*, 2005; Vaast *et al.*, 2006). Also, increased plant diversity in coffee farms ensures a variety of pollen sources for extra advantages associated with insect pollination in Arabica coffee. Insect pollinators in Arabica coffee have been reported for increasing coffee yields (Perfecto *et al.*, 2007).

Modified soil and microclimatic conditions which are due to increased presence of plants and semi natural vegetation could influence coffee foliage for productivity along the altitude gradient. These could improve on the coffee tolerance to adverse climatic conditions. Resilience in coffee trees is key in stabilizing coffee leaf biomass and productivity (Rao *et al.*, 2000; Varon *et al.*, 2007).

In the Mount Elgon region, coffee is grown under variable coffee and cropping intensities along the altitude (EcoTrust, 2012; Karungi *et al.*, 2018). How these influences coffee productivity is not clearly articulated. This study was set to determine the most suitable farming system for increased coffee leaf foliage and berry yield performance at the different altitudes in the MER.

5.2 Materials and method

5.2.1 Study site description

The study was conducted in the districts of Kapchorwa and Sironko, as described in chapter three section 3.2.1. The data on microclimate was collected as described in chapter three, section 3.2.2.

5.2.2 Coffee foliage and bean yield data collection

Data collection on coffee foliage and coffee berry yield was done on the same coffee farms; trees and coffee branches as described in chapter three, section 3.2.3. Within the selected coffee trees, 3 coffee branches (one for each of the positions at lower, middle and top parts) were tagged (total branches sampled: 5 coffee trees (3 branches for each) x 4 farming systems (3 farms for each) x 3 altitude levels and x 2 districts x 2 rounds = 2160). For the foliage, the total number of healthy leaves/branch were counted during the active vegetative period of coffee. For the coffee berry yield, the total number of marketable coffee berries (mature ripe and pest free) on each of the tagged branches above were inventoried.

5.3 Data analysis

The data on the leaf foliage and berry yield were analyzed in the Generalized Linear Mixed Models (GLMM) of GenStat 19, with a branch as a random factor and dispersion of 1 for fixed factors. The logarithmic link was used because the data were non normally distributed. The Wald tests were generated for tables. Mean separations were done using Fischer's protected LSD at 5%. The auto selection of potentially important predictors was done using a stepwise regression procedure of generalized linear regression model involving farmer practices and were dropped off by the model. The data on clean coffee foliage and bean yield, a simple linear regression was done to cater for the relationship with the pests.

For the relationships involving coffee bean yield, microclimate, semi natural vegetation and the leaf foliage, a Pearson's two tailed correlations were utilized and the principal component analysis was done as in chapter four section 4.3. All the five standardized variables contributed to the first principal component. Likewise, the second (vertical) coordinate of the vectors represented the coefficients of the second principal component.

5.4 Results

5.4.1 Effect of altitude and farming system on Arabica clean coffee foliage and bean yield

The effect of altitude, farming system; and altitude farming systems interaction on the leaf foliage and coffee bean yield were highly significant (Coffee foliage - Altitude $F_{df\ 2; 2146} = 1831.82$; $P < 0.001$; Farming system $F_{df\ 3; 2146} = 21.21$; $P < 0.001$; Altitude*Farming system $F_{df\ 6;$

$_{2146} = 78.27$; $P < 0.001$; Coffee bean yield, Altitude $F_{df\ 2; 2146} = 57.37$; $P < 0.001$; Farming system $F_{df\ 3; 2146} = 32.88$; $P < 0.001$; Altitude*Farming system $F_{df\ 6; 2146} = 11.18$; $P < 0.001$).

There were variations in the mean counts for the Coffee foliage/branch as the altitude and farming system changed (Table 5.1). Within the low altitude, leaf foliage was significantly highest in the Coffee+banana+shade trees while the rest of the farming systems did not differ from each other. Within the mid altitude, no significant differences in the leaf foliage were observed among the farming systems, whereas within the high altitude, the lowest foliage was in the Coffee+banana+shade trees.

Within the farming system, the foliage in the Coffee monocrop was highest in the high altitude whereas mid and low did not differ significantly. The trend was the same within the Coffee+annual and the Coffee+banana farming system. Within Coffee+banana+shade trees farming system, leaf foliage was highest in the high altitude followed by the low altitude and lowest in the mid altitude. In overall, the highest foliage score was recorded in the Coffee+annual crop and high altitude combination (Table 5.1).

Table 5.1. Means of coffee Leaf foliage counts/branch at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana+ shade trees	Altitude mean	SE
Low	5.32±0.3a ^A	5.772±0.4a ^A	6.356±0.3a ^A	8.8±0.4b ^B	7	0.7
Mid	6.1±0.8a ^A	5.744±0.9a ^A	5.122±0.6a ^A	5.483±0.5a ^A	6	0.2
High	16.178±0.3d ^D	18.2±0.29d ^D	16.394±0.3d ^D	11.71±0.33C ^C	16	1.1
Farming system mean	9.2	10	9.3	8.7		
SE	3.5	4.1	3.6	1.8		

Means followed by the same letter within the row (lower letter case- Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P < 0.05$

Coffee bean yields varied by altitude and farming system (Table 5.2). Within low altitude, the coffee bean yield was significantly highest in the Coffee+banana+shade trees and lowest in Coffee+annual crop; yield did not differ in Coffee monocrop and Coffee+banana farming systems. Within the mid altitude, the highest bean yield was in the Coffee+banana+shade trees and the rest of the farming systems did not differ significantly. Within the high altitude, the

Coffee monocrop and Coffee+banana did not differ significantly and so was the Coffee+annual crop and Coffee+banana+shade trees which through were higher than the former.

Looking at the farming systems, coffee bean yield was lowest in the mid altitude within the Coffee monocrop farming system whereas high and low altitudes did not differ significantly. Within the Coffee+annual crop, the highest bean yields were recorded in the high altitude while the yields in low and mid altitude did not differ significantly. As with the Coffee+banana, the lowest bean yields were in the mid altitude whereas high and low altitudes did not differ significantly. Within the Coffee+banana+shade trees, the coffee bean yields were highest in the low altitude followed by high altitude, and then lowest in the mid altitude (Table 5.2). Significantly the highest coffee bean yields among all the farming systems were recorded in Coffee+banana+shade trees at low altitude.

Table 5.2. Means of clean coffee bean yield (number of berries/branch) at different altitudes and farming systems

Altitude/ Farming system	Coffee monocrop	Coffee+annual crop	Coffee+banana	Coffee+banana +shade trees	Altitude mean	SE
Low	16±2b ^B	13.6±0.9a ^A	18.1±1.1b ^B	33±2.6d ^D	20.2	3.8
Mid	13.8±0.8a ^A	12.8±0.7a ^A	10.02±0.6a ^A	15.5±1.1b ^B	13	1
High	19.3±0.9b ^B	20.1±0.1c ^C	16.21±0.6b ^B	21±1.2c ^C	19	0.9
Farming system mean	16.4	15.5	14.8	23		
SE	1.6	2.3	2.4	5.2		

Means followed by the same letter within the row (lower letter case-Farming system); and means followed by the same letter within the column in (upper letter case-Altitude) do not differ significantly at $P < 0.05$

5.4.2 The relationship of yield, coffee foliage, microclimate, semi natural vegetation and pests' infestation

Results of the PCA biplot show that the PCI and PC2 cumulatively accounted for 65% of the total variation (Table 5.3a; Fig. 5.1). Temperature and relative humidity were highly correlated with coffee bean yield (clean coffee yield). Semi natural vegetation loaded least in the relationship (Table 5.3b). The biplot shows that the relationships of relative humidity, temperature and coffee bean yield were associated with specific farming systems. For the relationship of yield and the pests', the simple linear regression revealed a significant negative

effect of *H. hampei* berry infestation and coffee aphid leaf infestation on coffee bean yield (Table 5.3c).

Table 5.3a. Principal Component Analysis output for the cumulative variance in the relationship of yield, coffee foliage, and microclimate and semi natural vegetation

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.062	41.240	41.240	2.062	41.240	41.240
2	1.218	24.365	65.605	1.218	24.365	65.605
3	1.071	21.424	87.029			
4	.521	10.423	97.452			
5	.127	2.548	100.000			

Table 5.3b. Component matrix for the relationship of coffee bean yield, coffee foliage, microclimate and semi natural vegetation

Variables	Component	
	PC1	PC2
Semi- Natural Vegetation	0.325	0.302
Relative humidity	-0.85	0.314
Temperature	0.738	-0.615
Branch Leaves	0.44	0.648
Clean coffee yield	0.704	0.479

Table 5.3c. Regression parameter estimates, standard error, and T statistic for the relationship of pest infestation and coffee bean yield

Pest Parameter	Estimates	SE	T statistic
Constant	3.922	0.051	76.183
Coffee aphid leaf infestation	-0.200	0.049	-4.103***
Constant	4.185	0.042	100.293
<i>H. hampei</i> berry infestation	-2.751	0.157	-17.569***

Values with *** significant at <0.001,

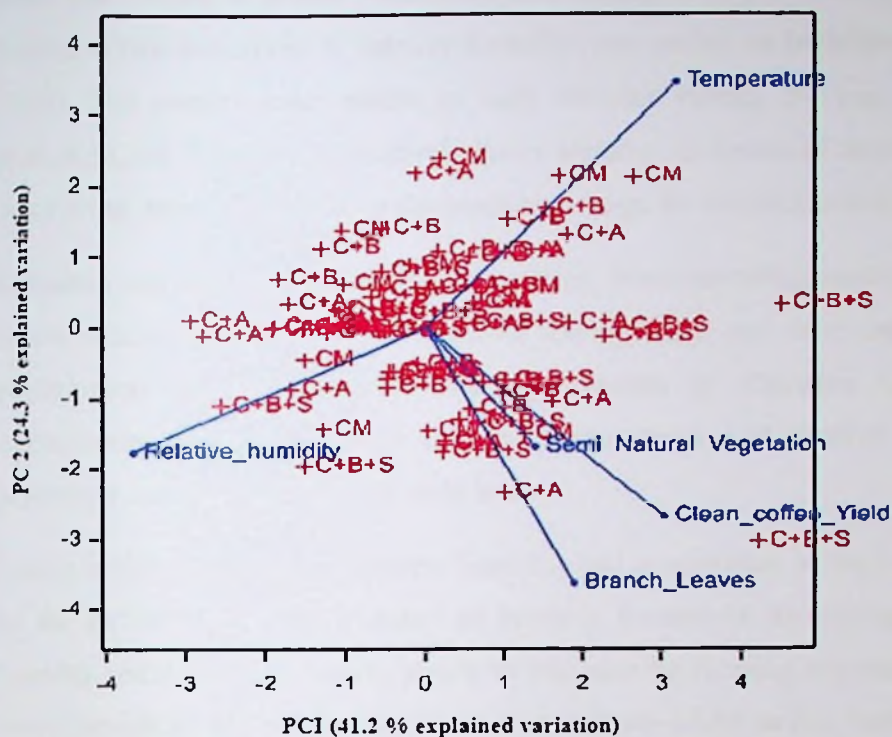


Figure 5.1 PCA biplot for the relationship of coffee bean yield, coffee foliage, microclimate and semi natural vegetation

5.5 Discussion

Coffee plant performance represented by coffee foliage and bean yield can be explained by the microclimate aspects of relative humidity and temperature of the outstanding fields. Good Arabica coffee physiological conditions for good yields have been reported at temperature ranges between 15-25°C and relative humidity above 50% (Channer & Eskeys, 2004; Waller *et al.*, 2007; Davis *et al.*, 2021). Karungi *et al.* (2018) working in the same area reported reduced relative humidities and increasing temperatures in open farming systems like the Coffee+ annual crop system compared to systems with Coffee+banana/shade tree inclusions. In this study, higher coffee foliage was reported at high altitude and Coffee annual farming system, a system with an average of 24°C for temperature and relative humidity of 59%. This system could have also reduced the abiotic stress from the major coffee leaf defoliators. In this study Coffee annual farming system was found with lower infestation of *T. aurantii*, the pest which is capable of coffee leaf defoliation (Guidolin & Consoli, 2018).

For coffee bean yield, higher green yields were found at low altitude but in the coffee+ banana shade tree system, a system with average temperature of 25°C and relative humidity of 65%. Arabica coffee sensitivity to relative humidity was earlier on highlighted by the work of Coste (1992). The present case, points to high altitudes having the best microclimate for coffee production, but if located in relatively lower altitudes, inclusion of shade trees can go a long way in buffering the microclimate to the conducive range for Arabica coffee production.

Increasing soil temperatures normally resulting from increasing ambient temperatures, and low relative humidity may affect the available soil moisture, and these can negatively impact plant physiological systems. Studies done by Damata & Ramalho (2006) indicated serious consequences of low and high extreme temperatures and relative humidity on the coffee physiology causing leaf loss and yield losses.

Results in this study showed relative humidity and temperature as the two key factors accounting for the coffee bean yield (number of berries). Extremely increasing the temperature/relative humidity could lower the coffee yields. In this case the farming systems which retain moderately lower humidities and moderately lower temperatures could be in a better position to accumulate higher coffee yields. Moderately cooler conditions existing in shaded coffee trees are capable of lowering the abiotic stress from the Coffee berry borer which is a heavy consumer of coffee beans (Ijala *et al.*, 2019). In this study CBB was found in a negative association with coffee bean yields. Because the study was set up on farmers' fields, there was no liberty of weighing the coffee beans to get the weight and only captured number of clean beans per plant. This may explain the anomalies with such studies as Guyot *et al.*, (1996) and Perfecto *et al.*, (2005) who reported that higher relative humidities and cooler conditions were conducive for the development of larger coffee berries, owing to longer periods of nutrients partitioning for better coffee yields and longer maturation periods.

5.6 Conclusion

The relative humidity and temperature microclimate created by the interaction of altitude and farming systems influenced coffee foliage performance and the coffee bean yield in the Mount Elgon region. In addition, the pests (*H. hampei* and the *T. aurantii*) which were associated with the microclimate factors had a negative effect on the coffee bean yield. High altitude and Coffee+annual farming systems favored coffee foliage whereas bean/berries were uniquely

highest in the Coffee+banana+shade tree farming system at low altitude. The introduction of shade trees in to the Coffee+banana fields could boost the coffee bean yields at lower altitudes.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussion

Altitude and/or farming system, and the resultant microclimate influenced the occurrence and diversity of the studied biological control agents, i.e., the coffee berry borer parasitoid complex and the generalists' Carabid predators in the MER farming areas albeit to variable extents. Four parasitoids namely *Cephalonomia stephanoderis*, *Prorops nasuta*, *Heterospilus coffeicola* and *Phymastichus coffea* were found to prefer particular habitats created by the interactions between altitude and farming systems that were usually driven by the prevailing microclimate. What was overarching was that the four parasitoids had a negative relationship with ambient temperature, whereas the pest (*H. hampei*, and separately, *T. aurantii*) had a positive one with temperature. As such, coffee fields at lower elevations will continue to experience elevated infestations by the coffee berry due to limited natural control as a result of unfavorable temperature conditions for the parasitoids of the pest *H. hampei*.

However, the introduction of shade trees and to lesser extent bananas in coffee fields has shown to create modifications in the environment leading higher relative humidity and cooler temperatures which favor the breeding cycles for the parasitoids. Karungi *et al.* (2018) also reported a reduction in ambient temperature of 2⁰C in the Coffee+banana+shade trees system compared to the coffee monocrop. These cooler conditions could favor the breeding cycles for the parasitoids maintaining high parasitism rates of coffee berry borer, even at lower elevations. Moreover, the floral bodies on banana and shade trees provide nectar sources and nesting sites for the parasitoids to flourish.

On the other hand, the generalist predatory Carabidae were more influenced by soil microclimate (below ground) than ambient microclimate (aboveground). There were specific genera niche preferences as a result of soil properties, and semi-natural vegetation diversity, which stemmed from the farming system and altitudinal placement. The coffee monocropped farms kept under a controlled slash system that promoted a grassy undercover favored the soil moisture-loving *Harpalus* genus of Carabidae. Twardowski *et al.* (2017) also reported a high Carabidae preference for grassy areas. This set up would be a good fit for farmers that keep coffee under

the slashed system, which additionally conserves the soil. Conversely, Carabidae of the genus *Chlaenius* favored Coffee+banana+shade tree systems, which emanated from the pH environment in those fields. This implies that farmers that opt for this system will attract this particular Carabidae and also offer the additional benefits already highlighted above, making it a more holistic system.

This study has revealed the Coffee+annual crops system as mostly limiting to occurrence of the two groups of biological control agents studied here, Hymenopteran parasitoids and the Carabidae. In the MER, this system is often used by farmers out of necessity rather than by choice because of land scarcity. For such farms/farmers, efforts can be geared towards strategic inclusion of semi-natural vegetation on their plots; this can be in form of borders, hedgerows and such. In this study, semi natural vegetation did favor the parasitoid *C. stephanoderis* and *Chlaenius* spp. one of the prominent Carabidae in the coffee farmlands.

The introduction of tree shading conditions in coffee farming was generally impactful in increasing the number of coffee berries/beans especially at low altitude. It is indeed generally agreeable that coffee agroforestry is good for bean weight and quality (Perfecto *et al.*, 2005; Vaast *et al.*, 2006; Waller *et al.*, 2007).

Therefore, strategic amelioration of temperature, relative humidity, soil moisture, pH and EC through conservation agriculture and agroforestry, inclusion of semi-natural vegetation, and maintenance of soil cover can increase the availability of parasitoids that control the coffee berry borer and the generalist Carabidae thus reducing the pest burden in the coffee fields. Reduced pest burden and better microclimates can in turn or simultaneously improve on the coffee yields for sustainable coffee production.

6.2 General Conclusions

Four Hymenopteran parasitoids (*Cephalonomia stephanoderis*, *Prorops nasuta*, *Heterospilus coffeicola*, and *Phymastichus coffea*) are present in the coffee farmlands of the Mt. Elgon region, which collectively could regulate infestations of *H. hampei*, a key pest of coffee. Significantly higher ambient temperature conditions at the lower altitudes are triggering an upward shift of parasitoids of *H. hampei* to cooler mid-high altitudes. Strategically, the inclusion of banana

and/or shade trees, and/or semi natural vegetation in the coffee systems, especially at low altitudes, could buffer microclimate, and consequently promote the parasitoids.

Three Carabidae genera (*Anisodactylus*, *Chlaenius* and *Harpalus*) were the most prevalent in the Mount Elgon coffee farmlands. Soil moisture, pH and EC ensuing from a blending of the farming system and altitudinal placement; and inclusion of semi natural vegetation were crucial in determining Carabidae genera specificity and niche preferences.

Temperature and relative humidity microclimatic conditions created in particular farming systems and altitudes were the drivers of the pest, *T. aurantii*, a pest on coffee that was found to have distinct relationships with specific genera of Carabidae.

The coffee bean yield was majorly influenced by temperature and relative humidity; in divergent ways. The Coffee+banana+shade trees system at low altitude had the highest coffee beans yields than the others.

6.3 Recommendations

Based on the conclusions above the following recommendations can be made:

- To reduce infestation of the coffee berry borer and promote the occurrence of the Hymenopteran parasitoids that regulate the pest, growers should embrace the Coffee+banana+shade trees system farming systems that buffer rising temperatures. This is especially relevant for farmers in the range of 1400-1499 m.a.s.l.
- To promote the generalist predatory Carabidae beetles that regulate the coffee aphid on coffee, especially *Anisodactylus*, *Harpalus* and *Chlaenius* spp., growers should adopt practices that enhance soil moisture retention through maintaining good ground cover and/or inclusion of shade trees+banana in their fields
- Growers are urged to embrace innovative ways of introducing semi natural vegetation in their coffee fields/proximity to promote biological control agents like the Carabidae beetles and the parasitic wasps so as to increase the unit productivity/yields of coffee farms. Semi natural vegetation can be incorporated in form of diverse hedges, borders, road reserves, and if possible, by letting adjacent plots to fallow in some periods
- Future research could focus on:

- Effects of introduction of alley cropping as a sustainable way of introducing annual crops into coffee farms on the infestation of coffee pests and their biological control agents
- Influence of soil amendments involving the use of fertilizer and manures on the pests' situations and abundance of predatory soil macro-organisms including Carabidae
- Impact of application of herbicides for bush clearance on Carabidae populations in the coffee farm lands

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APPENDICES

Appendix I: Pictorial of Laboratory and identification procedures



Morphological Identification of insects at the National Museum of Kenya using the identification keys from the museum



Insect collections for laboratory procedures